всеохватывающего (360°), телескопического угла и следит за поведением выявленной цели. Из программного комплекса «Ладога», через блок АЦП-ЦАП, на лазерную ГСН поступает сигнал об уменьшении ровно в 2 раза телескопического угла охвата обнаруженной цели (180°). Далее через многочисленные итерации по случаю дробления угла охвата выявленной цели ровно на половину, в итоге получают точные координаты цели. Время пеленга цели и удержания в телескопическом угле равно 750 нсек.

Конструкция датчика "Ладога-1М" предполагает эффективную эксплуатацию как минимум двух модулированных лазерных лучей, двигающихся синхронно друг относительно друга, один по часовой, а другой против часовой стрелки, что обеспечивает эффективный и быстрый радиопеленг для обнаружения и уничтожения цели [4—6].

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UDC 658.5

RUSSIAN TECHNOLOGIES OF THE DIGITAL REVOLUTION IN INDUSTRY. PART 2. DESIGNING AND PROGRAMMING TECHNOLOGICAL PROCESSES

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ABSTRACT

The Digital revolution in industry is supposed to cover all stages of the product life cycle, including design and programming of manufacturing processes. However, at these stages, things and processes are not yet accomplished in reality; they are only formed as models in the virtual world with the help of the Internet of Knowledge. Therefore, the Internet of Things concept, the basis of the "Industry 4.0" project, is not enough to conduct a full-scale digital revolution. The concept treats the stage prior to production quite meagerly.

This paper aims to develop a structure of the Internet of Knowledge as applied to design and programming of technological processes in digital production.

The key methodology to examine this problem is the methodology of artificial intelligence. It provides for comprehensive consideration of the problems that arise at all stages of the life cycle of engineering products.

The Internet of Knowledge has an ontological basis and includes meta-ontology, which comprises the ontology of objects, the ontology of tasks and the ontology of optimization. The Digital Revolution should give the knowledge carriers without programming skills an opportunity to enter pieces of information into the computer without intermediaries.

The materials of the paper are of practical value for the creation of integrated automation systems for the design and programming of engineering processes.

Keywords: Industry 4.0, digital manufacturing, intelligent systems, computer-aided process planning, computer-aided manufacturing, manufacturing execution system

Introduction

The ongoing Fourth Industrial Revolution (4IR) is widely recognized all over the world [1, 2, 3, 4, 5, 6, 7]. A thorough study devoted to this topic [5] includes a global map of American, European and Asian countries working in the sphere of 4IR development. Russia is not indicated on this map.

In the meantime, the leaders of the Russian Federation set the task of creating a knowledge-based digital industry in the country. This paper is devoted to the solution of this problem.

The Industrial Revolution is accompanied by the Digital Revolution. The Digital Revolution - the ubiquitous transition from analog technologies to digital ones - began in the 1980s and is still continuing in the first decades of the 21st century. The Digital Revolution brings about fundamental changes associated with the widespread use of information and communication technologies that started in the second half of the XX century and became the information revolution prerequisites, which predetermined the processes of postindustrial economy emergence.

To integrate the Industrial and Digital Revolutions, it is necessary to consider two worlds together: the virtual world realized by the Internet of Knowledge (IoK), and the real world realized by the Internet of Things (IoT).

The Internet of Knowledge has an ontological basis [8], the essential object of which is meta-ontology. From the point of view of the problems related to artificial intelligence (AI), *ontology* is an explicit specification of the knowledge conceptualization. Meta-ontology operates with common concepts and relations that do not depend on a particular subject area. Meta-ontology should contain concepts and relations required for the ontology of objects, as well as for the ontology of tasks and optimization.

The ontology of objects formally consists of a hierarchy of concepts, their definitions and attributes, as well as the axioms and inference rules associated with them. The object ontology based on the use of tasks provides, on the basis of technical tasks, the generation of 3D product models that adequately represent the products in the virtual world and meet the requirements of the tasks.

The ontology of tasks includes the tasks of structural and parametric synthesis of models of products and processes. It helps to create digital models of processes and production.

The third component of meta-ontology is the ontology of optimization; that has constituent elements of single- and multi-objective optimization.

The conceptual models of intelligent systems, at all levels from knowledge modules to knowledge banks, are based on the IDEF0 standard. In this regard, this paper also considers functional models from the level of the product life cycle to the level of construction units and processes.

The functional model of the product life cycle

The special challenges that Russia faces at the present time are import substitution (including information technology) and improvement of engineering manufacturing competitiveness and efficiency. Both of these tasks are closely related to the life cycle management (PLM) systems of engineering products.

The NX system [9] is one of non-Russian PLM systems implemented in Russian enterprises. The weak points of introducing foreign systems in Russian industry are [10]:

•fairly high cost of licenses (2-3 thousand dollars per license), implementation and maintenance;

•lack of full-fledged localization and support of standards;

•almost absolute lack of integration with domestic computer-aided design (CAD) systems;

•complex customization (it requires considerable programming in C ++ or Java).

These reasons induced the Russian company SPRUT Technology [11, 12] to develop PLM components that provide automated design (SPRUT-TP) and programming (SprutCAM) of technological processes, as well as scheduling and production management (SPRUT-OKP).

These components can work with domestic systems of automated design and design data management, which ensures the creation of a full-scale domestic PLM that takes into account all Russian standards and traditions.

The main stages of the product life cycle include: design, production, operation and disposal. The results of the design stage are documentation and information models for production. Production gives new products for human use. After the use is over, products must be disposed of (recycled).

The Internet of Knowledge is fully applied at the design stage, which is carried out in the virtual world. The Internet of Things can be useful at the subsequent stages that occur in the real world.

Fig. 1 shows the decomposition of the product lifecycle design function. In this IDEF0 diagram, the first functional block is “Marketing”. In accordance with the two main marketing concepts, the outputs of this block are marked as “requirements specification (product improvement)” and “production improvement”. The “requirements specification” is the input of the “product design” block, and the “production improvement” is the input of the “design of technological processes and equipment” block.

The requirements for the content and design of the specification are defined by the standard.

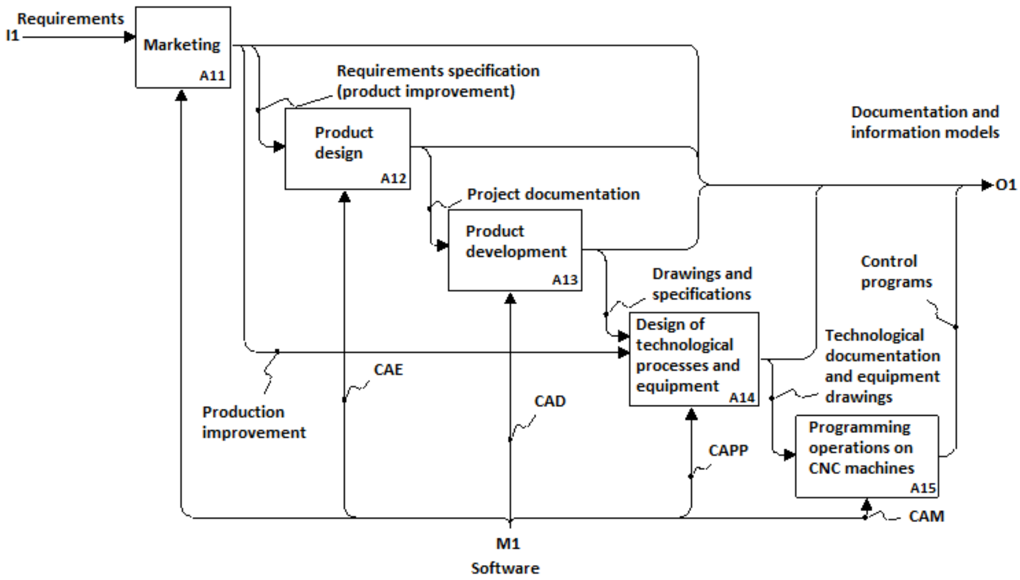

Fig. 1. Decomposition of the design function

Innovative design includes the product emergence at the stage of research and development (R&D). The share of expenses for this stage, or research intensity, is the main characteristic of innovation and strategic prospects.

The class of systems used for design calculations has the general name CAE.

Product development is carried out on the basis of the design calculations, which help to determine the main characteristics of the product. The main task of product development is to build the model of the product as a production object and to obtain the necessary set of drawings and specifications. The design and development tools at this stage are CAD systems.

Technological processes design is based the obtained design and development documentation, with the help of computer-aided process planning (CAPP) systems; equipment (dies, press-tools, accessories, special tools) is constructed as appropriate. It should be noted that in European PLM systems, CAPP systems are neglected [9].

The obtained technological documentation and tooling drawings are used in the programming of machining operations on computer numerical control (CNC) machines. The means to perform these actions are the systems of the computer-aided manufacturing (CAM) class.

The described functions form the content of the engineering preproduction.

Product functional model

Every product part is designed to perform certain functions [13 , 14] . These functions are realized with the help of the part's functional or complex elements that are located on the respective sides and formed by a set of adjacent form features. The functional elements of parts are intended to meet the specific needs associated with the manufacture and operation of the product. The needs directly related to the operation of a product are provided by the design elements of its parts, and those related to the maintenance of the product by an operator during its work - by information elements. The needs arising during manufacture of the product are provided with technological elements (Fig.2).

The need for a technical system can be formalized as

$$P = (D, G, H),$$

where D indicates the action leading to the realization of the need of interest, G specifies the object of the action and H is the indication of special conditions and restrictions, under which the action D is performed.

The classification of functional elements is presented in Table 1.

The functions of operation elements are to ensure the interaction of the product with the external medium. In the simplest case, this is associated with separation of media, which is provided by the elements of containers and seals. In power plants, the working bodies' elements provide for conversion of one energy type to another, as well as the formation of gaseous and liquid media flows. In ground vehicles, the elements interacting with the road surface provide motion on a solid surface.

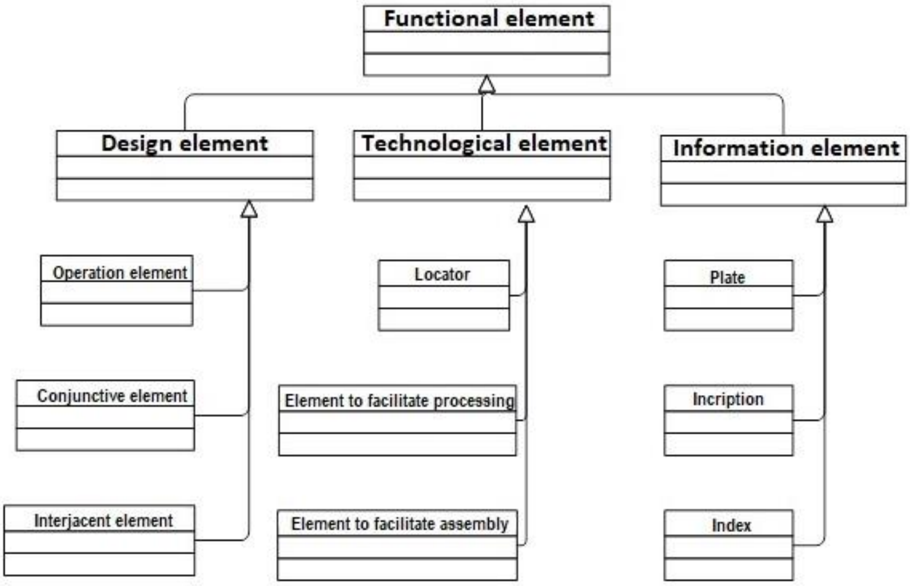

Fig. 2. The class diagram of functional elements of a part

The operation elements of audio, video, and radio systems generate and convert streams of corresponding signals. The main point of mechanical interaction with the surrounding medium is in generating motion in accordance with the specified laws using cams and conoids, or – in case of force interaction - using compression and leaf springs, etc. Tooling operation elements ensure generation of geometry and material cutting. Lastly, interaction with the operator requires presence of mechanical control devices (handles, buttons, etc.), as well as provision of necessary aesthetic perception of the product.

Assembly units are formed by conjunctive elements of parts. Connection of parts is possible be means of movable contacts or fixed detachable and permanent contacts. The elements of the connection with a movable contact provide generation of the motion of machine work members (guiding ways), the conversion of one motion type to another type (lead screws, ratchets, etc.), the transmission of torque by the elements of tooth, worm gears and other gears, as well as lubrication of surfaces.

The elements of detachable connections of parts with a fixed contact provide torque transmission, resistance to force, locating of parts, as well as the location of fasteners and compatibility of adjacent parts.

The last subclass of structural elements is the group of intermediate elements that ensure integrity, strength, rigidity, smoothness of surfaces and reduction of the parts mass.

Technological elements are necessary to ensure the locating of parts during processing, to exit the tool cycle at the end of a machining pass and to facilitate the product assembly.

The last class of functional elements are information elements designed to provide the worker with necessary information.

Complex elements are made up of form features (Table 1). A form feature is one surface or several adjacent surfaces that perform a specific design or technological function and are processed using a certain type of technological transition. The form features include the sections of bores and outer revolving surfaces of various types, exposed, semi-exposed and hidden surfaces, including planes, openings, ledges, etc. The main form features may have additional elements: grooves, chamfers, rounding, fillets, notches, etc.

Assembly units are formed by combining the components and parts comprised in the units.

Connections are divided into two large classes: detachable and permanent. Detachable connections are divided into movable and fixed. Hinged and spring joints are related to detachable movable connections.

Fixed detachable connections can be threaded, wedge, key, spline, pin-hole, splint, locking and flange ones.

