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RUSSIAN TECHNOLOGIES OF THE DIGITAL REVOLUTION IN INDUSTRY. PART 1. METHODS AND MEANS OF DIGITAL MANAGEMENT

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ABSTRACT

The Digital revolution in industry is supposed to cover all stages of the product life cycle, including product design and planning of manufacturing processes. 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.

This paper aims to develop an integrated structure of the Internet of Knowledge, which is used in the virtual world, and the Internet of Things.

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 of engineering products design and production.

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. The RF Government approved the program "Digital Economy of the Russian Federation". The program defines goals, objectives, directions and timeframes for the implementation of the state policy aimed to create conditions necessary for the development of a digital economy, in which data in digital form is a key factor of production. This paper is devoted to the solution of this problem.

The term Industry 4.0 is commonly used to describe 4IR. This term appeared in Europe in 2011, at an industrial exhibition in Hanover, when the government of Germany began talking about the need for a wider use of information technologies in production. The essence of the new revolution lies in the fact that the material world is connected to the virtual one, which leads to formation of new cyber-physical complexes united in one digital ecosystem. Robotic production and "smart" factories are the components of the transformed industry. The Fourth Industrial Revolution means increasing automation of all production processes and stages: digital design of a product, creation of its virtual copy, joint work of design and production engineers in a single digital space, remote setup of equipment at a plant to meet the technical requirements of the manufacture of designed product, automatic ordering of necessary components in the right quantity and control of their supply, monitoring of the finished product from the factory warehouse to a store and the end customer.

The 4IR basis is the Internet of Things (IoT) - the concept of a network of physical objects ("things") equipped with built-in technologies to interact with each other or with the external environment. The concept considers the organization of such networks to be a phenomenon capable of rearranging economic and social processes, excluding human participation in a part of actions and operations.

The 4IR is supposed to include automation of absolutely all stages and processes, including product digital design, its virtual creation, joint work of specialists in a single digital space, etc. That is, the Revolution must cover the stages when products are not things yet, but exist in the virtual world in the form of information models.

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, and the real world realized by the Internet of Things (Fig. 1). It is advisable to build the Internet of Knowledge (IoK) on an ontological methodology [8].

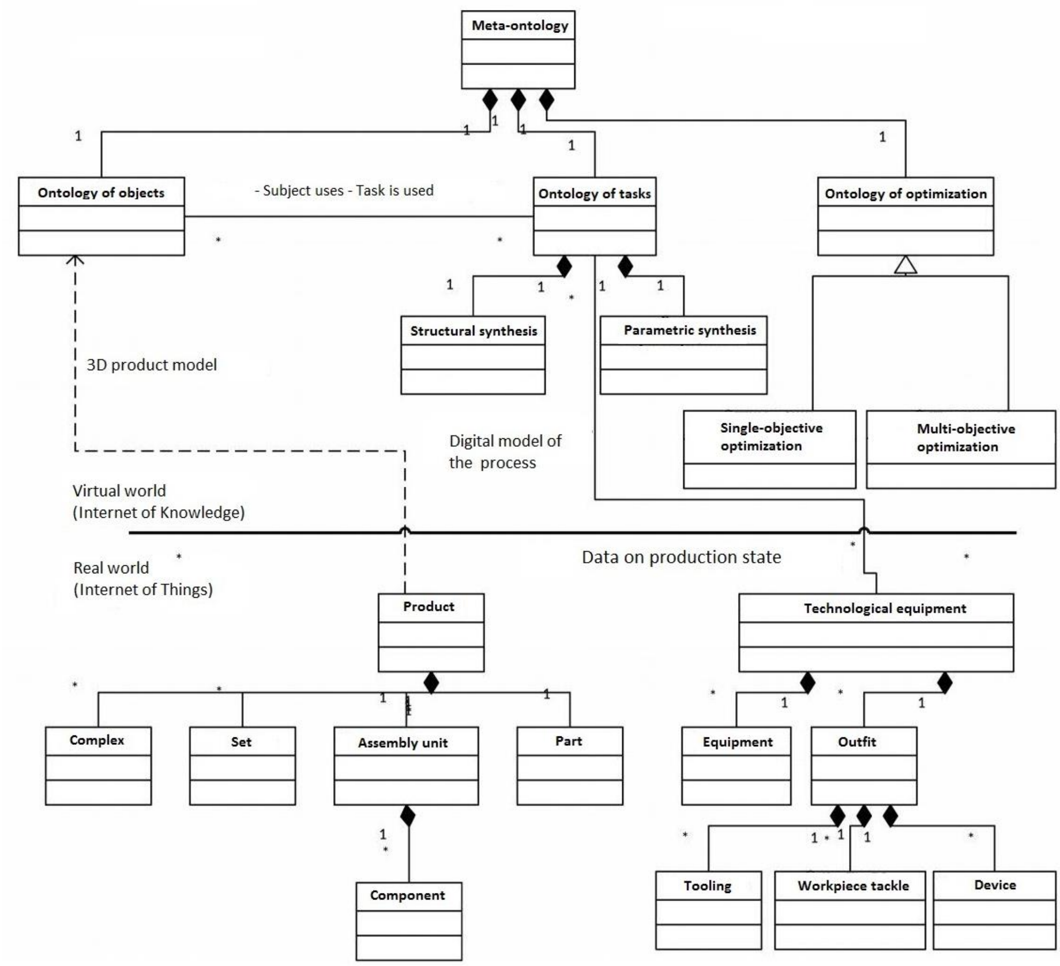


Fig.1. Integrated structure of the Internet of Knowledge and the Internet of Things

Knowledge is the result of the cognitive activity process. Usually knowledge means only such result of cognition that implies imperishable truth, can be justified by logic or facts and allows empirical or practical verification. Thus, speaking of knowledge, we often mean true knowledge. True knowledge is a true reflection of reality in a person's thinking - an idea, a description or a message about what actually is.

Written sources were carriers of knowledge before the Digital Revolution. When the Digital Revolution began, the carriers of knowledge became software resources. Software tools were initially based on algorithmic basis and used algorithmic languages. The knowledge carriers without programming skills could not enter pieces of knowledge into the computer. They required intermediaries: a developer (algorithmist) and a programmer (Fig. 2a). At the start of artificial intelligence (AI) development, the languages used to describe knowledge were quite sophisticated. Thus, the scheme of entering knowledge into the computer did not change [11]. Users again needed intermediaries like knowledge engineers and programmers (Fig. 2b). There was a semantic gap between the process participants, as a rule. Each of the intermediaries represented knowledge, introducing their own considerations. As a result, knowledge did not fully reflect understanding of the knowledge carrier.

The Digital Revolution shall radically change this scheme and allow knowledge carriers without programming skills to enter knowledge into the computer without intermediaries (Fig. 2c). This became possible due to the methodology of expert programming [10, 12]. In this methodology, knowledge is described in the language of business prose, which is very close to the literary language, but formalized so that it is possible to automatically generate software that corresponds to the source texts. The examples of expert programming use are given below.

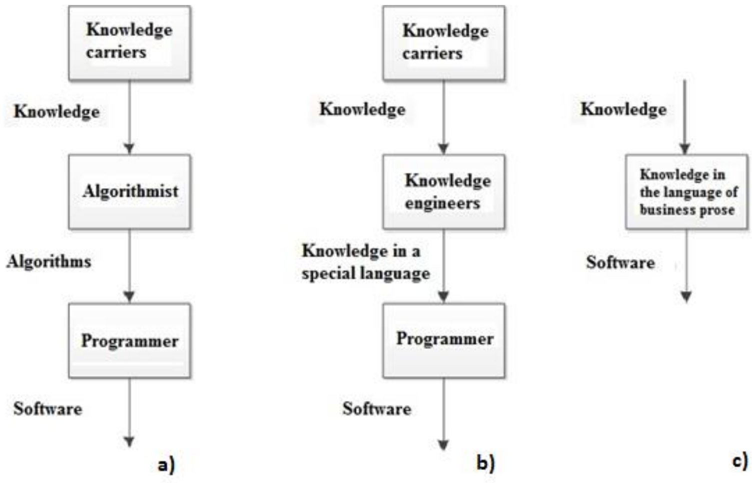


Fig. 2. The schemes of knowledge entry

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

Meta-ontology comprises three components: the ontology of objects, the ontology of tasks and the ontology of 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.