The design and technological modules presented in Table 2 form the basis for a knowledge base of an intelligent system for technological processes design.

Table 1

FUNCTIONAL CLASSIFICATION OF PARTS ELEMENTS

Class	Sub-class			Type			Part elements
	Name	Function		Function			
		D,G	H	D	G	H	
Design elements	Operation elements	Interaction with the media:	external	Separation of	media		Elements of containers, seals, etc.
			aerodynamic or hydrodynamic	Conversion of	energy	mechanical to aero/hydrodynamic (energy)	Pressure and suction surfaces of compressor blades, pumps, propellers
				Generation of	flow	aero/hydrodynamic (flow)	Elements of air and water lines, wheel hubs, pipes, etc.
			mechanical	Generation of	motion		Elements of cams and conoids
				Resistence to	force		Elements of compression and leaf springs, etc.
			technological	Primary forming of	material	plastic (material)	Forming elements of molds and dies
				Separation of	material	by cutting, solid (material)	Cutting tool elements
			Human-related	Ensuring	ergonomics		Corrugations, elements of handles, knobs, buttons, etc.
				Giving	some properties	aesthetic (properties)	Shaped surfaces
	Conjunctive elements	Connection of parts	with a movable contact	Generation of	motion of	machine work members	Guide elements
				Conversion of	motion:	rotational to linear (motion)	Elements of screw pairs
				Transmission of	torque	rotational force	Rims of gear and worm wheels, elements of worms, etc.
			with a fixed detachable contact	Transmission of	torque	rotational force	Elements of interference, keyed, splined connections
				Resistence to	force		Threaded elements, etc.
				Locating of	parts	in an assembly unit	Pins, axial holes, planes, etc.
			with a fixed permanent	Resistence to	force/torque		Elements of welded,

			contact				soldered, riveted connections
	Interjacent elements	Provision of properties	to parts	Ensuring	the strength, rigidity of the part	of a part	Ribs, fillets, bosses, equal-strength elements, etc.
				Reduction of	the mass of	a part	Undercuts, cavities, etc.
				Ensuring	the integrity	of a part	Shaft sections, housing walls, etc.
Technological elements	Locators	Locating of a part	in a device				Center holes, etc.
	Elements for processing	Facilitation of processing	of a part				Grooves
	Elements for assembly	Facilitation of assembly	of a part with other elements				Chamfer, countersinks, etc.
Information elements	Elements for information purposes	Providing a person	with necessary information				Plates, inscriptions, indexes, etc.

Table 2

CLASSIFICATION OF DESIGN AND TECHNOLOGICAL MODULES

Design		Technology	
Design element	Form feature	Step	Tool
Body of rotation	Dimension cylinder	Rough turning Final turning	Straight turning tool Contour cutting tool
	Dimension face		Straight turning facing tool Facing tool Parting-off tool
	Plain cylider section		Straight turning facing tool Contour cutting tool
	Threaded cylider section	Rough turning Turning Thread	Straight turning facing tool Contour cutting tool Threading tool
	Shaped rotational surface	Rough turning Final turning	Contour cutting tool
Groove	Outer groove	Rough turning Final turning	Grooving tool Contour cutting tool
	Face groove	Rough turning Final turning	Grooving tool Contour cutting tool
Hole	Plain cylindrical hole	Centering	Center bit
		Drilling	Drill tool
		Drilling out	Drill tool
		Countersinking	Counterboring tool Countersinking tool
		Core drilling	Core drill Base core drill
		Rough boring Final boring	Boring straight turning facing tool Boring contour cutting tool
		Reaming	Reamer

	Threaded cylindrical hole	Centering	Center bit
		Drilling Drilling out	Drill tool
		Countersinking	Counterboring tool Countersinking tool
		Thread	Tap
	Internal groove	Rough boring Final boring	Boring grooving cutting tool Boring contour cutting tool
Prismatic body	Exposed plane	Milling	Face milling cutter
	Exposed contour	Milling	End milling cutter
Boss	Exposed plane	Milling	Face milling cutter
	Semi-exposed contour	Milling	End milling cutter
Plane recess	Semi-exposed plane Hidden plane	Milling	End milling cutter
	Semi-exposed contour	Milling	End milling cutter
Opening	Exposed contour	Milling	End milling cutter
Shoulder	Semi-exposed contour	Milling	End milling cutter
Shaped surface	Shaped exposed surface	Milling	Radius end milling cutter

Fig. 3 presents the design and technological model of a shaft-type part that has the elements described in Table 2. The basic part is a body of rotation having six sections, including a dimensional section that includes a dimension cylinder and face ends with chamfers. This section has a non-axial hole with chamfers. The part has two dimensional ends with axial holes. The hole on the left dimension end is a standard center, and the hole on the right end is a multi-sectional one with a chamfer and an internal groove. In addition, the part has two plain sections (right and left) with chamfers and grooves. The dimensional ends have adjacent cylindrical threaded sections with external grooves. One section of the part has a conical surface with an outer cylindrical groove and it has a slot.

The part's 3D model can be created by using corresponding design and technological modules as model components.

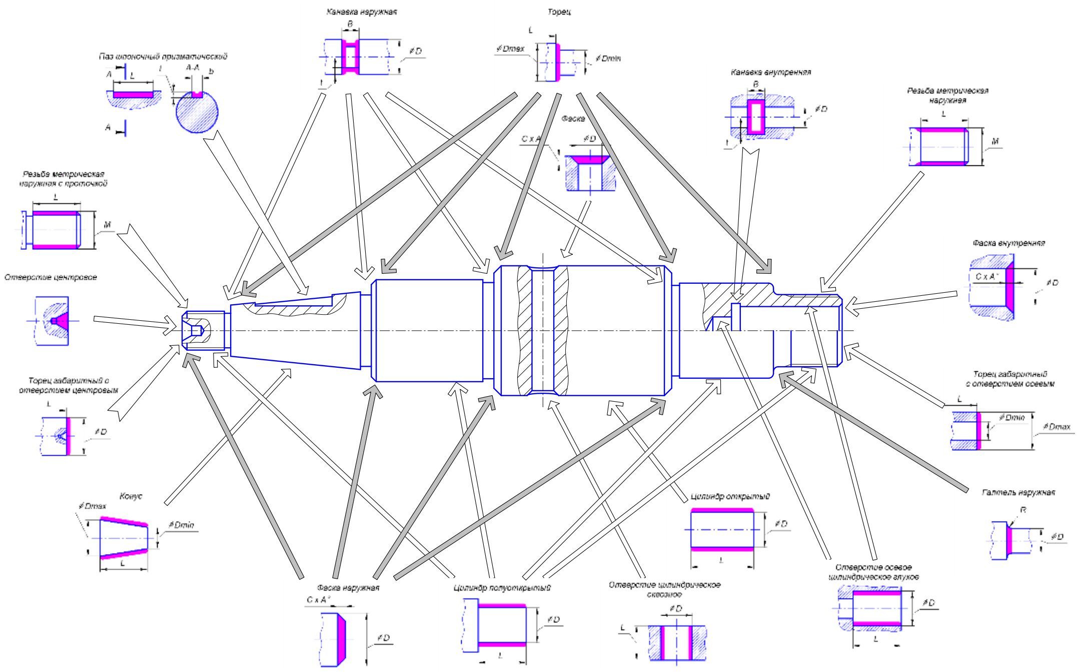

Fig. 3. Design and technological model of a part

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In Russia, engineers can use one of the best systems in the world - the domestic-made system SprutCAM [11].

SprutCAM [11, 13, 14] gives an opportunity to select design and technological elements in the part's general 3D model. In order to make a selection of objects of a certain type, it is necessary to configure the filter of objects selection. At that, the list of allowed objects will reflect only the objects of a valid type; they will be available for selection when specified in the graphic window.

There is an advanced intelligent selection of geometric elements; it starts by double-clicking on a geometric element in the graphics area. For example, a double click on the inner cylinder selects all the inner cylinders of the given radius (Fig. 4).

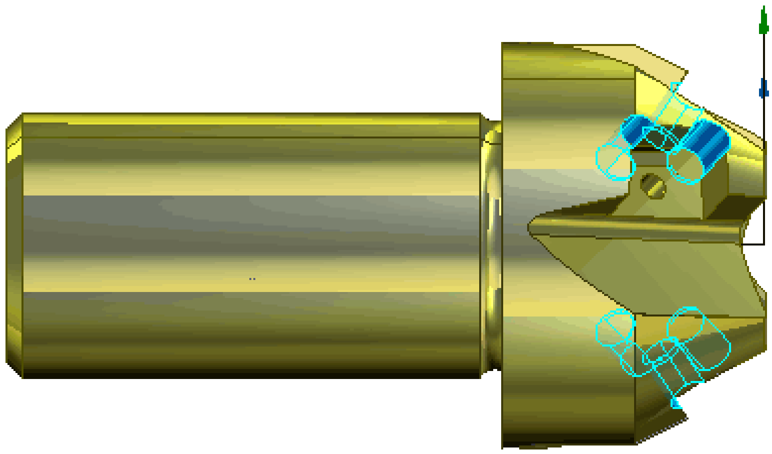

Fig. 4. Intelligent selection of design and technological elements on a 3D model of a part.

Conceptual and kinematic models of CNC machines

Modern digital production should employ not only 3D models of products, but also 3D models of technological equipment.

The conceptual and kinematic models of CNC machines are based on the standard model of coordinate systems, using the MachineMaker system [11]. The standard coordinate system is a right-angled coordinate system, in which the X, Y, Z axes indicate positive movements of tool relatively the movable parts of the machine.

The principle of "radial movement" does not involve the rotation of the spindle carrying the tool, or the lathe spindle.

Thus, using the Unified Modeling Language (UML) methods, it is possible to make a basic conceptual model of CNC machines (Fig.5). The machine design depends on the operation implemented on it; this operation usually belongs to one of the basic technological procedures: material cutting, electrophysical processing, deposit welding to form 3D products and edge cutting machining.

The object class "CNC machine" is intended here for the kinematic modeling of the mentioned technological procedures; its attributes are the designation and name of the machine, as well as the parameters that define the parameters of the machine axes.

The machine is designed to process the workpiece, which is placed on one of its operating members, for example, those associated with the displacement along the X axis. This is indicated by a dotted arrow showing the dependence of the "Workpiece" object on the "X axis" object.

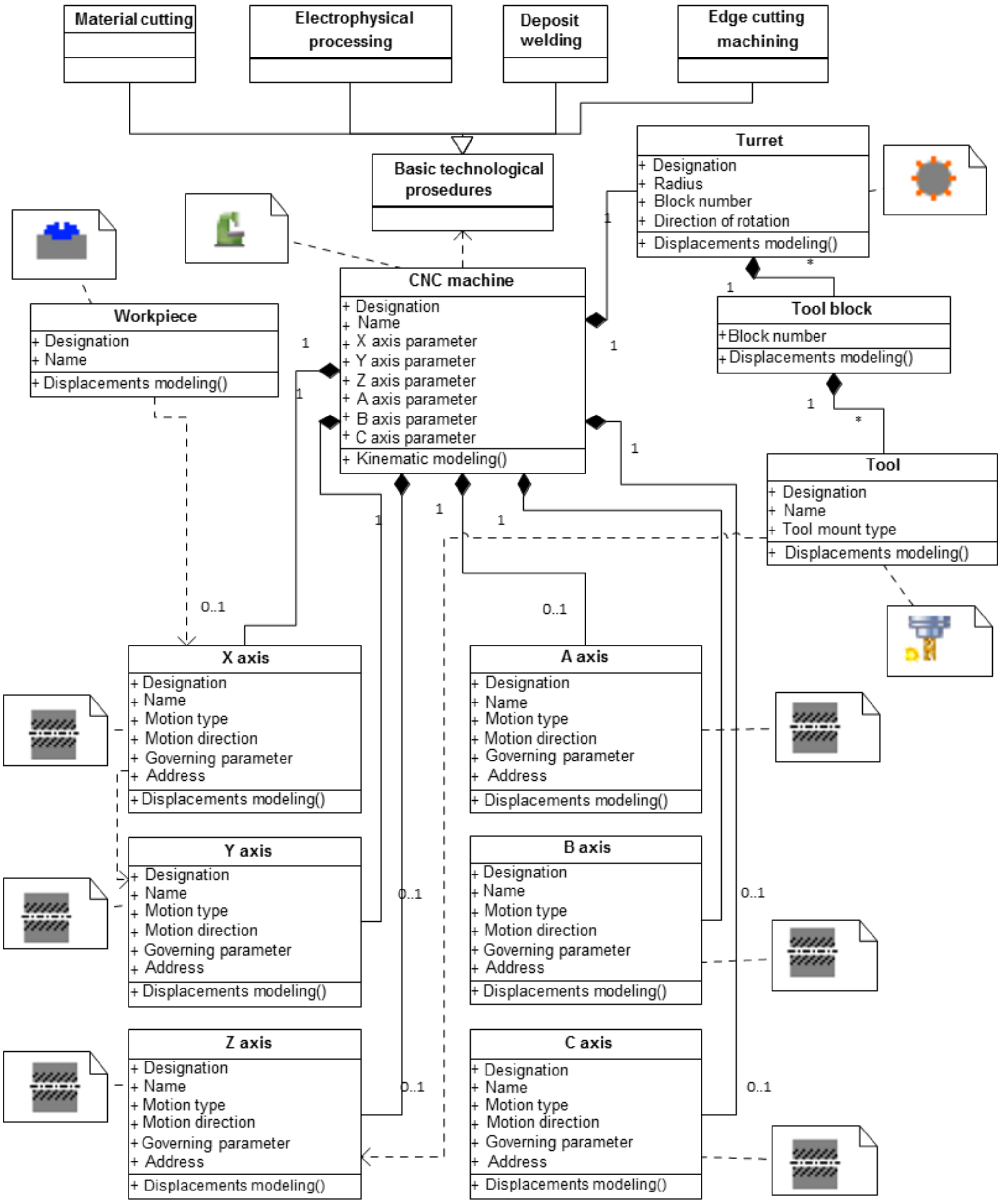

Fig. 5. The basic conceptual model of CNC machines.

Processing must be performed using the tools that can be located in the turret, which is part of the machine structure. The turret can have several blocks of tools, each of which contains several tools that represent the working parts of the machine.

The machine includes operating members that ensure displacement along the main axes: three linear (X, Y, Z) and three rotary (A, B, C) ones. Each of these axes can be included or not included in the machine, as evidenced by the multiplicity of the corresponding edges 0..1.

Based on this conceptual model, using the MachineMaker tool, we can generate the machine kinematic model. The tree of this model's objects is presented in Fig. 6.

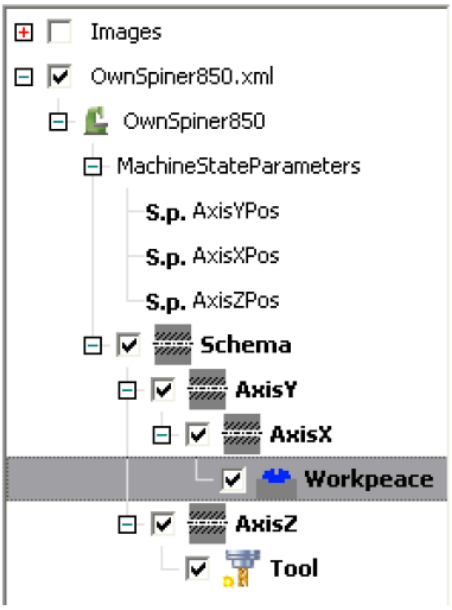

Fig. 6. The kinematic model of the CNC machine (corresponds to the machine in Fig.7).

This model corresponds to the machine, whose general view (prepared by the MachineMaker interface) is shown in Fig. 7.

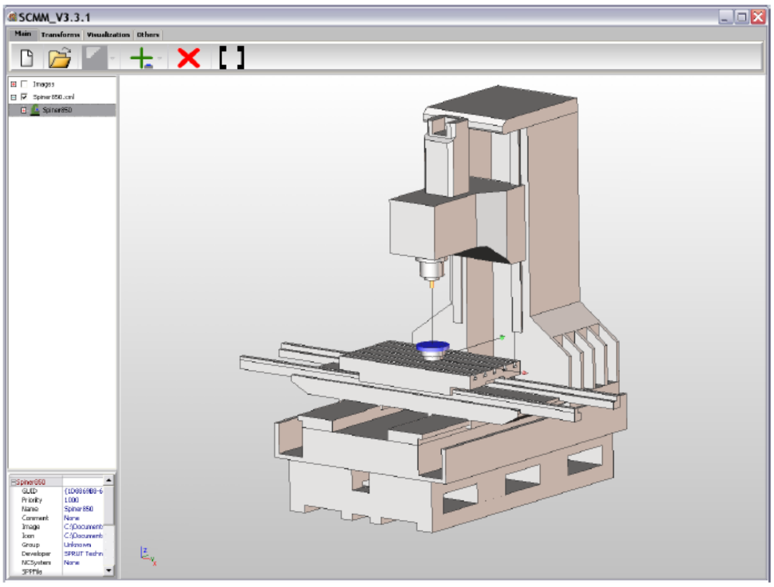

Fig. 7. The general view of the CNC machine (corresponds to the model in Fig. 6).

The kinematic model of the machine, which is stored in the file OwnSpiner 850.xml, describes the machine designated as OwnSpiner850, with the machine state parameters “MachineStateParameters” and its kinematic diagram “Schema”. The dotted arrows of object classes dependencies (marked on the conceptual diagram) determine the location of the modules on the kinematic diagram. The X axis depends on the Y axis, since the operating member defining the displacements along the X axis is structurally located on the operating member that defines the displacements along the Y axis. The spindle module, in which the tool is fastened, is located on the operating member that provides displacements along the Z axis.

To get the possibility of presenting the machine model as shown in Fig. 7, we must have 3D models of the operating members (Fig. 8).

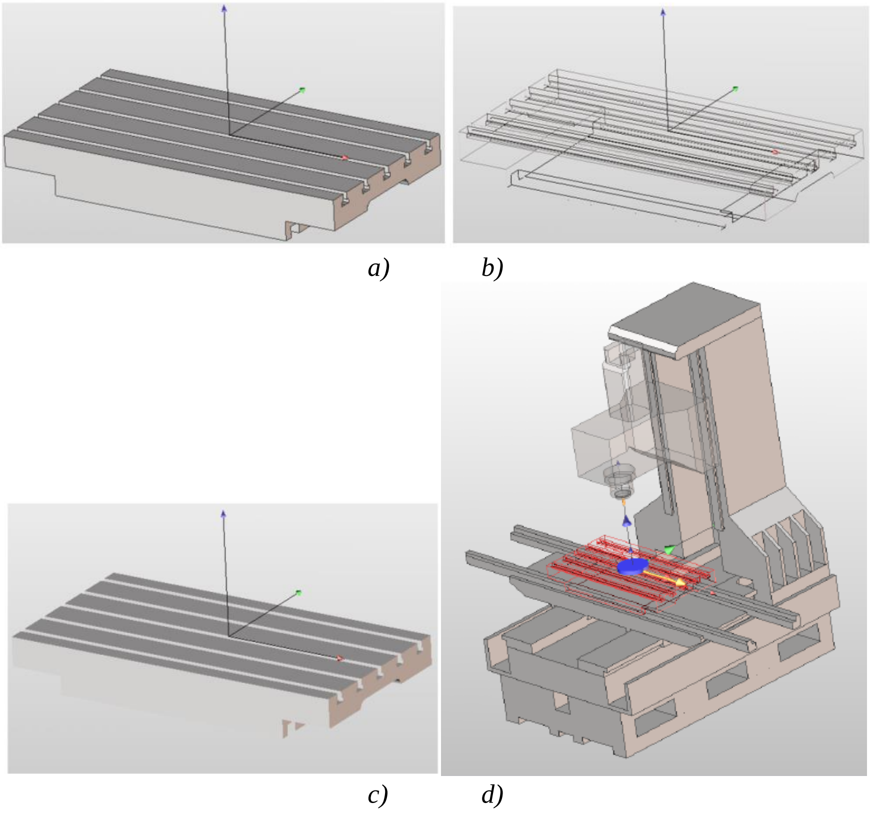

Fig.8. Equipment 3D models: a) with tinted edges, b) wire-frame, c) tinted without edges, d) with various modes of displaying the machine objects.

Conceptual meta-models of robotic technology complexes in machine-building

The basis for the analysis of robotic technology complexes (RTC) is a conceptual meta-model in the UML language (Fig. 9) [15].

As a rule, every machine-building enterprise has many different robots. The complex of technical facilities, which includes a robot, is a robotic complex. In order to distinguish robotic technology complexes from other robotic complexes, we should use the definitions of standards. Technological process is a part of production process that comprises targeted actions to change the object of labor and (or) define its state. Thus, a robotic technology complex must ensure the implementation of the mentioned actions. For example, an automated transport and warehouse system does not perform these actions and, being a robotic complex, cannot be classified as a robotic technology system.

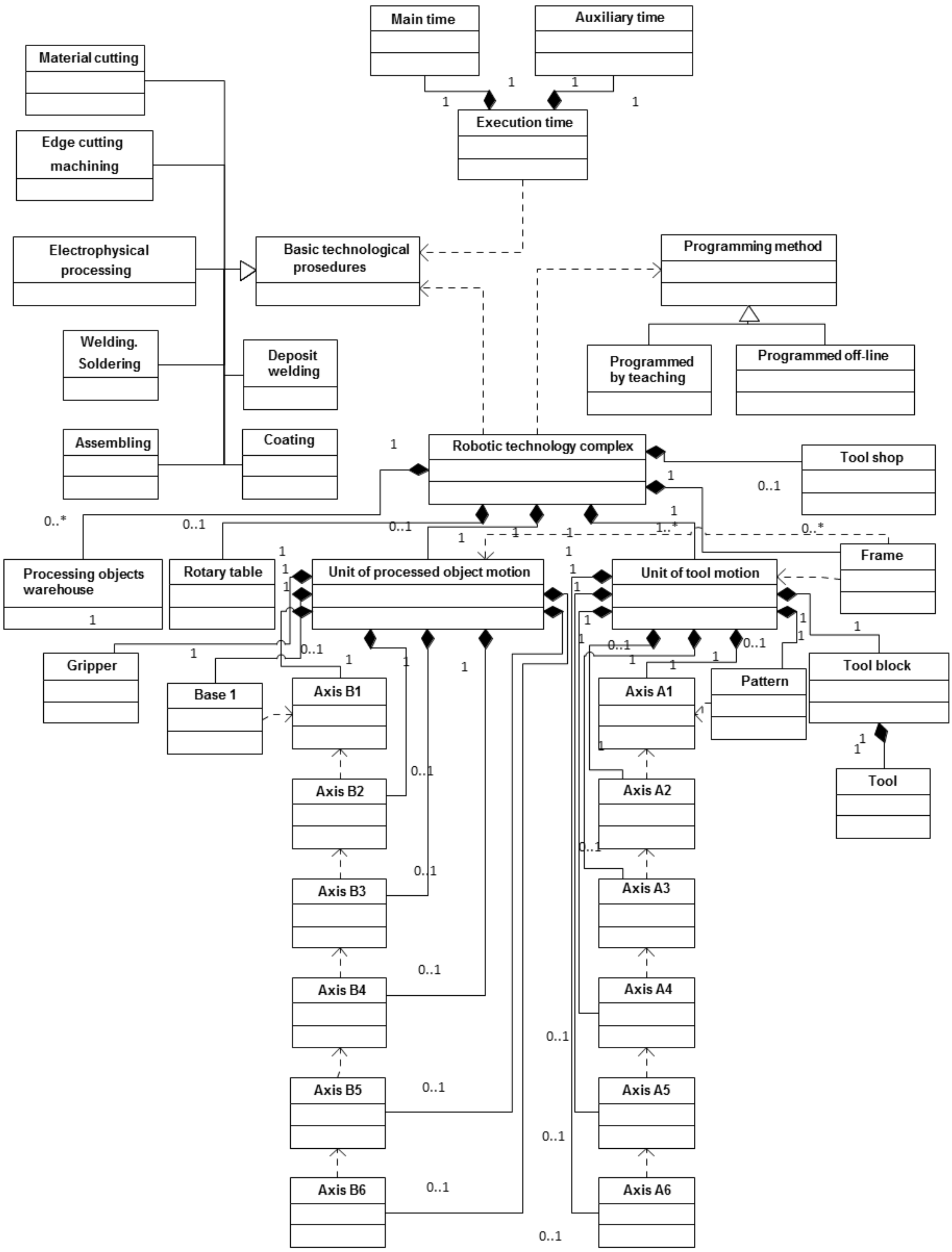

Fig.9. Integrated class diagram of robotic technology systems.

For a deeper analysis, it is necessary to consider the structure of execution time (Fig. 9). It includes the main and auxiliary time. The main time is aimed at achieving the direct goal of the technological operation for qualitative and (or) quantitative changes in the object of labor. Auxiliary time is associated with the actions that provide the ability to perform the basic function (i.e. the technological operation purpose). Being a part of a robotic technology complex, a robot should be bound with at least the main time, although it can also be used to perform auxiliary actions, completely taking all the execution time.

The norms of execution time depend on the applied technological procedures (Fig. 9). Such methods include material cutting, machining, electrophysical processing, welding and soldering, as well as assembling and deposit welding.

The main RTC components are the unit of the tool motion and the unit of the processed object motion, the first of which may be present in the RTC in several copies, and the latter may be missing. Each of the units is, in fact, a robot. Coordinated work of these robots is provided by the RTC control system.

The unit of the tool motion includes a tool block and a tool fixed on it.

Each unit usually has a pattern and a set of coordinate axes. Fig. 9 illustrates that each axis may or may not be part of the robot. This example considers sequential robots, and the correlation of the axes is marked with dotted arrows.

Let us consider the example of an RTC for five-coordinate milling of long objects. In this case, the object is an aerodynamic wing with the dimensions 4400 mm (length)x600 mm (width)x68 mm (height). Fig. 10 presents a subset of the conceptual meta-model for this case. Out of the main technological procedures, there is only edge cutting machining left on the diagram. The RTC includes only one six-coordinate unit of tool motion and a frame. Fig. 11 shows a three-dimensional model for constructing the kinematic scheme of such an RTC, and Fig. 12 - an example of processing using this RTC.