In the described approach, the world of things consists of products made with the help of 3D printers or machine tools and robots that make up a part of the technological equipment at a particular production site. The manufacturing process is regulated by digital models generated with the help of corresponding systems, including the necessary tasks.

The designing of processes is carried out using data on the state of production, obtained from the Internet of Things.

Intelligent system of semi-automatic generation of 3D product models

There is a number of works devoted to the creation of intelligent CAD-systems [10], [12]. However, they do not set the task of creating semi-automatic design systems capable of generating 3D models.

To enable the generation of 3D models with the help of knowledge bases, it is necessary to create a knowledge module (KM) with a mechanism, which can generate a product 3D model with dimension values calculated in others modules, basing on the CAD-parameterized model of a part and (or) assembly unit.

Let us look at the operation of such KM with the example of generating a 3D model of a simple part – an inset bearing cap of a cylindrical reducer (Fig. 3) [13, 14]. The CAD-system used for the example is SolidWorks.

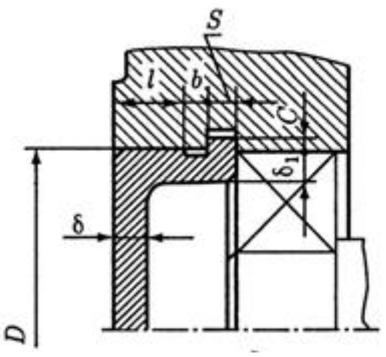


Fig. 3. A drawing of an inset bearing cap

Initially, it is necessary to draw a sketch of the parametrized 3D model and set the basic dimensions. Since the part in Fig.3 is a rotatory body, its sketch represents a generatrix profile (Fig. 4).

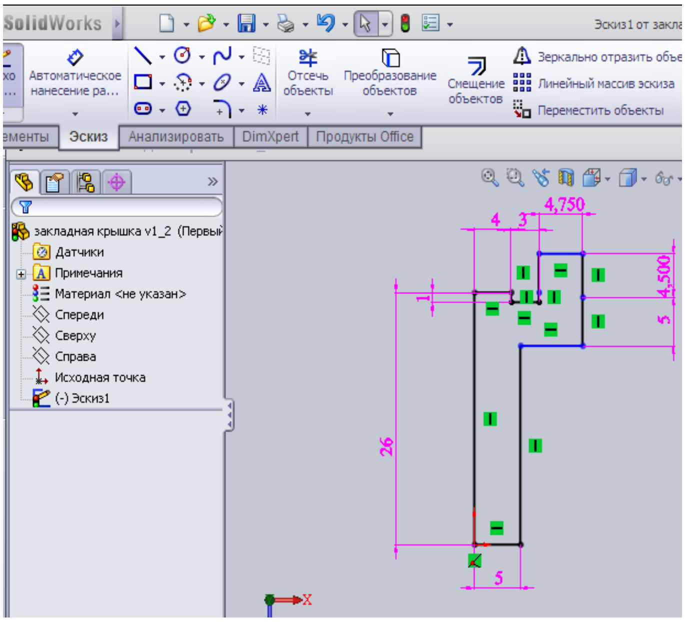


Fig. 4. The generatrix profile in SolidWorks

To parameterize the model, we must enter dimension dependencies in the SolidWorks table of equations. By double clicking on the dimension to be parameterized, we call the dialog box “Modify” and choose “Add equation” from the drop-down list. In the “Add equation” box, the dependent dimension is indicated in the first place; the control dimension and required arithmetic operations with it go after the equal sign (Fig. 5).

In the dialog box we should type a dimension name, which can be found by clicking on the required dimension (the “Value” tab, “Primary Value” section). We can also enter a value in the dialog box by clicking on the dimension itself.

After editing the sketch, we can proceed to creation of a 3D model, by rotating the resulting contour around the axis (Fig.6).

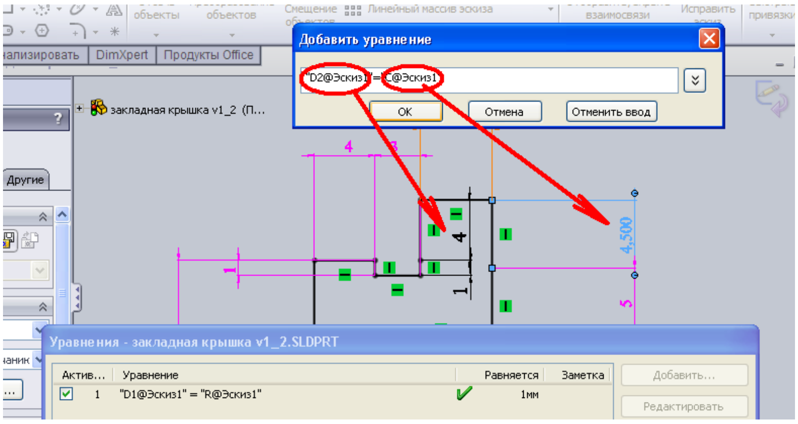


Fig. 5. Equations adding in SolidWorks

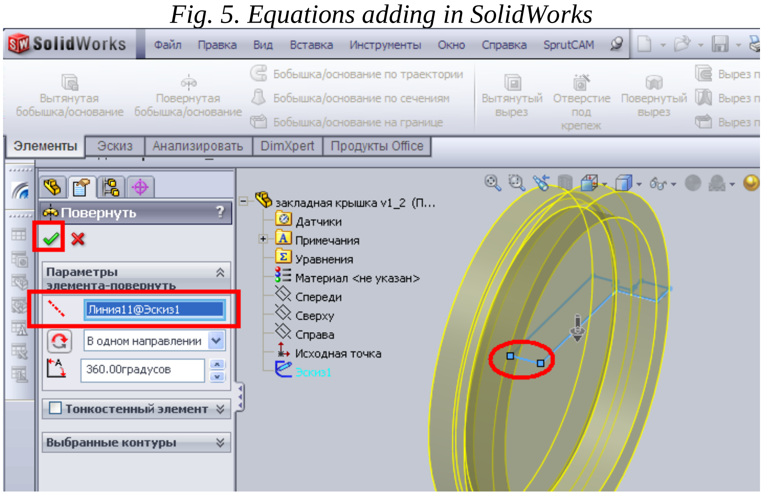


Fig. 6. Creation of a 3D model in SolidWorks

The constructed 3D model should be connected to the knowledge base through a specialized knowledge module. This module provides the following functions:

1. Downloading and opening of SolidWorks 3D models (The file format is *.SLDASM,*.SLDPRT)

2. Display of the dimensions and dimension values of that model (Dimensions are displayed in the format: <dimension name>@<design tree object>@<3D model name>).

3. Comparison of 3D model dimensions with the variables in the Sprut ExPro dictionary [9,10] (using a drop-down list).

4. Generation of the text of the PRT module subprogram, which changes the 3D model dimensions according to the variable values in the Sprut ExPro knowledge base [9, 10].

5. Loading of this subprogram into the "Mechanism" interface of the module.

The interface of the 3D model generation module in the Sprut ExPro system is presented in Fig 7 [9, 10].

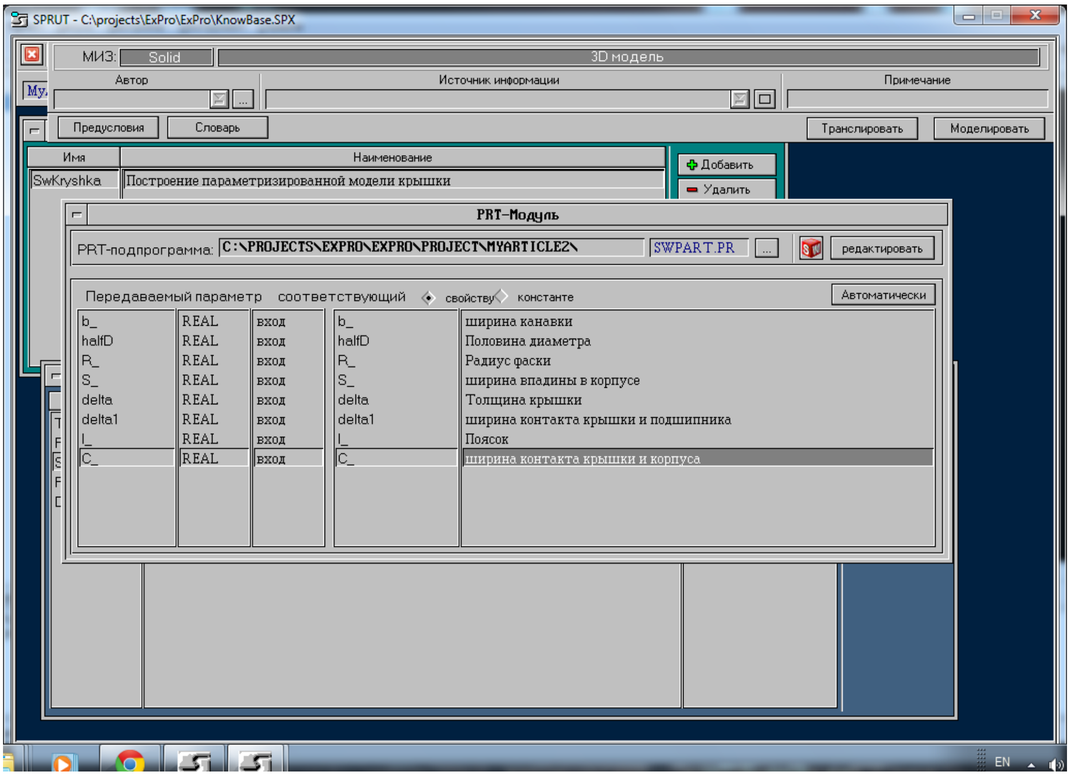


Fig.7. The interface of the 3D model generation module in the Sprut ExPro system.

The knowledge base for designing and generating 3D models

The development of the knowledge base method begins with the creation of a dictionary [9, 10, 14]. The dictionary of the method for designing an inset bearing cap is presented in Table 1 and corresponds to the drawing shown in Fig.3.

It should be emphasized that dictionaries can be written in any language. Thus, the knowledge base in business prose will be presented in the corresponding language. The dictionary (Table 1) was initially compiled in Russian.

Table 1

THE METHOD DICTIONARY

Name	Description	Type	Input	Output	Form
D_	Cap diameter, mm	REAL	*		input
halfD	Half the cap diameter, mm	REAL			local
S_	Width of the socket in the housing, mm	REAL			local
b_	Groove width, mm	REAL			local
l_	Belt width, mm	REAL			local
C_	Width of the contact of the cap and the housing, mm	REAL			local
delta1	Width of the contact of the cap and the bearing, mm	REAL			local
delta	Cap thickness, mm	REAL			local
R_	Chamfer size, mm	REAL			local

The semantic network of modules (ranked automatically) for the method of designing an inset bearing cap is presented in Table 2. Every method is a knowledge base generated on the basis of knowledge modules.

In this case, the method has one input variable - the cap diameter. Each knowledge module is a production rule that has an identifier and a name, a precondition, input and output properties, and a mechanism to convert them. The modules are automatically translated into subprograms in the programming language selected by that the user. Thus, the user can choose both the input language of the knowledge representation and the resulting language of the software generation.

Table 2

KNOWLEDGE MODULE OF THE METHOD

Rank	Name	Description
1	Faska	Chamfer size selection
1	Table	Selection of dimensions by diameter
2	Formula	Dimensions calculation
3	Solid	3D model generation

INPUT PROPERTIES

Name	Description	Type	Value
D_	Cap diameter, mm	REAL	63

Table 2 presents the following modules: Faska - Chamfer size selection, Table - Selection of dimensions by diameter, Formula – Dimensions calculation, Solid - 3D model generation. These modules are executed unconditionally in the knowledge base and therefore do not contain preconditions. An example of a technological design with a precondition will be given below.

The first rank covers the modules, which have the cap diameter as an input variable, including the below-given modules for the chamfer size selection and the groove width, as well as the modules for the cap thickness, the mechanism of which are tables.

KM: “Faska” - Chamfer size selection

Input properties

Name	Description	Type	Value
D_	Cap diameter, mm	REAL	112

Mechanism - Table

Configuration of properties in the table

D_
R_
b_

Table

[10,50]	(50,100]	(100,)
1	1.6	2
3	5	8

Output properties

Name	Description	Type	Value
R_	Chamfer radius	REAL	2
b_	Groove width	REAL	8

KM: “Table” – Selection of dimensions by diameter

Input properties

Name	Description	Type	Value
D_	Diameter of contact with the housing	REAL	50

Mechanism - Table

Configuration of properties in the table

D_
delta

Table

[50,62]	[63,95]	[100,145]	[150,220]
5	6	7	8

Output properties

Name	Description	Type	Value
delta	Cap thickness	REAL	5

All other dimensions required to generate a 3D model of the part are calculated by formulas on the basis of these data, using the calculation type module.

KM: “Formula” Dimensions calculation

Input properties

Name	Description	Type	Value
delta	Cap thickness	REAL	8
b_	Groove width	REAL	1

Mechanism - Formula

delta1=0.95*delta

S_=0.95*delta

C_=0.5*S_

l_=b_

Output properties

Name	Description	Type	Value
delta1	Width of the contact of the cap and the bearing	REAL	7.6
l_	Belt	REAL	1
S_	Width of the socket in the housing	REAL	7.6
C_	Width of the contact of the cap and the housing	REAL	3.8

Fig.8 shows the interface of the knowledge base for designing and generating a 3D model of an inset bearing cap in the system Sprut ExPro [9, 10].

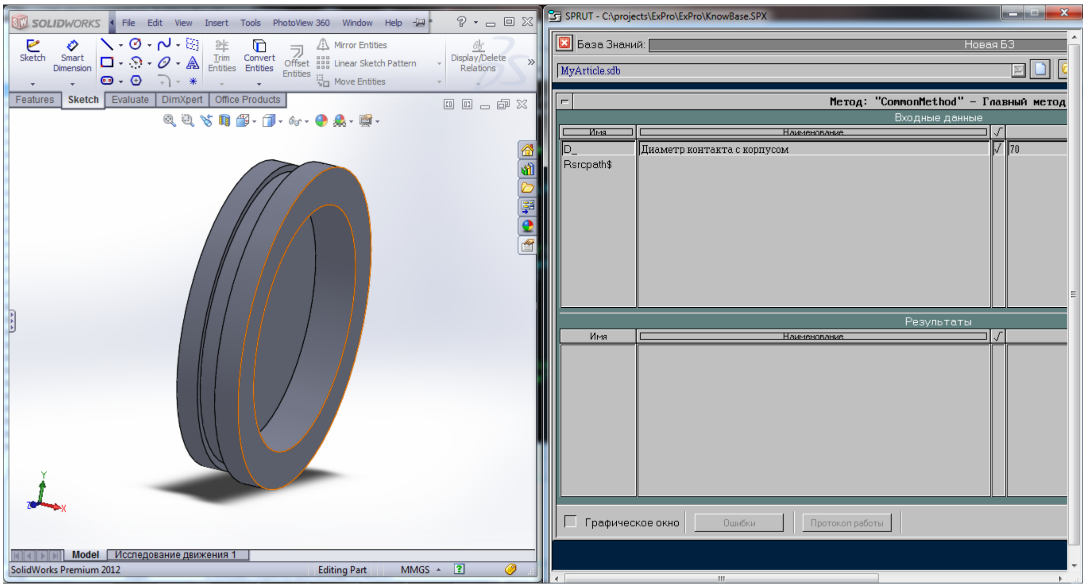


Fig.8. The interface of the knowledge base for generating a 3D model of an inset bearing cap in the system Sprut ExPro

To automate technological preparing in computer-integrated production, they use systems of two classes: systems to automate the design and standardization of technological processes [17], [18] (Computer-Aided Process Planning, CAPP) and systems to automate the programming of operations on computer numerical control (CNC) machines (Computer-Aided Manufacturing, CAM).

The CAPP functions include 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). CAPP systems must perform planning and normalization of all operations, which is necessary for proper operation of production planning systems. At that, these systems do not ensure accurate calculation of the basic time for operations on CNC machines; that requires full calculation of toolpaths. Such a calculation is performed in the systems of programmed processing on these machines. However, these systems do not make precise calculations of allowances and processing regimes, as well as assignment of norms of auxiliary time for the operation and steps. In this regard, it is advisable to create an integrated system. This paper describes such a system; it was created on the basis of the Russian projects SPRUT-TP и SprutCAM [18].