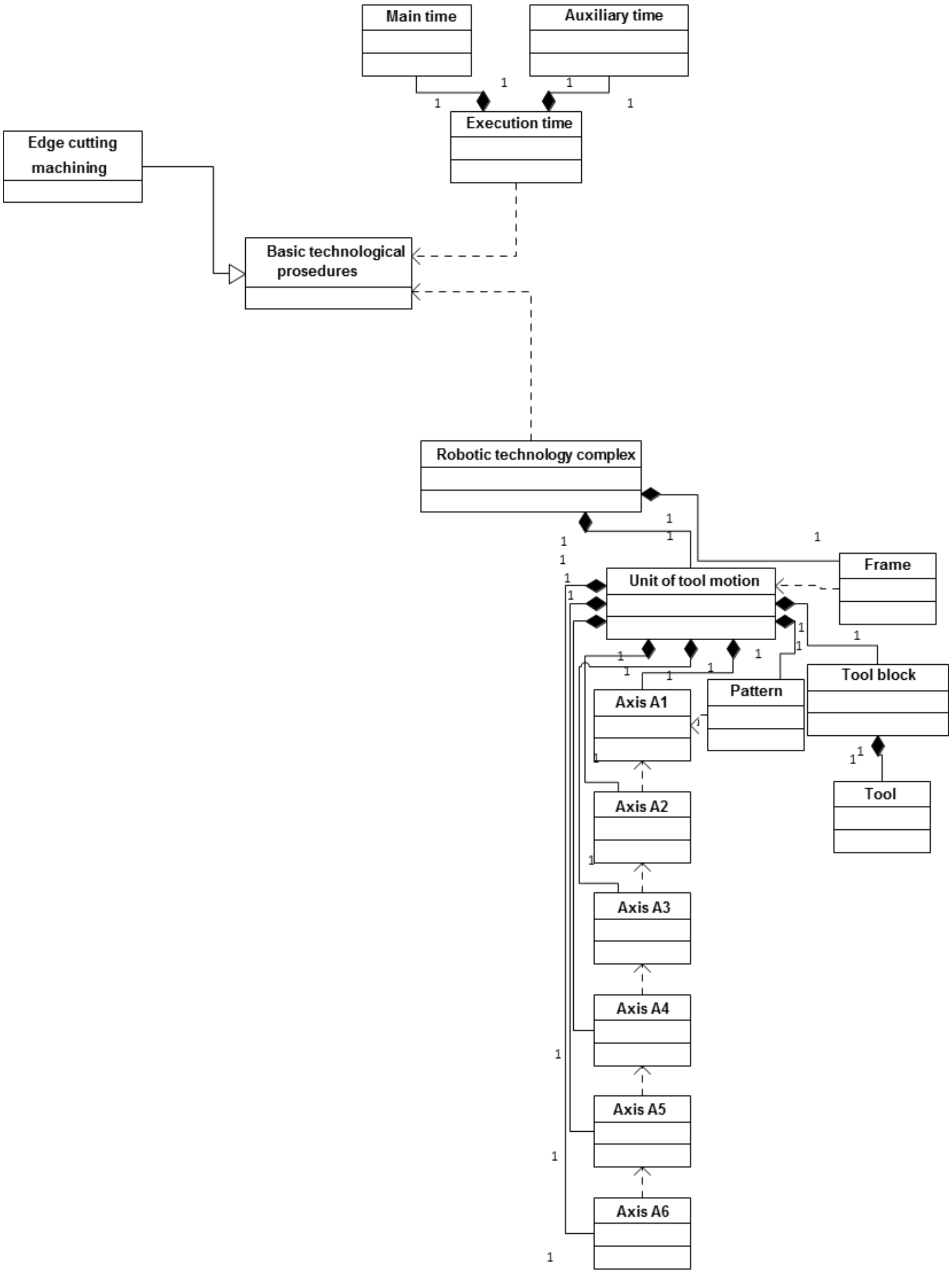

Fig.10. The sample class diagram of a robotic technology complex for processing of long parts.

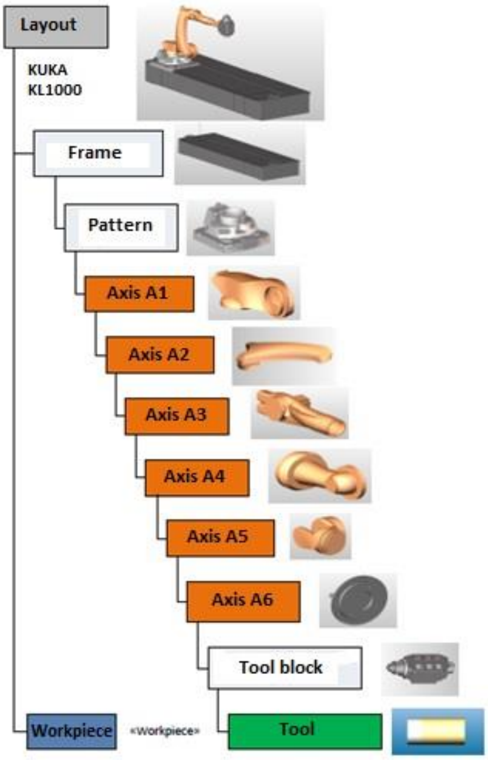

Fig.11. The representation of the three-dimensional model for the kinematic scheme in Fig. 10.

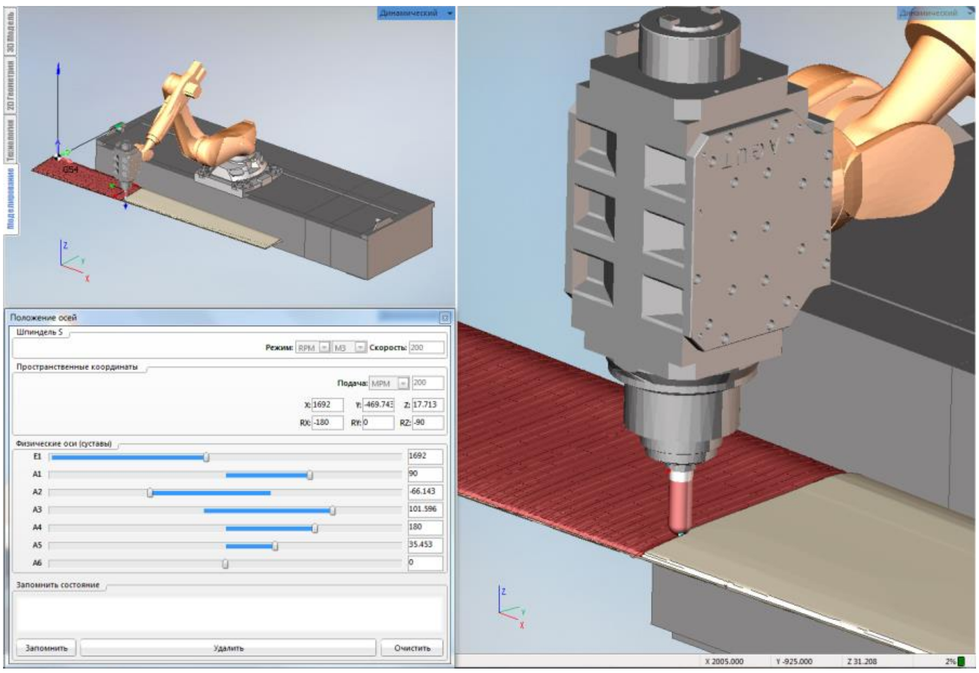

Fig.12. An example of processing of a long product using an RTC.

3D models of technological tooling

To perform parts processing operations, the facilities must have proper tooling, including tools and accessories [13, 14].

A programming system should provide a possibility to impose spatial constraints associated with the tooling; they are taken into account when calculating the tool path. It is necessary to specify areas of three-dimensional space, which the tool should avoid to penetrate during processing. Constraints can help to take into account the location and dimensions of the tooling (Fig. 13), to specify the part areas that should not be processed or overcut in the step, or, on the contrary, to allocate the areas to be processed in the model for each operation.

All tool movements, regardless of the step type, can be made only outside the limiting (prohibited) model. Finishing operations can machine only those parts of the processed model that are outside the prohibited model. Rough operations can select material only from outside the prohibited model.

In the general case, the limiting model can be defined by a concurrent combination of two types of elements: two-dimensional areas parallel to XY (forbidden zones and processing zones) and surface objects (solid bodies, surfaces and grids). For curve processing, engraving, and sampling, the limiting model can be defined only by two-dimensional areas.

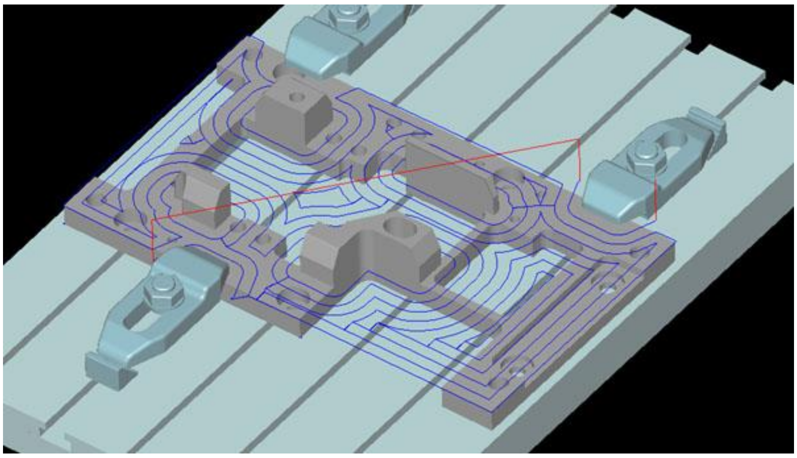

Fig.13. Constraints of the processing area using the tool 3D model.

The tool 3D model facilitates the control of the tooling elements collisions (with each other and with the equipment). Fig. 14 shows an example of a controlled spindle collision with the tool flange.

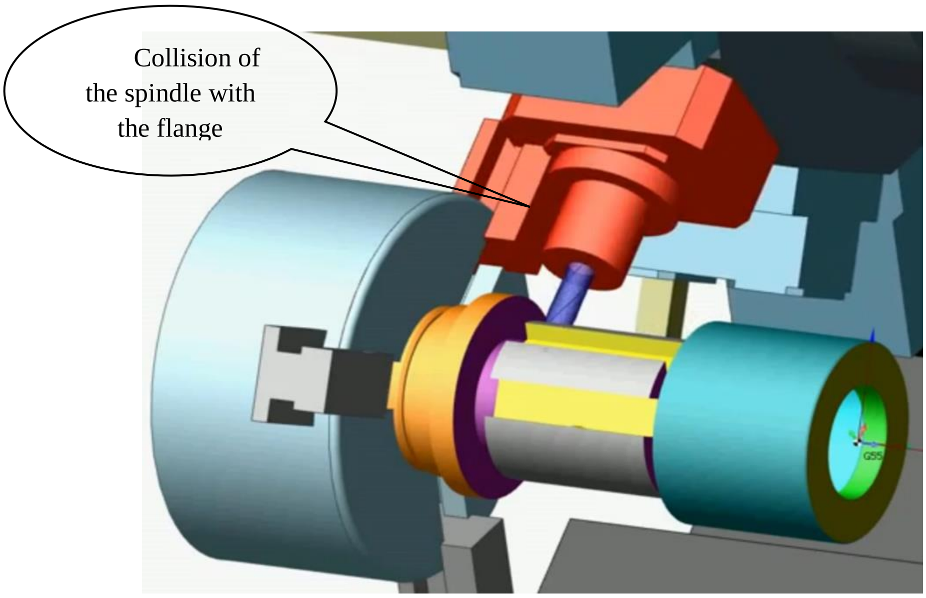

Fig.14. Collision control using tool 3D models

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The structure of the technological preparation system

Fig. 1 displayed the functional model of engineering preparation system. It follows from Fig. 1 that designing and programming of technological processes (TP) are the stages after product development [16, 17]. These stages form the basis of the technological preparation of production (TPP), the use case diagram of which is presented in Fig. 15.

At present, production is mainly order-based; its features are shown in Fig. 15. In the production of any type, a product must be designed prior to the start of technological preparation of its production. In the case of job order production, it is necessary to create an order containing a list of sets, assembly units and parts to be manufactured in specified quantities.

To determine the nomenclature and the total number of all parts manufactured to fulfill the order, it is necessary to produce a so-called explosion (obtaining information about the original components of the products). This operation is performed using the specifications of all sets and assembly units and calculating the total number of parts having the same designation but included in different specified order items.

After determining the complete nomenclature of order parts, it is necessary to find the parts, which were used in production for other orders and the TPs of which are already developed. As a result, there appear a great number of technological processes to be developed. Engineers draw up plans for TP designing; their implementation should be monitored by the TPP head.

These plans give a start to the development of the TP for the product. Creation of intelligent systems for TP design requires object models of products. In the cases where the route TPs of the parts manufacture include operations on CNC machines, these operations are programmed using geometric models of the parts.

If the process engineer cannot find the necessary tooling (tools, accessories) in the resource database when developing a TP, he must develop a technical task (TT) for the design of this tooling. A new TP is to be designed in accordance with this TT. Since such tooling is usually subject to fabrication at the enterprise, it becomes necessary to develop TPs and operation programs (OP) for corresponding parts processing.