A multi-agent system to design and program technological processes

Fig. 9 shows a diagram of the agents classes included in the developed integrated system. The key agents are “Part” and “Workflow”. The diagram shows the agent attributes required to generate the output document "Operation Sheet". The methods used to assign values to attributes are indicated for each agent.

The "Part" agent has two attributes – "Part description" and "Part name", the values of which are entered using the SPRUT-TP system.

The attributes of the agent "Technological process" are determined by the header of the standard operating sheet. These attributes values are formed during the design of the technological process in the SPRUT-TP system.

The technological process consists of operations, which may include operations performed on CNC machines. In accordance with the Russian State Standard ESKD GOST 3.1118-82, operations are described by lines of different types; the main ones are lines of type A and type B. Type A lines describe the operation itself; type B lines determine the equipment, on which the operation is performed. The attributes of the "Operation" agent include all components of both lines, as well as of those of type O lines (they contain the description of actions), and type T (they have the operation tooling data). The operations design is performed in the SPRUT-TP system. The code and the equipment name are exported to the SprutCAM system.

Any operation may include descriptions of localizations that are considered as separate auxiliary steps. Localizations determine the mode of the part placement on the machine and contain a description of the step content and the standard time for its execution. Localization attributes are formed in the SPRUT-TP system (Fig.9).

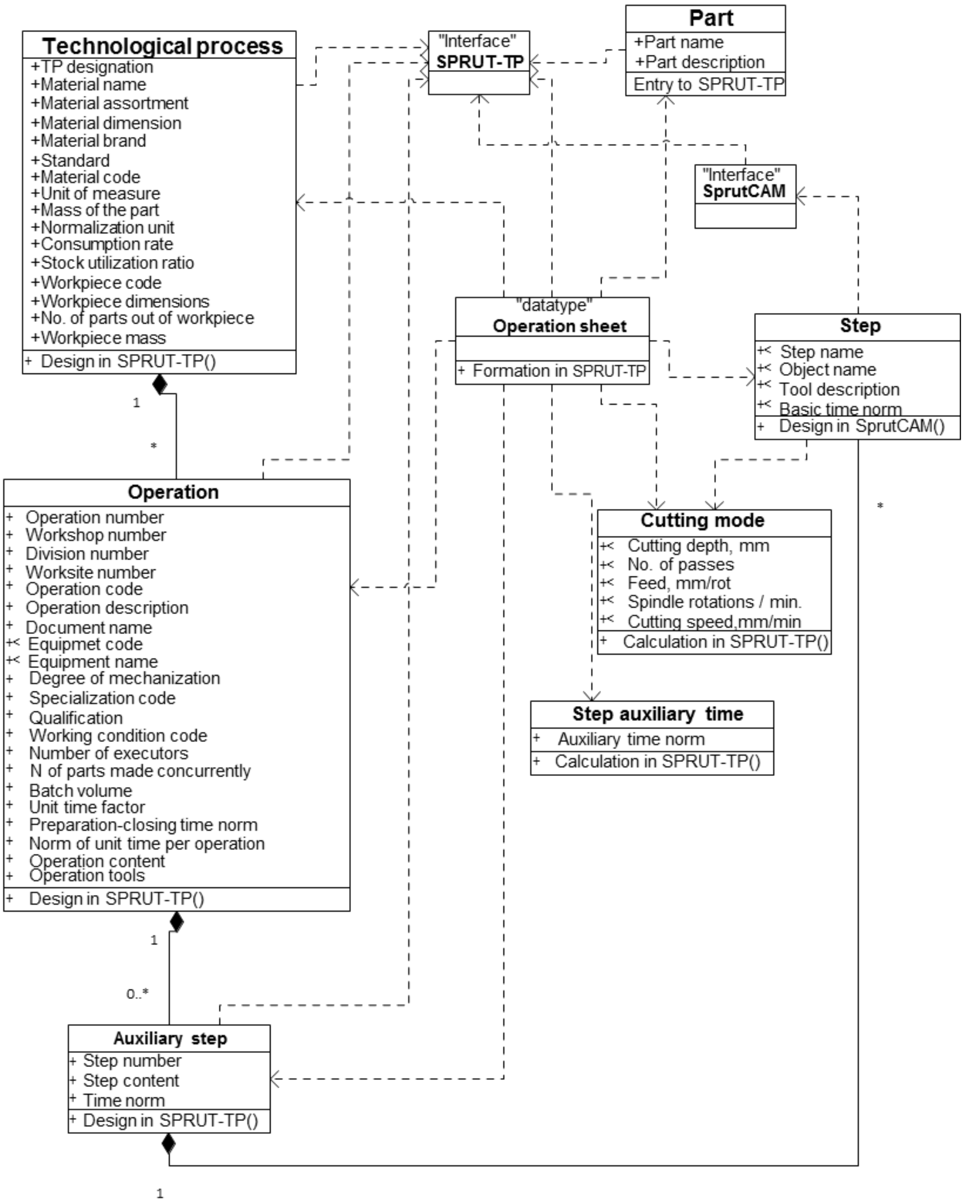


Fig.9. Diagram of agent classes

Each localization can cover execution of one or several main steps of the part processing that are designed in the SprutCAM system.

SprutCAM selects the step name and determines the job for processing. When creating a job, the system dynamically tests the object being processed (it is a piece of the geometric model of the part) and selects a cutting tool from the resource library. In order to define the standard time for a step, it is necessary to calculate the toolpath (performed by SprutCAM), as well as allowances and cutting modes (determined by the SPRUT-TP knowledge base and exported to SprutCAM) (Fig.9).

To normalize the processing fully, it is necessary to calculate the auxiliary time rate for the step; that is performed in SPRUT-TP.

All the information described is transferred to the XML model of the operation sheet, from where it can be derived as a standard document by the SPRUT-TP system.

The agent class diagram described above is a static description of the system. UML uses dynamic diagrams to model the dynamic aspects of the system. They include an interaction diagram that describes interactions, which consist of multiple agents and their relations, including the messages they exchange. A sequence diagram is a diagram of interactions that emphasizes the temporal ordering of messages.

To create such a diagram, the agents involved in the interaction should be positioned in its upper part along the axis X. The interaction-initiating agent is usually placed on the left and the others - to the right (the farther away, the more subordinate is the object). Then, along the Y axis, there are messages sent and received by the objects, and later ones turn out to be lower. This gives a visualization that allows understanding the development of the control flow in time.

The agents participating in the described system are “Production engineer”, “SPRUT-TP”, “SprutCAM” and “Operation sheet” (Fig.10).

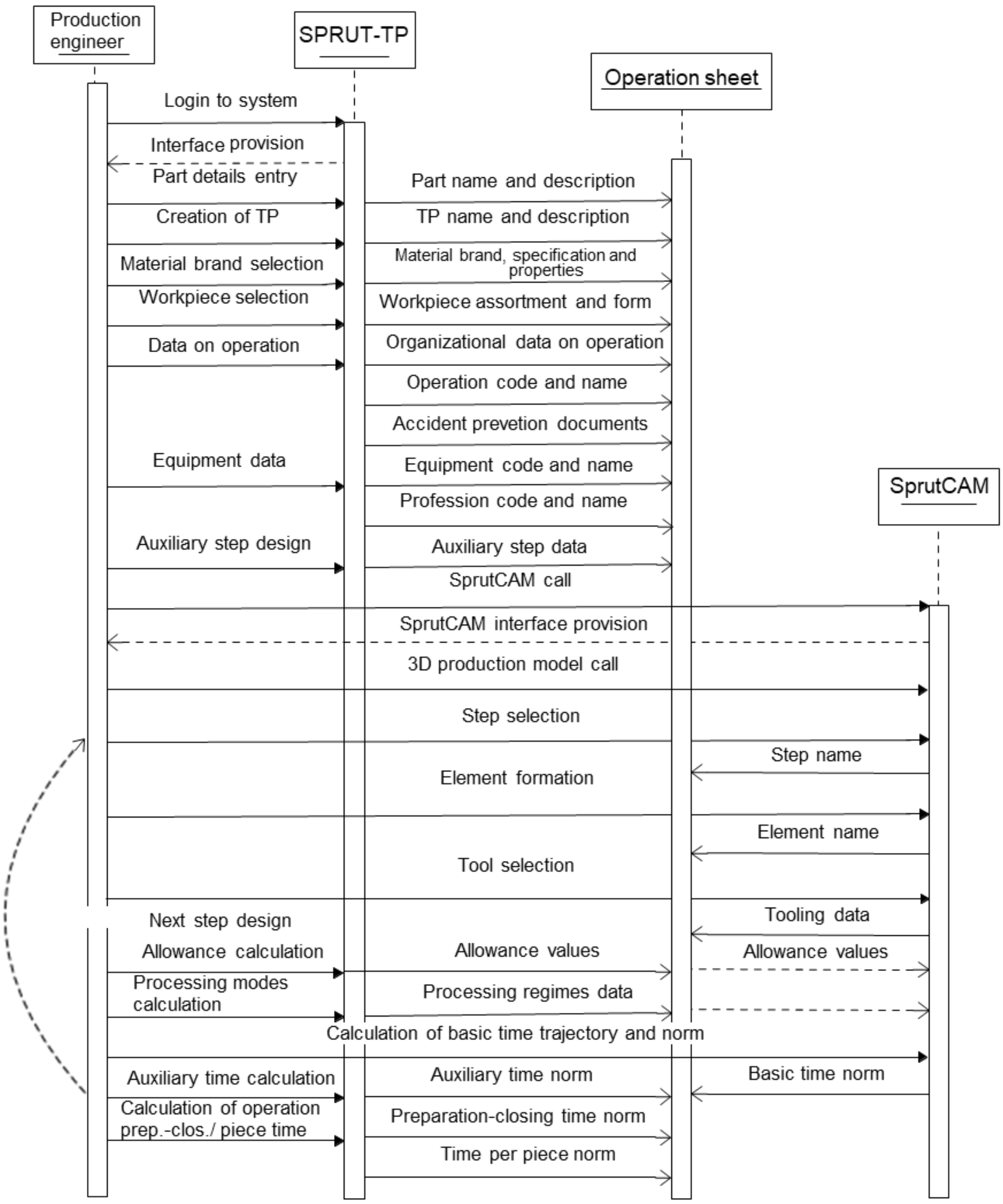


Fig.10. Sequence diagram

The interaction-initiating agent is the object “Production engineer”, it is a system operator. The production engineer logs into the SPRUT-TP system and its interface opens. This interface is used to enter the details of the part, including its denotation and name. Then the operator creates a technological process (TP) and gives a designation and name of the TP.

The next step is to enter data on the material of the part, including the name, assortment, size and brand of the material and its standard, the code and measurement unit. The mass of the part is entered in accordance with the part drawing.

Next goes the workpiece description, including the workpiece code, its profile and dimensions. The number of parts to be made from the workpiece is specified by the production engineer.

SPRUT-TP has the possibility of calculating the material utilization factor (MUF), the rate of use (UR) and the workpiece mass (WM). The calculation can be simple, extended and reverse.

In the simple methodology, the WM calculation is carried out only for the rolled stock entered in the SPRUT-TP resource database. If the workpiece is not rolled stock, the WM is assigned by the production engineer and indicated in the corresponding field of the form. Next, the mass of the workpiece is read by the system from the form field to calculate MUF and UR. The WM calculation is performed only when specifying the parameters of the part. At that, the engineer need to enter the workpiece dimensions in the dimension window, although the dimensions of the selected (or specified) assortment standard size are automatically entered in the corresponding fields from the resource database by default.

In the extended calculation option, the WM characterization is also made only for the rolled stock stored in the SPRUT-TP resource database. If the workpiece is not rolled stock, the WM is defined by the engineer and recorded by him in the corresponding field of the form. Next, the mass of the workpiece is read by the system from the form field to calculate MUF and UR. If the calculation is made when specifying the parameters of the part, the engineer need to enter the dimensions of the assortment standard size in the dimension window; by default, they automatically come from the resource database. During the calculation, the system requests the parameters of the rolled products or sheets. The system automatically tries to determine the type of the rolled metal and the corresponding calculation procedure. However, if it fails, there will be a window, in which the workpiece type is specified manually.

In the case of reverse calculation, the MUF is specified by the engineer; the rate of use and the mass of the workpiece are calculated from the MUF value.

It should be emphasized that all the described actions to determine the technological process attributes must be performed only if the design of the operation is processed separately on a CNC machine. As a rule, such an operation is included in the routing technological process, which is designed in the production control office, and all the mentioned data are already available in the system.

When using UML, the components of task ontology are object methods. However, the traditional algorithmic approach used to construct methods in UML does not correspond to the explicit specification of knowledge conceptualization from the point of view of a “non-programming” user. In this connection, the ontology of tasks should be created using knowledge bases.

At present, CAD systems do not meet the requirements of the ontological methodology. In the worst case, a CAD system can generate a geometric 3D model, which is transferred to the processing programming system in CNC machines (CAM system), most often using a metafile in the IGES standard. The 3D model helps to form drawings of products with all the necessary technical requirements, but this information is not available for further computer processing. At that, when changing the values of the exported attributes, there is a complete regeneration of all interconnected drawings.

Digital industrial technologies in Industry 4.0 systems

The work [5] has references to nine digital industrial technologies, which form the foundation of Industry 4.0 systems:

1.Advanced robotics
2.Additive technologies
3.Augmented reality (or AR – an environment with direct or indirect augmentation of the physical world with digital data in real time using computer devices)
4.Modeling
5.Horizontal and vertical integration
6.Industrial Internet
7.Cloud technologies
8.Information security
9.Big data and analytics

The first four technologies are considered in the second part of this paper. The next section is devoted to horizontal and vertical integration.

Discussion of the technologies indicated in points six, eight and nine go far beyond the scope of this paper.

As for cloud technologies, they should be used, in various forms, at all stages of Industry 4.0 systems development. Their use case diagram is presented in Fig.11.

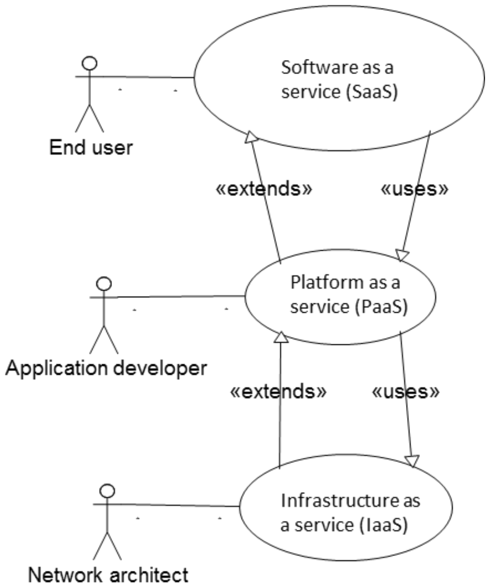


Fig. 11. The use of cloud technologies in creating Industry 4.0 systems

The end-users of digital production utilize software as a service in their work. This paper describes software tools for automated design and programming of technological processes, as well as for operational management of production. Developers of CAM applications use, as a service, this or that platform to create knowledge bases. Here they describe the methods and means of creating the knowledge bases for the technological processes design. Finally, the digital production architect uses a conceptual model, which contains the infrastructure of the production.

It is absolutely necessary to add the tenth technology to the nine ones listed above - artificial intelligence, which allows non-programmers to create systems that automate their activity on the basis of knowledge-describing non-algorithmic languages that are as close as possible to the human languages of business prose. The existing examples of such systems will also be given below.

Industry 4.0 systems provide advantages in four directions. The first advantage is increase in productivity due to reduction in the time per piece and better production management. The second advantage is flexibility provided by the wide possibilities of modern CNC machine tools (machining centers) and robots. The third one is the product quality ensured by real-time computer-aided means of control and measurement. The fourth advantage is the reduction of time spent on design and production, due to system integration.

Germany experts formulated several principles of Industry 4.0 design, in accordance with which companies can implement scenarios of the fourth industrial revolution at their enterprises [5].

The first principle is interoperability, which means the ability of machines, devices, sensors and people to interact and communicate with each other via IoT.