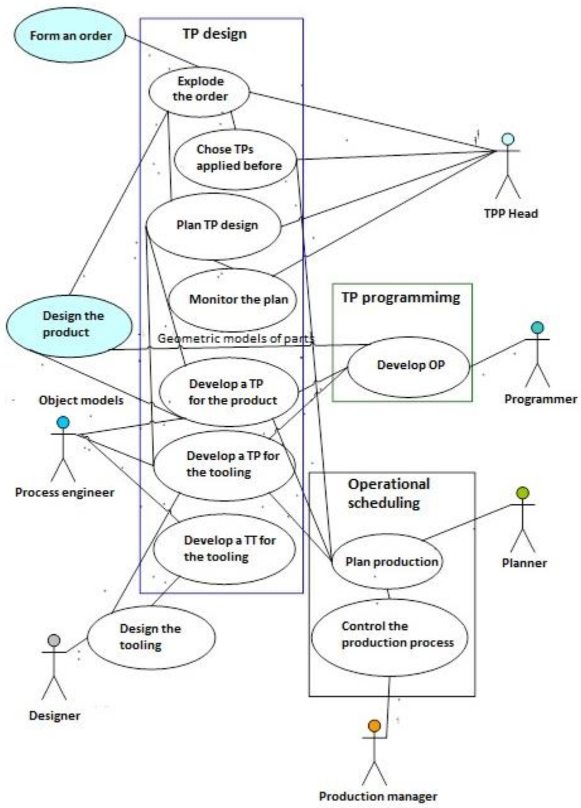


Fig.15. The use case diagram for a technological preparation system of job order production.

After the development and normalization of all TPs to the order, it becomes possible to provide for operational production scheduling. The production progress is monitored on the basis of these plans by the respective managers.

As it follows from Fig. 11, the technologist must select a product to start designing a TP. In SPRUT-TP, import of product data can be done through Project Manager (Fig. 12), which allows the data exchange with different CAD systems [12]. It helps to call the data on the complexes, sets, assembly units, parts and standard products.

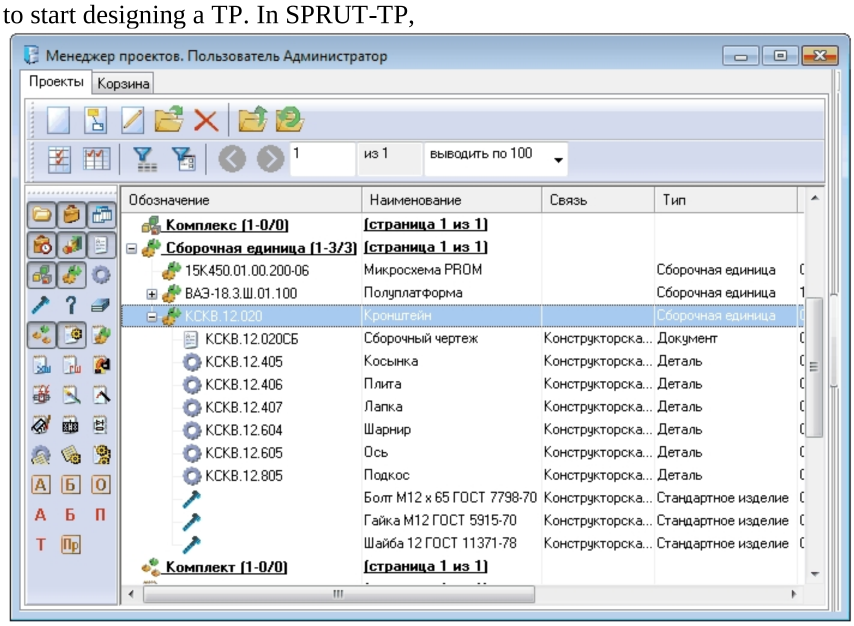


Fig.16. Project Manager.

An intelligent system of technological process design

The development of the intelligent CAPP systems theory is underway in China [18, 19, 20, 21]. The scientists consider application of various methods of artificial intelligence - multi-agent systems, neural network models. However, they did not get significant application [9].

To create an intellectual system for technological process design, it is necessary to develop a formal model of the ontology *O*, i.e. to define the finite set of object domain concepts, the finite set of relationships between the concepts of the given application domain (AD) and the finite set of interpretation functions defined for the concepts and/or relationships of the ontology *O* [22, 23].

The set of concepts can be divided into the following main groups:

description of the production structure ($f_1, \ldots, f_5$),
description of the production resources ($f_6, \ldots, f_8$),
technological indicators ($f_9, \ldots, f_{18}$),
technological objects ($f_{19}, \ldots, f_{26}$).

As applied to the construction of a technological class diagram, the fundamental group is description of technological objects. The remaining concept groups are required to set the properties of these objects.

The class diagram of technological objects is presented in Fig. 17. The root object in this diagram is "Technological process" - the part of the production process, which includes targeted actions to change and (or) determine the state of the object of labor. "Technological process" is a generic notion; it has distinctions that correspond to various technological procedures. The diagram shows the main procedures: primary forming, pressure shaping, processing, assembling and coating. Other methods include: technical control, testing, relocation, conservation, decondervation and packaging.

In terms of structure, a technical process consists of operations that are related to different methods. For example, a casting operation refers to the method of forming, die stamping - to the pressure shaping, turning - to processing, fitting and assembly - to assembly, and chrome plating - to coating.

An operation consists of a fixing stage, each of which is carried out with customary fixing of the processed workpiece or the assembled assembly unit. Each fixing stage may include one or several main and auxiliary steps. Finally, a step may consist of one or several working and auxiliary moves.

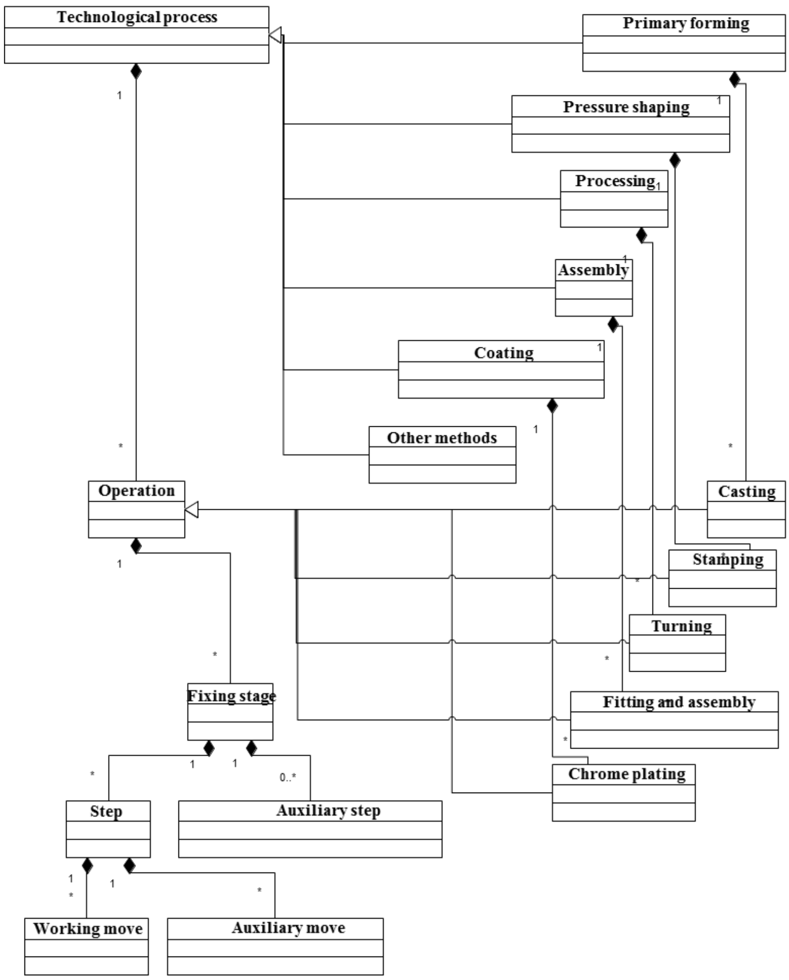


Fig.17. The class diagram of technological objects

The classes of the main technological procedures are presented in fig. 17; they are divided into subclasses. Primary forming includes the casting, modeling and sintering subclasses. Pressure shaping consists of the subclasses of forging, stamping and surface plastic deformation. The class of processing includes cutting, thermal, electrophysical, electrochemical and metalwork processing, as well as material cutting. Assembly comprises the assembly of detachable connections, welding, soldering, riveting, bonding and mounting. Coatings is divided into the obtaining inorganic and organic coatings.

Other technological procedures include technical control, testing, relocation, conservation, deconservation and packaging.

In Russia, the generic decomposition of technological operations is defined by the Unified System of Technology Documentation (ESTD) standard, which determines the codes and names of operations that are subject to mandatory use in technological documentation.

The output of the designed technological processes data in the factual form (in the form of a database) and in the documental form (in the form of technological documents) is performed by the interface module (Fig. 17).

The set of basic technological objects properties (Fig. 18) is determined by the set of parameters required to complete the relevant technological documentation. For the object "Technological process of processing", these properties include the TP designation, as well as the data of the part's material and the data of the workpiece. This object's method provides the TP design and normalization. The "Operation" object has properties that determine its number, the organizational and structural coordinates of the workplace at which it is to be performed, the code and name of the operation according to the ESTD standard, equipment and labor resources data, production organization data, time norms, the description of content and tooling. The method of this object, as well as the method of the previous object, provides the design and normalization of the operation.

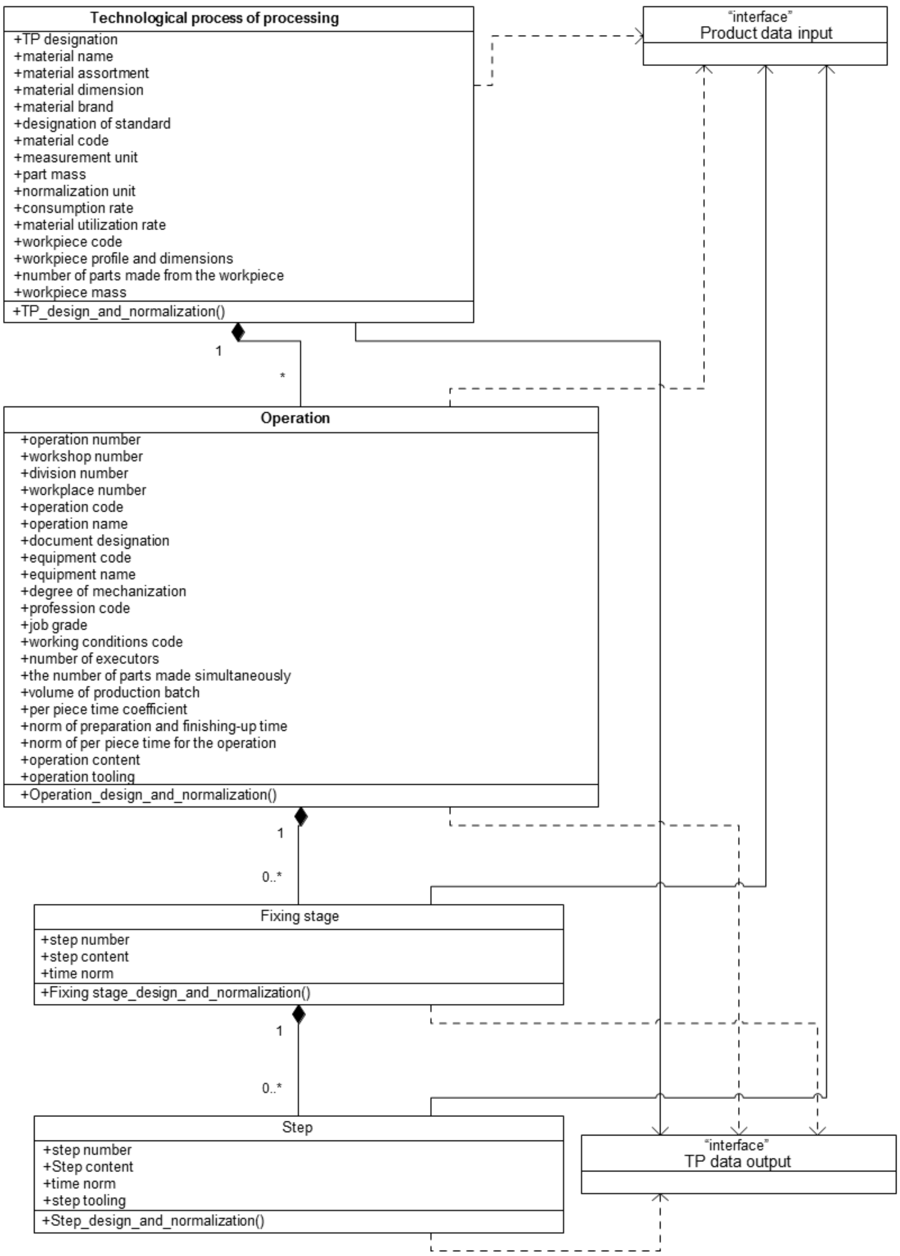


Fig.18. The class diagram of base technology objects.

When forming the technological documentation, it is customary to record the fixing stage data as an operation step. Therefore, it is numbered continuously with steps. However, its content and normalization differs from steps; that is taken into account in its method.

The properties of a step are similar to those of the fixing stage, but they also include the data on the tooling used on this step. The method of this object depends on the specifics of the performed processing or assembly.

In some cases, operations are not divided into fixing stages and steps.

Fig. 18 presents the ontology of objects for design objects - technological processes. Designing applies the object ontology of technological equipment. The general model of CNC equipment used in digital production is shown in Fig. 19. Technological means have two basic types: equipment and tooling.

Technological equipment (technological machines) are the technological means, which have materials or workpieces, instruments to affect them, and technological tooling to perform a certain part of the technological process.

Technological equipment is divided into classes in accordance with the technological procedures division (Fig. 17).

Technological equipment is selected depending on the part design and the requirements to ensure accuracy and surface quality. In some cases, engineers develop technical tasks for the design of special machines.

Tooling includes tools, accessories and fitments for the production of billets, including dies, casting molds, models and press molds. The tool can be cutting, measuring and ancillary.