This leads to the next principle - information transparency that appears as a result of such interaction. The virtual world gets a digital copy of real objects, systems of functions, which exactly repeats everything that happens to its physical clone. The result is accumulation of the most complete information about all processes that occur with equipment, "smart" products, production in general, etc. This requires aggregating all possible data from sensors and taking into account the context, in which the information is generated.

Technical assistance is the third principle of Industry 4.0. Its essence lies in the fact that computer systems help people make decisions through collecting, analyzing and visualizing all the information mentioned above. This assistance may also consist in full replacement of people with machines in dangerous or routine operations.

The fourth principle is decentralization of managerial decisions, delegation of some of them to cyber-physical systems. The idea is that automation should be as complete as possible: sooner or later, unmanned production should appear wherever machines can work effectively without human intervention. Employees will be assigned the role of supervisors, who can join in emergency and non-standard situations.

The application of these principles in the Russian software is considered below. The first principle is related to the IoT use. Fig. 12 shows the general IoT scheme [5] within the German Industry 4.0 project. At the "lower" level of production, there are devices (TP facilities) that include technological equipment (including control and test equipment), technological tools (including working tools and controls), the means of TP mechanization and automation. The 4IR conditions assume all these devices are equipped with CNC devices that are connected by means of local wired and wireless computer networks or cloud technologies. These devices are controlled with CAM systems; one of them, the Russian system SprutCAM [17] (listed in world's TOP 5 in its sphere), is described below.

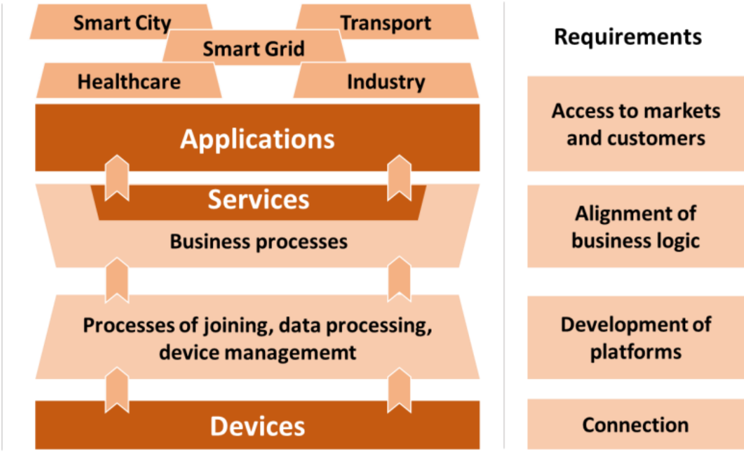


Fig. 12. Vision of industrial IoT in the Industry 4.0 concept (Germany)

In the production environment, business processes (Fig. 12) are divided into two sublevels: engineering and organizational. The engineering level is provided by CAPP systems and involves the design of technological processes. The organizational level is associated with production scheduling and is provided by the use of MES systems. The technological process planning in Russia is regulated both in form and content. The TP form is regulated by the standards of the unified system of technological documentation (USTD), and the content is regulated by the documentation on the TP standardization. The next sections describe Russian products: the CAPP system SPRUT-TP and the MES system SPRUT-OKP [17, 18].

Diagram of integrated system use

Fig.13 и Fig.14 show use case diagrams in accordance with the 4IR conception. They clearly reflect the technology of horizontal and vertical integration. The horizontal integration is associated with software tools that support different stages of the product life cycle. Fig. 13 also points out the interconnected tools for TP planning (SPRUT-TP) [18, 20, 21, 22, 23, 24, 25], programming (SprutCAM) and production scheduling management (SPRUT-OKP). The first two tools are used by production engineers.

The vertical integration is associated with administrative levels of management and includes levels from general director to storekeeper [21, 22].

The initial impulse for production planning is given by a customer that can be a private person or a legal entity, even a government body. The customer can form an application in the subsystem “Manager”. Based on this application, using the subsystem “Economist”, an economist makes a calculation to form an order (Fig. 13).

The subsystem “Economist” is intended for automated registration and determination of actual production costs. The calculations made in this module are related to:

- the operational evaluation of labor and material costs for manufacturing products in the main production units as of date of calculation, during the month and for the month;
- evaluation of the actual cost price of the workshop’s commercial output for the reporting period,
- evaluation of work in progress,
- calculation of losses from spoilage,
- distribution of indirect costs.

All of the above information is transferred to the production system control unit (Fig.13).

General Director together with Directors for economics and production create the order approval procedure using the subsystem “Manager” (Fig.13).

Basing on the approved order, production technology specialists link the technological processes developed in SPRUT-TP to the production centers. The can do that on the subsystem “Production engineer” (Fig.13).

This subsystem helps to describe and fill the directories that form the virtual enterprise model. The subsystem is intended to automate the works on keeping up-to-date data of the manufacturing bill of the enterprise materials and their assembly units, and to enter the workflow for manufacturing the objects of production from the SPRUT-TP system.

The subsystem “Production engineer” is applicable at enterprises with various design preproduction organization: with documentation design at the enterprise or obtaining it from the outside. The integrated automation of the main functions of the engineering level is provided within the enterprise management system. That helps to achieve two mains strategic goals:

- automation of the main elements of production design and technological preparation;
- support of up-to-date primary design and technological standards to ensure the functioning of SPRUT-OKP.

The users of this subsystem receive a wide range of reference information, which is most fully represented in various kinds of documents.

The obtained information can give a start to production planning, which is provided by the subsystem “Planner” (Fig.14). Planning can be done using a variety of methods: backward planning, forward planning, priority planning, cycle and stage planning. Planning "backward" is used when starting products in production on order. The release date is fixed, the launch date is calculated. Planning "forward" is used when starting products in production to replenish the warehouse. In this case, the launch date is fixed, the release date is calculated..

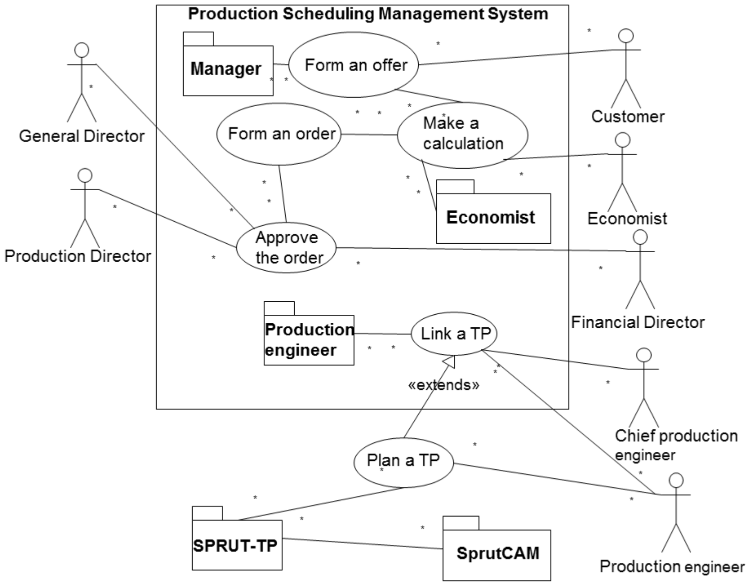


Fig.13. The use case diagram of enterprise management

In the case of directive planning in accordance with cyclograms, the start and release dates are set by directive. Orders are created according to the entered cyclograms at given production intervals.

In the case of directive planning in accordance with production stages, products are planned for the stages, whose deadlines are set by directive. Production of assembly parts and their assembling is planned separately in accordance with the directive stages.

When scheduling the orders based on equipment loading, the calculation of start/release dates for a lot is done taking into account other production orders so that the equipment is not overloaded.

Fine-tuning of planning is done with the methods of sequential movement of operations, parallel-sequential movement of operations and the method of using alternate worksites.

The function of dispatching, with the formation of operational data on manufacturing progress is performed by the subsystem “Dispatcher” (Fig.14).

The subsystem can be used in supply chain, processing, assembling, thermal treatment shops and the covering shops of machine-building enterprises, for single-piece to large-scale productions.

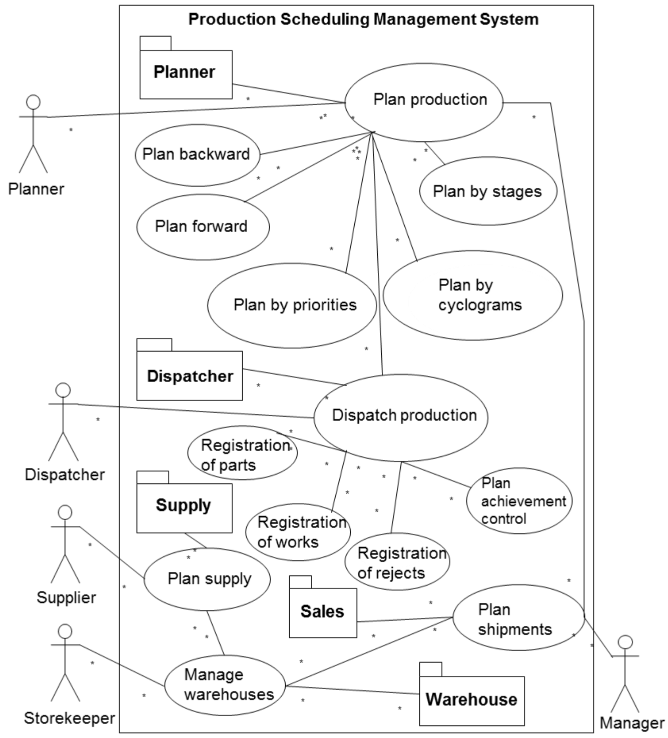


Fig.14. The use case diagram of enterprise management

The subsystem is applicable both for centralized and unit-oriented management structure. In big production units, material flow is organized in the form of “through” run along all routes of operations.

The subsystem makes registration of general works, part-by-part works and rejects; it also controls the plan achievement (Fig.14).

The Industry 4.0 systems are beyond the scope of one enterprise. This is provided by the subsystem “Supply” (it makes the planning for supply chain) and the subsystem “Sales” (it makes the planning of deliveries).

Warehouse management is provided by the subsystem “Warehouse” (Fig.14). This subsystem performs registration of inventory movements. The resulting data of inventory movement are used in production planning.

The subsystem "Warehouse" is developed to automate storekeepers’ work places and simultaneously provide all other SPRUT-OKP modules with required information on enterprise inventory movement.

The “Warehouse” module implementation pursued two main objectives:

- To provide the other modules with reliable information on the movement of tangibles in the enterprise;
- To develop a basis for computer-assisted work of warehouse managers / custodians of the enterprise.

These two objectives predetermine the two operating modes of the module: joint (together with the other SPRUT-OKP modules) and autonomous.

The module users are warehouse employees engaged in the registration of inventory movements.

The system provides servicing of three main types of warehouse movements: arrival (receipt to the warehouse), shipment (discharge from the warehouse) and inventory control- update of the available system data on stocks basing on physical inventory calculation (weighing).

The processing of goods arrival and shipment can be based on simultaneous use of different documents defined by the user during the system setup and installation. For example, the processing of arrived goods is possible with an invoice and/or a materials receipt ticket, and/or an accounting reference, etc.

Here, the function screen and the resulting print-out are considered to be documents. The term “Document” is also used in the description of non-documented and manual processing of movements.

Inventory control is carried out on the basis of the standard document - an inventory sheet issued by the system.

Intelligent system of technological processes planning

It was noted above that in addition to the nine technologies proposed by The Boston Consulting Group [5] for the creation of advanced Industry 4.0 systems, there is the tenth technology - artificial intelligence. We consider the main principles of this technology by the example of automated TP design [16].

Traditional product design includes the stages defined by standards. These include preliminary, engineering and detail design. Preliminary design should contain fundamental solutions that give a general idea of the device and the principle of the product operation. Engineering design includes final engineering solutions that give a full picture of the developed product layout, as well as initial data for the development of working documentation. The result of detail design is the documentation, which makes it possible to manufacture the product in accordance with technical requirements.

The foundation for intelligent systems construction is knowledge bases [15, 16, 20]. When making their structure, it is advisable to take advantage of the centuries-old experience of material products creation. Fig.15 represents the knowledge pyramid corresponding to the principles of product design described above.

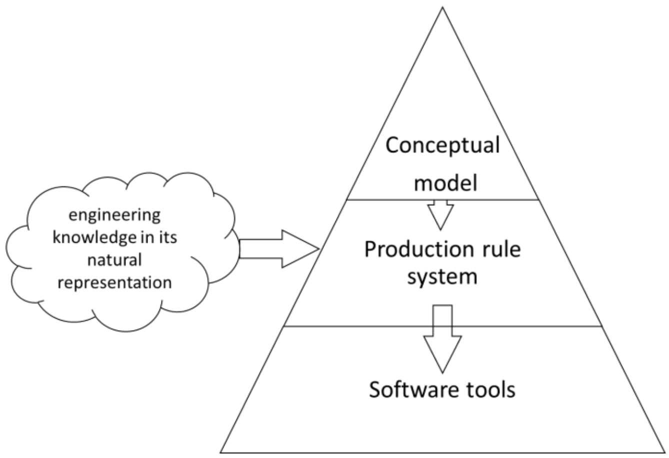


Fig.15. Pyramid of knowledge

At the top level of the pyramid, there is a conceptual model of digital intelligent production, it corresponds to the preliminary design of the system. The conceptual model gives grounds to generate a production system; that corresponds to engineering design. Software tools are at the pyramid base; they are the detail design of the system.

The transformation of knowledge during the transition from one level to another is provided by appropriate toolkits.

Constructing the upper levels of the pyramid utilizes engineering knowledge in its natural forms presented in books and practices.

In constructing conceptual models, it is advisable to use methods and means approved by international standards [15, 16]. IDEF3 methodology is most suitable for technological processes design. IDEF3 is a recognized standard to describe technological processes; it defines the notation for representing the meta-models of the processes structure and a sequence of changes in the properties of the manufactured object.

IDEF3 documentation facilities and modeling aids allow achieving the following tasks:

1) To document the knowledge about the variants of technological operations execution and certain products' manufacturing steps, in order to develop of knowledge bases for generating the TP structure of processing a particular part or an assembly-welding unit;

2) To build diagrams of processed objects' state during technological processes.

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.16). The first TPM functional element (UoB) is a block blanking operations; it is appropriately decomposed separately as a secondary model (Fig.17). This model starts with an exclusive-OR disjunction (XOR). Such junctions are most often used in TPM formation. This junction, in addition to the formal identifier J6, has its own name "Billet" and relates to the fan-out junction type. Each outgoing arrow has its own name: "casting", "forming" and "circle". Thus, we can assume that "Billet" is a character variable that takes one of the three indicated values. The listed blanking operations are performed depending on these values. If the variable takes the value "casting", then the corresponding casting operation is performed. In the case of the "forming" value, the "Saw-cutting" operation, which prepares the billet for forming, and the "Forming" operation itself are performed.

In the case when the value of the variable "Billet" is "circle", the billet of the wheel is cut off from the corresponding rolled section by means of the "Milling-cutting" operation. In all cases, the billet is fed to the "Annealing" operation to improve the machinability of the material.

After blanking operations, the main surfaces of the rim, the disc and the wheel hub of the gear and the axial bore are processed in the "CNC Lathe" operation (Fig.16).

In a general case, the described TP meta-model 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, the bound variables are: "Spline way", "Heat treatment" and "Accuracy degree". The free variables are "Billet", "Grooving" and "Toothing".