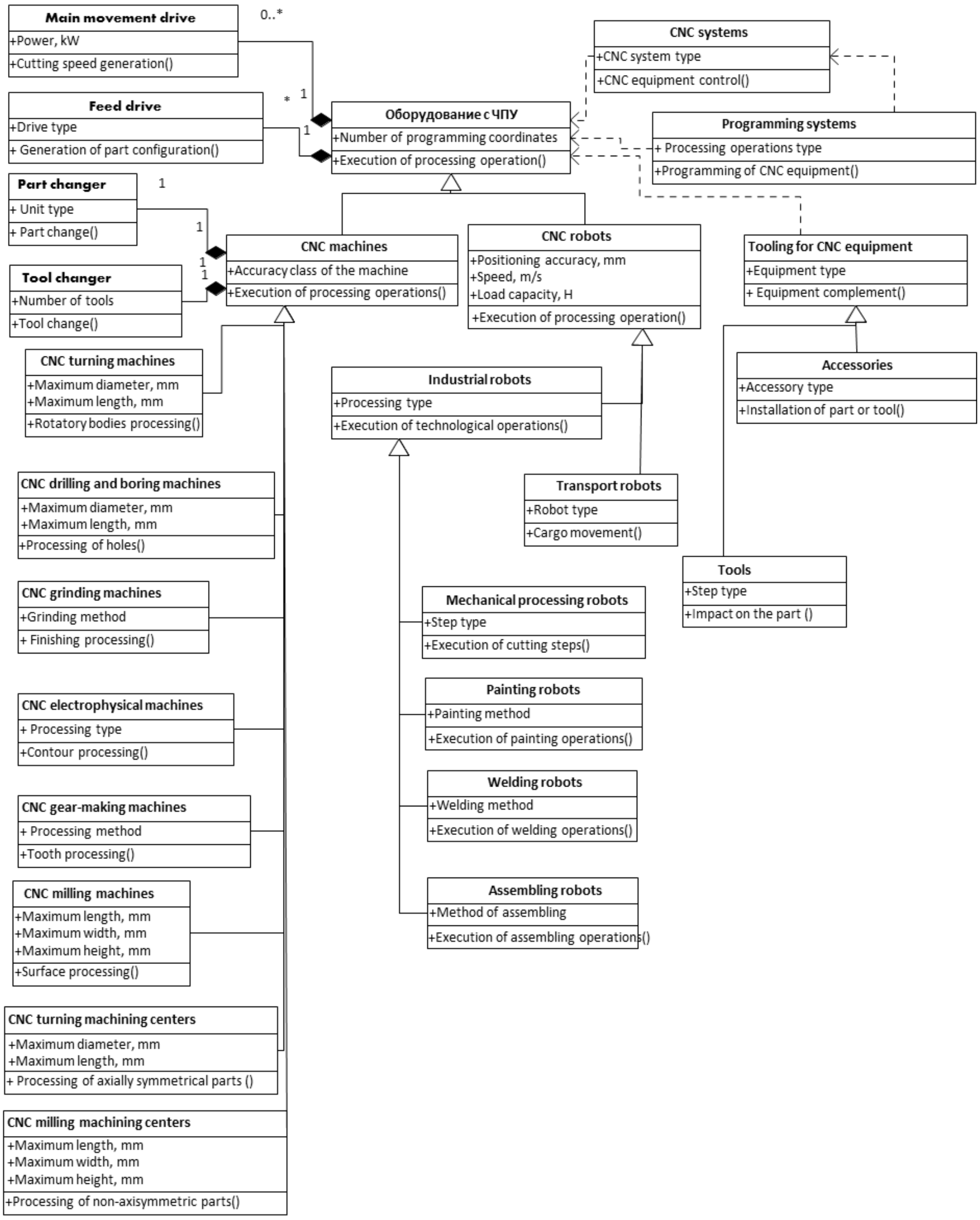


Fig.19. CNC Equipment Ontology

Fig. 19 shows a class diagram of CNC equipment. The root class in this diagram is “CNC Equipment”. In this class, as well as in the others, the indicated number of the most important attributes (the number of programmable coordinates) is minimal. The main procedure in the diagram is processing.

The main components, which are parts of the CNC equipment and which are directly related to programming, are marked as “Main movement drives” and “Feed drives”. The main characteristic of the main movement drives is power capacity, and the purpose is generation of cutting speed. According to the purpose, the main movement drives are pats of the metal-cutting equipment, but they are absent in the machines for electrophysical processing.

The feed drives of various types provide the configuration of the part, as a rule, some feed drives are part of CNC equipment.

The control of CNC equipment depends on the “CNC system”, as well as on the “Programming System”, which depends both on the equipment design and on the features of the CNC system.

The execution of a machining operation on CNC equipment depends on the tooling (accessories and tools) used.

CNC equipment has two basic types - “CNC Machines” and “CNC Robots”.

Important components of CNC machines are the part changer and the tool changer.

Fig. 19 presents the main types of CNC machines: turning, drilling and boring, grinding, electrophysical, gear-making, milling, as well as multi-purpose machining centers for turning (turning, drilling, boring and milling processing) and milling (drilling, boring and milling processing).

CNC robots have two main varieties: production (technological) and transport (logistics). Production robots include machining, painting, welding, and assembly robots. Transport robots are not considered in this work.

The tooling for CNC equipment includes two varieties: accessories and tools (Fig. 19). In the design process, process engineers use Resource Manager to select the necessary technological means (Fig. 20).

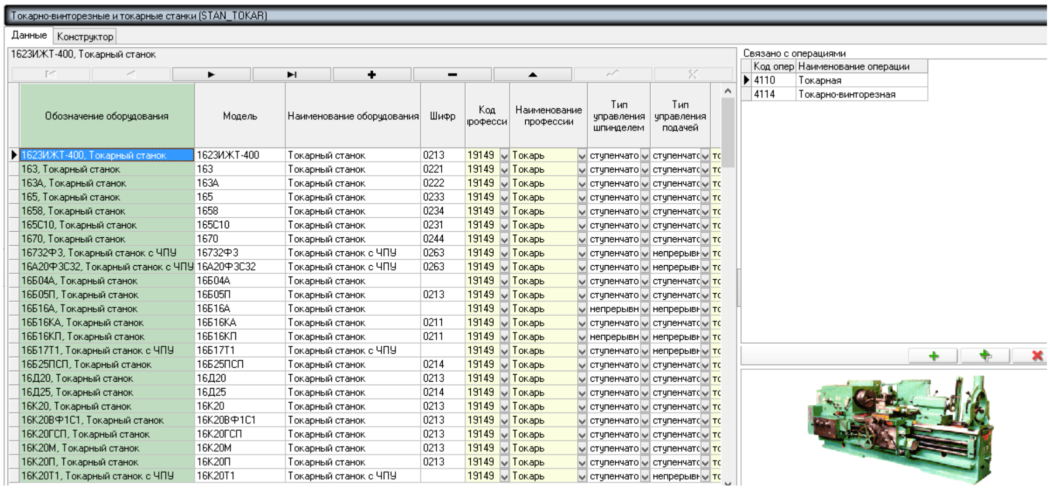


Fig.20. Work in Resource Manager

Methods of technological process structure design on the basis of knowledge bases

The object ontologies of products, technological equipment and technological processes as design objects were described above. In this section we are considering the ontology of tasks for the TP structural design and the example of the ontology of optimization problems.

To determine the compound of technological design methods, it is necessary to analyze the functional diagram of TP design (Fig. 21). In this diagram, the control of each block is carried out by the user.

The first functional block is the block of synthesis of the technological process structure. Its input information is contained in the product model; a sequence of operations and steps is formed at the output. The implementation mechanism for this function is a technological knowledge base.

The next functional block predetermines the TP equipment, i.e. the choice of machines, devices, tools and other technological means. The result is establishment of operations and steps, as well as indication of resources required for their implementation. The TP equipping is carried out by the technological knowledge base using the technological resource database (Fig. 20).

Then there is a functional block that provides the TP normalization, that is, the calculation of the necessary norms of the time for operations and steps. Its output is a sequence of equipped and normalized operations and steps, on the basis of which specialists can make technological documentation and form a TP model. The mechanism for the implementation of this function is a knowledge base that uses technological data (if necessary).

Formation and editing of technological documentation can also be done manually with the help of the corresponding interface object.

To create a model of an equipped discrete TP structure, in addition to production objects *I*, it is advisable to consider the means of labor *(MT)* as a carrier of the model, i.e. the equipment and tooling (accesories and tools).

$O_t = <I, MT; P_1^3,..., P_n^3>$

Here, the model signature is the set of ternary relations or triplets {P13,..., Pn3}. Except the information about the type of technological operations and steps that transfer an object from the i-1-th state (ii-1) to the i-th state (ii), each triplet Pi3, contains information about the types of technological means mti that can be used at that

(ii-1, ii, mti)

It should be emphasized that since the processing modes that determine the norm of processing time depend on the tool used, normalization can be implemented only using the model of an equipped TP.

To form the models of technological process structure, it is advisable to use the standard method and notation. IDEF3 is most suitable for this. IDEF3 is a standard for describing technological processes and defines a notation for representing the meta-models of the process structure and the sequence of changes in the manufactured object properties.

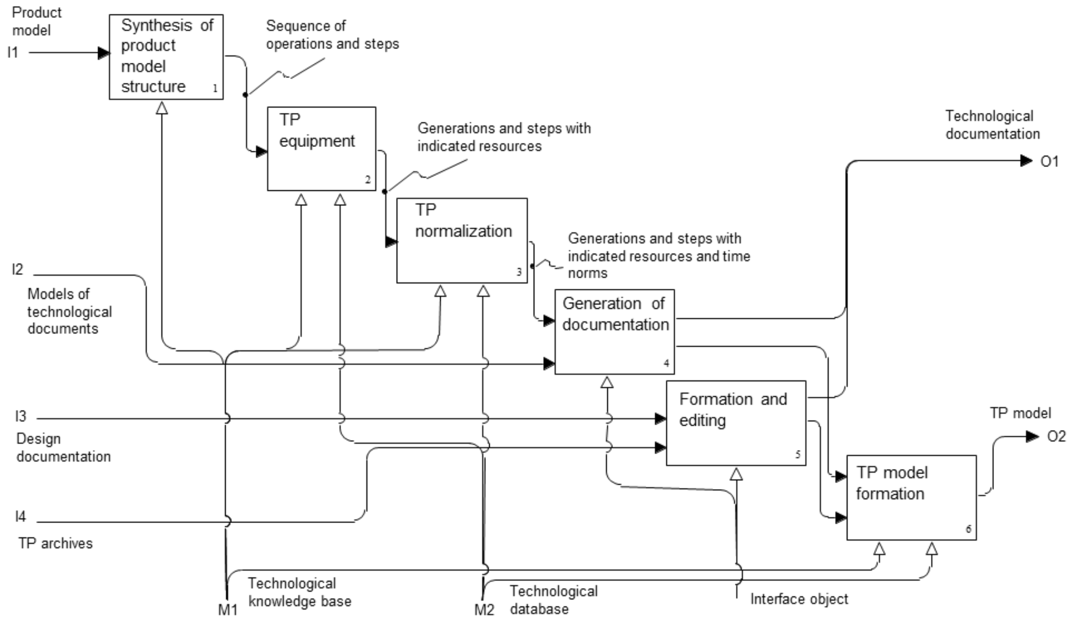


Fig.21. The functional diagram of technological process design.

Let us consider the application of the IDEF3 method by the example of a technological process meta-model (TPM) for the processing of cylindrical toothed gears (Fig. 22).

In a general case, the meta-model of a technological process is an AND-OR graph. The AND junctions determine an unconditional sequence of operations. The OR junctions involve enumerated variables with a fixed set of legitimate values, which determine the selection of a variant for the technological process. These variables are divided into two classes: free and bound. The values of free variables can be chosen by the production engineer; the bound ones are determined by the design documentation. In the described TP meta-model for tooth gear processing, the bound variables are: “Spline way”, “Heat treatment” and “Accuracy degree”. The free variables are “Billet”, “Grooving” and “Toothing”.

The availability of free variables in a meta-model gives the possibility to choose between alternative technological processes.

$$\Omega = \{\omega 1, \omega 2, \ldots, \omega n\}$$

To choose a preferable option from a set of admissible ones, it is necessary to introduce a selection criterion. In technological process design, such criteria are usually labor content and technological cost. These criteria are reflected in the function q, which is commonly called the value function or the objective function.

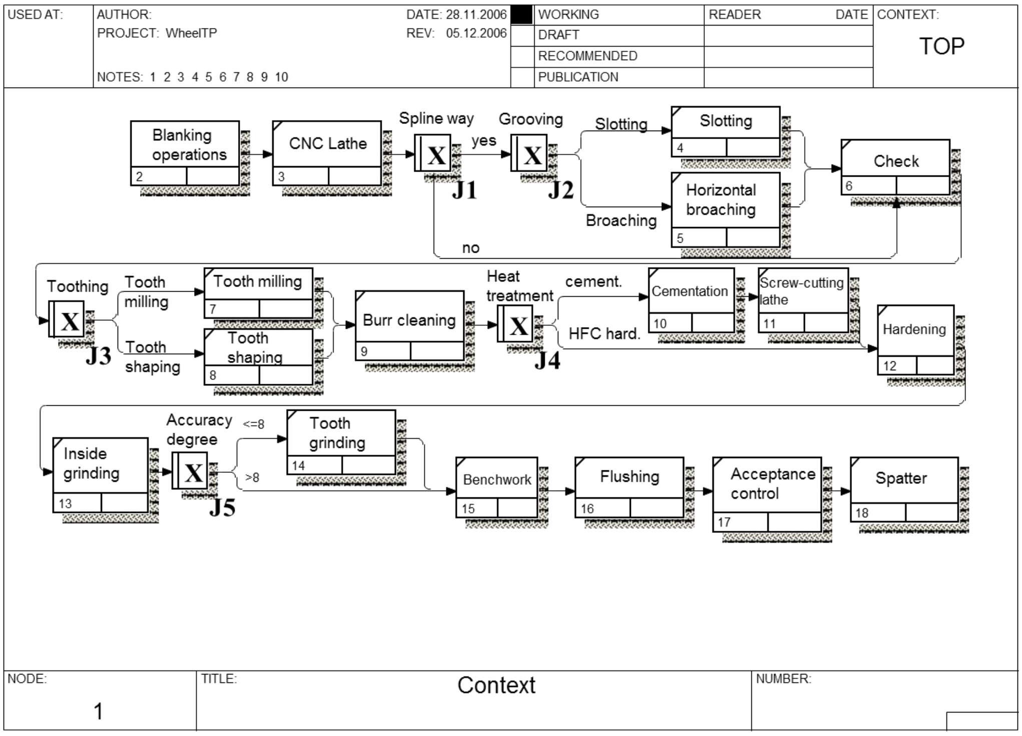


Fig. 22. Process Flow Diagram (PFDD) of cylindrical gears processing.

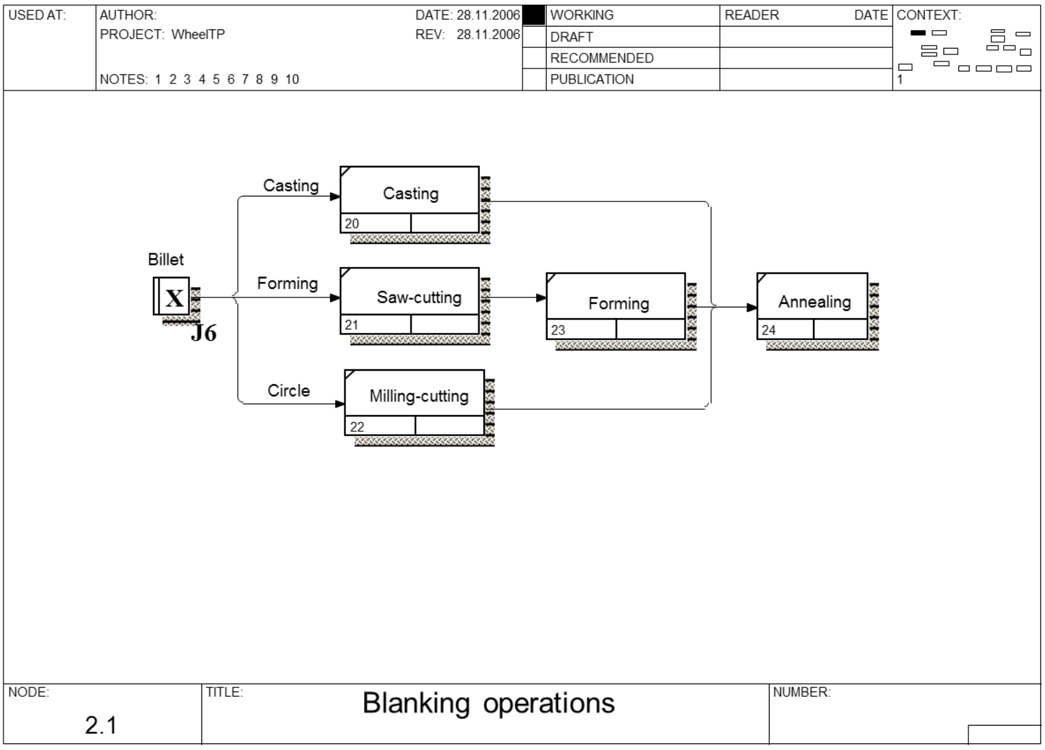


Fig. 23. Secondary diagram of blanking operations for cylindrical toothed gears

If the meta-model does not have many free variables, like in the case described above, then the problem of finding the best solution can be solved by a simple search. But when the number of free variables reaches several dozen, it makes sense to apply regular methods to find the best solution – for instance, the methods based on genetic algorithms (GA).

Here, the coded values of free variables can be used as a gene - a hereditary material unit responsible for the formation of alternative characteristics. Then the chromosome is n linked genes that are located in a linear sequence “from left to right”.

The location of a particular gene in the chromosome is commonly referred to as a locus, and the alternative forms of the same gene that are located in the identical chromosome loci – as alleles (allelic forms).

A chromosome containing specific allele values in its loci is called a genotype (genetic code); it contains all hereditary genetic information about a technological process variant. Let us construct a TP genotype in accordance with Fig. 22 and Fig. 23. Let Locus 1 locate the code for the free variable “Billet”, set as follows: casting - 0, forming - 1, circling - 2. Locus 2 corresponds to the variable “Grooving” with the values: slotting - 0, broaching - 1. Locus 3 holds the variable “Toothing” codes with the values: tooth milling - 0, tooth shaping - 1. Then the genotype of the technological process of toothed gear processing with stamping, slotting a keyway and crown teeth will take like that given in Table 3.

Table 3

AN EXAMPLE OF A TP GENOTYPE

Locus	Allele	Phenotype
1	1	Billet - forming
2	0	Grooving - slotting
3	1	Toothing – tooth shaping

For the GA to work, it is necessary to pre-form the initial population - a set of TP variants. This population can be formed by a process engineer guided by the TP meta-model. Next, there launches a genetic algorithm that provides the search for the best solution by generating new variants of the technological process. To change the existing set of TPs, a simple GA uses three operators: selection (reproduction) for performing natural selection, crossing-over (crossing) for reproduction of descendants with hereditary characteristics of parents, and mutation for mutagenesis. The best methods are selected from the existing set of TP option, by comparison with the values of the objective function. Crossing allows getting a new TP variant from two; it partly inherits the gene values from one variant, and partly - from the other. Mutation allows a random change of values of this or that gene. The process lasts either a given number of times, or until the best options appear.

The above diagrams of processes in the IDEF3 standard represent conceptual knowledge models of TP structural synthesis. It is necessary to enter this knowledge into a computer and ensure automatic generation of routing technological processes depending on the values of the control free and bound variables. The language of such knowledge representation should be as simple as possible and accessible to non-programmers. For production engineers, it is most natural to fill in standard technological documentation, for example, route sheets. For this reason, the SPRUT-TP system [24, 25, 26, 27] uses modernized standard route sheets that represent knowledge of the TP operations structure. In these sheets, a technological process is described by standard lines of type A and type B. Type A lines set operation parameters; type B lines describe the equipment used (Fig. 24). In order to be able to generate process diagrams in the IDEF3 standard, it is necessary to add lines to standard technological lines of type A and type B; such line should set conditions for operations entry in the final technological process. These conditions should allow describing logical connectives of the exclusive-OR type.

To define logical connectives in the route sheet form, there are lines of the type “Condition” and “End of condition”. These lines, together with the standard technological lines between them, represent an analogue of the condition-action rule. The whole array of such information can be considered as an analogue of a knowledge base of the production type, where rules are regulated in time.

Fig. 24 shows a fragment of the fill-in form for the diagram of cylindrical toothed gear processing; it relates to IDEF3 diagrams presented in Fig. 22 and Fig. 23. The content of Fig. 24 corresponds to the diagram of Fig. 23. Depending on the value of the variable #Zagot#, there is a selection of one or other blanking operations, which are recorded in the final document. Next come the unconditionally assigned operations “Annealing” and “CNC Turning”.

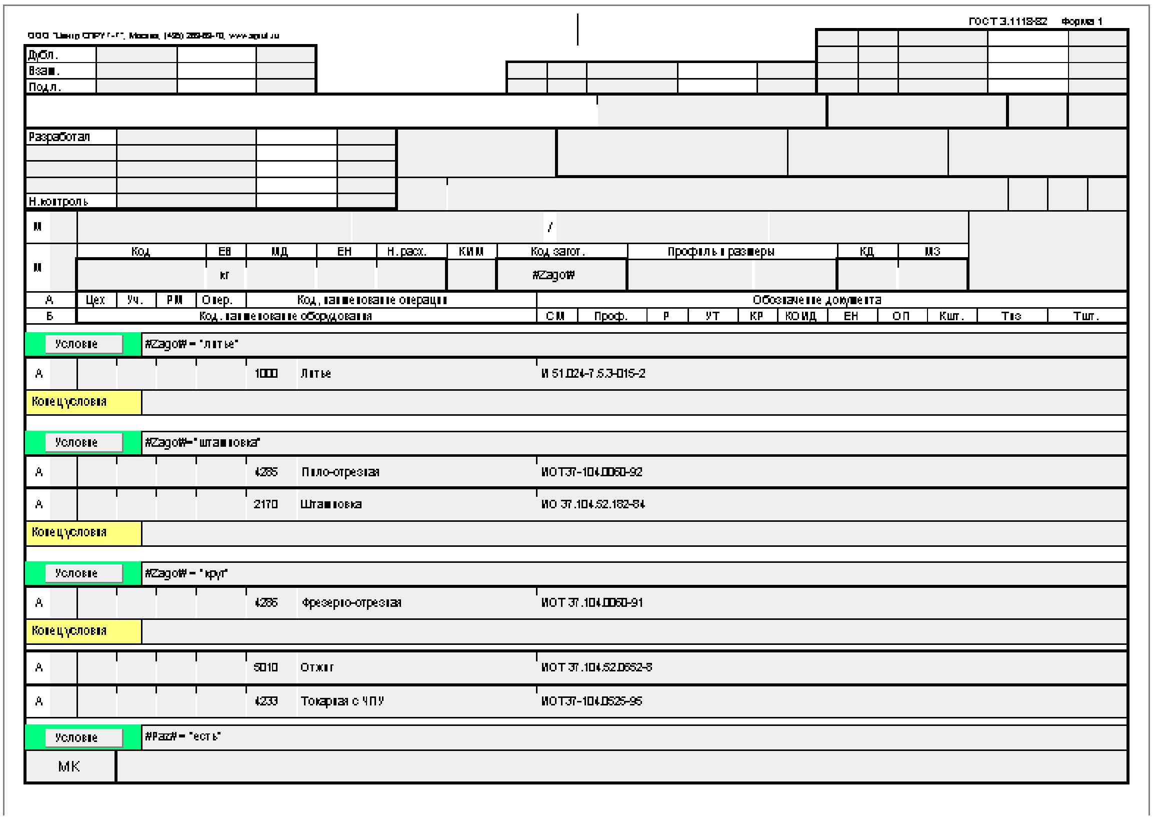


Fig.24. The fill-in form for the diagram of processing cylindrical tooth gears (sheet 1)

The design of processing steps differs from the synthesis of the route technology structure. In the case of machining, it is based on the decomposition of the part into form features.

Above we considered the methods for the synthesis of the processing TP structure. Designing the processes of assembly and welding have their own features that will be discussed below.

Systemologic processing models are based on graphs. The generalized concept of a graph is the concept of a hypergraph. Hypergraph has many vertices and many edges that are sometimes named with a set of letters and words, respectively. The main difference between a hypergraph and a graph is that the number of vertices incident to an edge is not limited to two.

The assembly sequence is mainly determined by the product design and can be represented as a technological assembling diagram, which is a symbolically represented sequence of completing the product and components during assembly [16]. Assembling diagrams provide visualization of the entire technological process. In these diagrams, each product element is represented by a rectangle labeled with the component name, index and quantity (Fig. 25).

The part or the previously completed assembly unit, from which assembling is started by attaching other parts and assembly units to it, is called the base part or the base assembly unit.

In Fig. 25, the base parts are: the part P15 for the assembly unit AU3, P10 for AU2, P6 for AU1, and P1 for the product. The assembling process is depicted in the diagram by a horizontal line in the direction from the rectangle with the basic component image to the rectangle representing the finished product or assembly unit. Above the horizontal line, in order of assembling, there are rectangles – symbols of parts; the rectangles depicting assembly units are below the horizontal line. For the example product from Fig. 25, the first part to be attached to the base part P1 is P2, secondly goes the assembly unit AU1, then the parts P3 and P4, then the assembly unit AU2 and finally - the part P5.

A technological assembling diagram is the basis for the design of the technological assembling process. The basis for constructing a hypergraph of product assembling is the data that are stored in the product specification model.

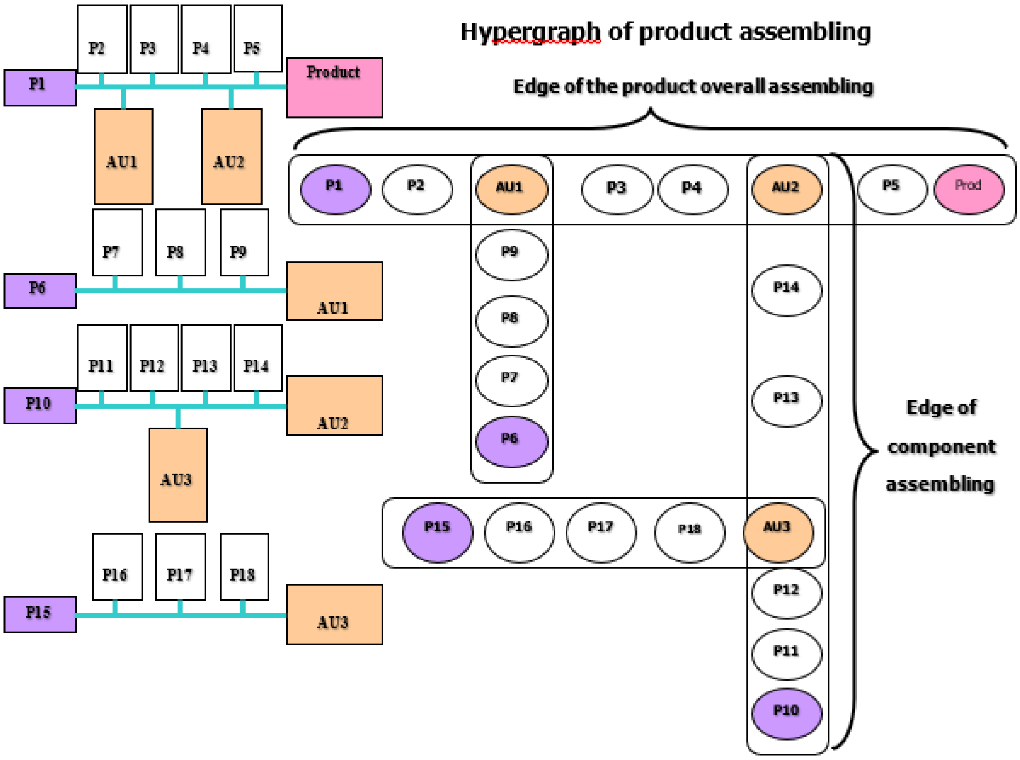


Fig.25. A hypergraph model of technological assembling diagrams

The methods of TP parametric synthesis on the basis of knowledge bases

The problem of technical working time norm-setting, i.e. the problem of work measurement, is especially important in technological process design. The technically justified norm of time is the time required to complete a unit of work; it is ascertained by calculation on the basis of rational use of labor (living labor) and tools (materialized labor) in the given production conditions, taking into account best practices. Setting the technical norm of time is not limited to determination of remuneration and labor productivity. Technical norms are the basis for defining the required equipment quantity and load, production capacity of sites and workshops; they are also the basis of operational (calendar) planning.

Standardized working timetable includes preparatory-finishing time, operational time, time for maintenance of the workplace, and breaks for rest and worker's personal needs. Norm-setting is carried out using knowledge bases built upon productional knowledge modules.

The norm of time per piece (Tp) is the standard time for the workload required for one evaluated unit (for example, one part) when performing a technological operation.

The norm of operational time (Top) is the norm of time to perform a technological operation; it consists of the sum of the main time norms (Tm) and the norms of auxiliary time (Ta), which do not overlap.

Overlapping auxiliary time takes into account the worker's actions performed simultaneously with the processing; therefore, it is not included into the norm of operational time.

In some cases, engineers make an aggregated calculation of Tp using the so-called incomplete time per piece (Tip); the time per piece is calculated on the basis of Tip using correction factors.

Knowledge module: "NzK27aT" – Setting of Tip, rough slotting, steel

Starting conditions

Name	Description	Type	Condition
HarObrD$	Processing character	STRING	Rough before finishing, rough before shaving
GrMatDet$	Part material group	STRING	Carbon steel, constructional alloyed steel

Input properties

Name	Description	Type	Value
HarObrD$	Processing character	STRING	Rough before finishing
Nd	The machine electric motor power, kW	REAL	2.5
l_	Processed surface length, mm	REAL	48
m_	The part module,	REAL	3

Mechanism - Table
Properties configuration in a table

			l_
HarObrD$	Nd	m_	tnsh1z

Table

			(, 20]	(20, 25]	(25, 30]	(30, 40]	(40, 50]	(50, 60]	(60, 70]	(70, 80]	(80, 90]	(90,)
Rough before finishing	(,1.5]	[0,)	0.33	0.39	0.46	0.53	0.65	0.8	1	10.5	1.20	1.30
	(1.5, 3.7]	[0,4]	0.3	0.36	0.4	0.52	0.6	0.73	0.9	0.94	1.1	1.3
		(4,5]	0.5	0.58	0.68	0.83	1.03	1.27	1.47	1.7	1.85	2.04
		(5,)	0.6	0.74	0.83	1.06	1.22	1.54	1.82	2.08	2.43	2.65
	(3.7, 5]	[0,5]	0.44	0.52	0.59	0.63	0.9	1.08	1.34	1.46	1.6	1.75
		(5,6]	0.53	0.6	0.7	0.87	1.08	1.36	1.54	1.8	1.95	2.15
		(6,)	0.87	1.04	1.18	1.49	1.82	2.18	2.74	2.97	3.27	3.63
	(5,)	[0,)	0.77	0.89	1.05	1.3	1.6	1.83	2.34	2.56	2.84	3.2
Rough before shaving	(,1.5]	[0,)	0.35	0.4	0.47	0.58	0.7	0.88	1.02	1.14	1.3	1.38
	(1.5, 3.7]	[0,4]	0.35	0.39	0.46	0.55	0.65	0.83	0.98	1.10	1.26	1.37
		(4,5]	0.5	0.58	0.66	0.86	1	1.25	1.48	1.7	1.97	2.15
		(5,)	0.68	0.8	0.9	1.17	1.4	1.71	2	2.24	2.56	3
	(3.7, 5]	[0,5]	0.45	0.52	0.59	0.74	0.93	1.14	1.3	1.5	1.66	1.8
		(5,6]	0.6	0.7	0.8	1	1.24	1.55	1.75	2.05	2.24	2.46
		(6,)	0.88	1.06	1.2	1.48	1.84	2.26	2.74	2.94	3.48	3.84
	(5,)	[0,)	0.86	1	1.15	1.45	1.75	2.14	2.68	2.9	3.2	3.54

Output properties

Name	Description	Type	Value
tnsh1z	Aggregated norm of incomplete per piece time for rough processing of a tooth, min	REAL	0.6

Intelligent system of technological processes programming

CNC equipment is essential for the construction of digital production. Operation of this equipment in the 4IR conditions is impossible without high-performance CAM systems that provide automated technological processes programming. In Russia, engineers can use one of the best systems in the world - the domestic-made system SprutCAM [11]. More than 7000 licenses to use this system have been sold to the world's largest companies in the USA, Germany, Japan, Switzerland, Italy, Great Britain, France, Australia - Apple Inc., AEROSPACE, NASA, GE, HP, Intel, HITACHI Inspire the Next, PHILIPS, BMW, TOYOTA, etc.

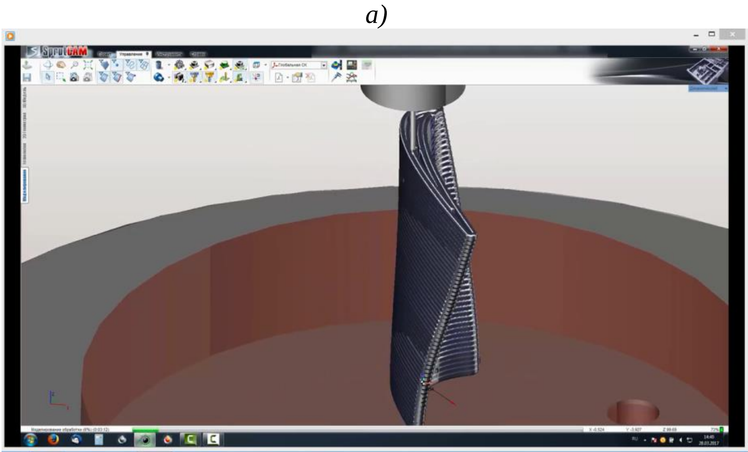
SprutCAM provides programming of all stages and types of technological processes for any CNC machines and robots.

From among the base nine industrial technologies of Industry 4.0 [5], SprutCAM fulfils the following: advanced robotics, additive technologies, augmented reality and technological process modeling.

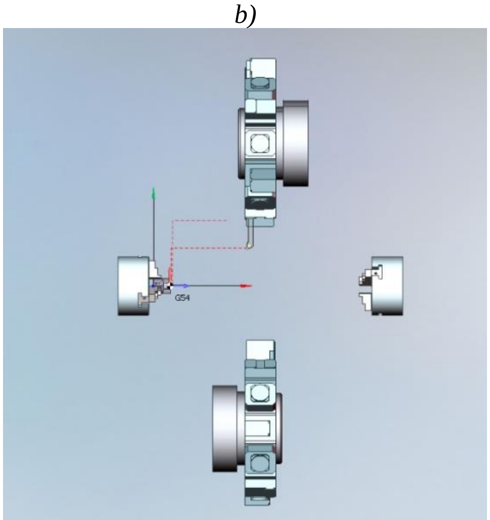
Fig. 26a shows a part of the technological complex for cladding panels processing by robots. An example of additive technology for blade growth is shown in Fig. 26b. The programming scheme of double-sided machining on a turning-milling two-spindle machining center is shown in Fig. 26c. 3D modeling for the detection of constraints imposed by a device is shown in Fig.13, and the one for detection of tooling collision - in Fig. 14.

To reduce the labor intensity for programming the part's processing with an insignificant change in its design, SprutCAM introduces intelligent functions for re-importing the part model from 3D modeling systems [13, 14]. If the 3D model file that was previously imported into the system is modified by the designer, such modification will be detected. SprutCAM will suggest updating the part for processing. At the same time, the system will recalculate all the previously created processing technology, adapting it to the new design of the model. Thus, the preparation of a control program for launching a new product into production is reduced to the minimum number of user actions.

a)



b)



c)

Fig.26. Industrial technologies in SprutCAM: a) robotics; b

) additive technologies; c) augmented reality.

SprutCAM can analyze a three-dimensional model for processing and build a tree of design and technological elements (FBM) [13, 14]. To form an output processing trajectory, a user only needs to specify an element or a group of elements and select a step out of the step list suggested by the system. This list is generated by the system automatically, taking into account the set of tools available in the library and the typical machining steps previously created by the user.

Results

Intelligent systems of technological processes design and programming should certainly be considered in the integration of the processes occurring in the ongoing Industrial and Digital revolutions. This problem of their development is still not sufficiently addressed in scientific literature.

These systems are created within the Internet of Knowledge. IoK has an ontological basis and includes meta-ontology, which comprises the ontology of objects, the ontology of tasks and the ontology of optimization. The ontology of objects provides generation of 3D models of manufactured products and technological equipment, including machines, robots, accessories and tools. The ontology of tasks makes a structural synthesis of production processes, as well as the synthesis of their parameters. This relates to both processing and assembling. This paper circumstantiality discusses all the mentioned ontologies. The digital models of manufacturing processes are transferred to production management systems for implementation.

The ontology of optimization is used to obtain the best product and processes; it can be single- and multi-objective. The paper describes the method of technological processes optimization with the use of genetic algorithms.

The Digital revolution should enable the non-programming knowledge carriers to enter knowledge into the computer without intermediaries. That can be done by way of expert programming methodology, in which knowledge is described in the language of business prose, which is very close to the literary language, but formalized so that it becomes possible to automatically generate a software matching the source texts. Business prose can be formed in any language, and software can be generated in different programming languages.

Knowledge bases are generated on the basis of knowledge modules representing a condition-action rule, which has an identifier and name, a precondition, input and output properties, and a mechanism for converting the first to the second. Modules are automatically translated into subprograms in the programming language selected by the user. Thus, the user can choose both the input language of the knowledge representation and the resulting language of the software generation. The examples of these modules application for various design purposes are given above.

To automate technological preparing in computer-integrated production, there are systems of two classes: systems to automate the design and standardization of technological processes (CAPP) and systems to automate the programming of operations on CNC machines (CAM).

The CAPP function is the formation of a complete set of technological documentation (routing and operation sheets, tooling lists, materials, etc.) on the basis of design documentation (specifications, assembly drawings and parts drawings). CAD systems must perform planning and normalization of all operations, which is necessary for the proper work of production scheduling systems.

It is expedient to use a multi-agent system for designing and programming of technological processes.

The nine industrial digital technologies recommended by The Boston Consulting Group to create Industry 4.0 systems should be supplemented with the artificial intelligence technology.

Discussion

The digital revolution in industry is supposed to cover all stages of the product life cycle, including product design and manufacturing processes planning. At these stages, goods and processes are not accomplished as real things but formed as models in the virtual world. Therefore, the Internet of Things concept, the basis of the “Industry 4.0” project, is not sufficient to conduct a full-scale digital revolution. It is necessary to use an integrated structure of the Internet of Knowledge and the Internet of Things.

The Internet of Knowledge should be accessible to everyone and should not require special education in the field of information technology. Knowledge should be presented in the language of business prose as close as possible to the literary language of different countries. However, such presentation should allow automatic conversion of knowledge into programming languages with simultaneous generation of software tools that implement interactive dynamic representation of knowledge in computers.

The results of the Internet of Knowledge functioning should be 3D models of products, (machines, robots, tools and accessories) and, eventually, the digital models of their production processes generated by users in a semi-automatic mode.

Conclusion

Russia possesses all necessary technologies for the 4IR realization. It should be emphasized that the artificial intelligence technology, which was not mentioned in The Boston Consulting Group recommendations but described in sufficient detail in this paper, is the most important technology for further development of the systems involved in the 4IR. The systems created on the basis of this technology could receive the name “Industry 5.0”.

Bauman Moscow State Technical University conducts annual conferences “Effective methods of automation of technological preparation and production planning”. In fact, these conferences are devoted to the Industrial revolution in Russia. In 2017 the conference held 555 specialists from 248 enterprises working in 95 Russian cities.

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