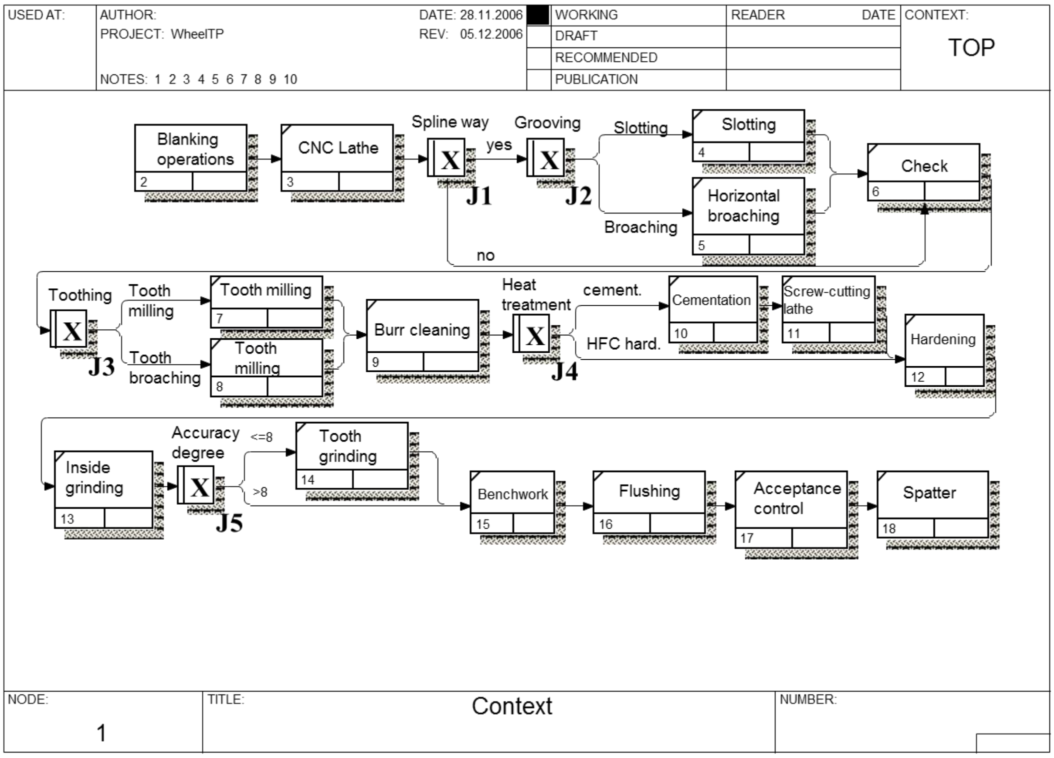


Fig.16. Process Flow Diagram (PFDD) of cylindrical gears

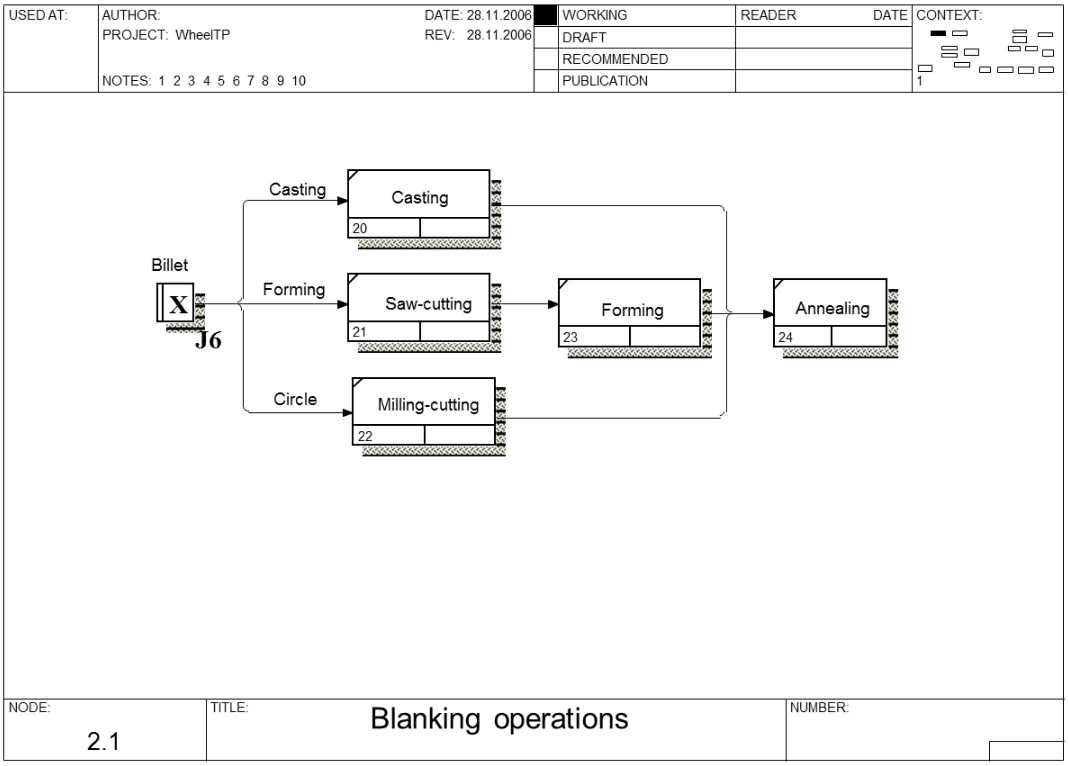


Fig.17. Secondary diagram of blanking operations for cylindrical toothed gears

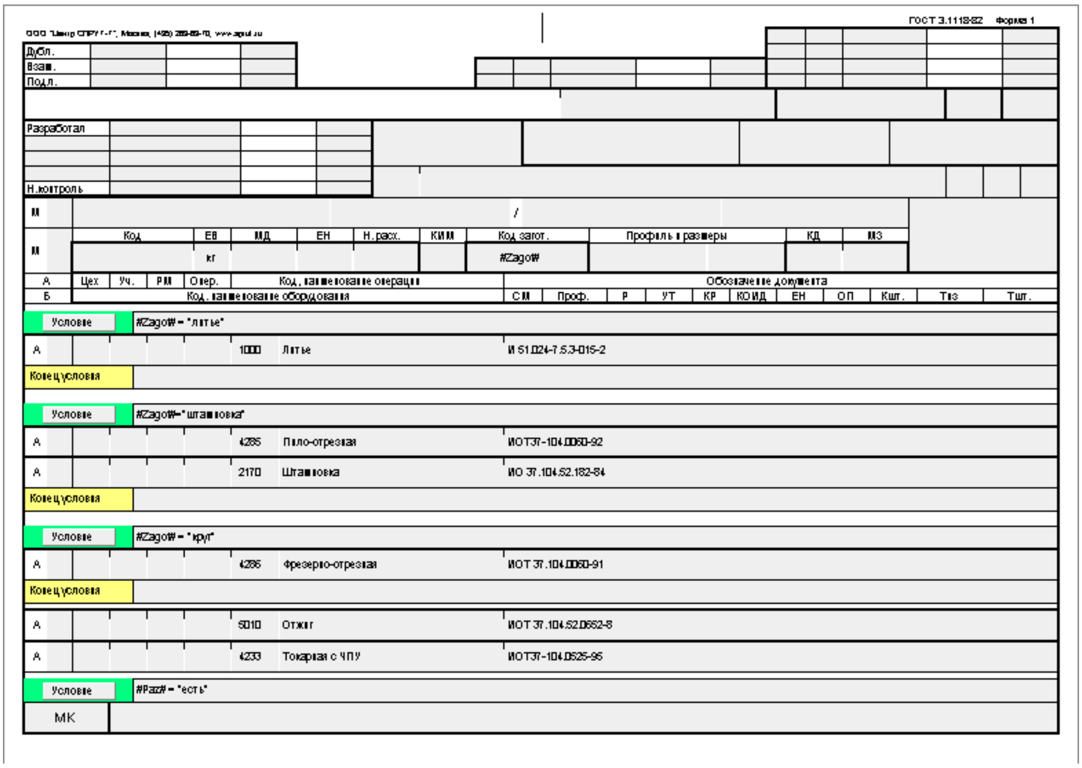
The above diagrams of processes in the IDEF3 standard represent conceptual knowledge models of TP structural synthesis. It is necessary to enter this knowledge into a computer and ensure automatic generation of routing technological processes depending on the values of the control free and bound variables. 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] uses modernized standard route sheets that represent knowledge of the TP operations structure. 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 map 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.18 shows the form to enter the diagram of processing cylindrical tooth gears; its relates to the IDEF3 diagram presented in Fig.17 [15, 16].

Thus, SPRUT-TP succeeded in combining the software functions as a service (SaaS) (because the end user-production engineer designs a specific technological process directly in the standard route sheet) and the platform as a service (PaaS) (that is used by the developer of knowledge bases for the structural synthesis of group technological processes (Fig.19).

However, in addition to structural synthesis, any design should take into account parametric synthesis. With regard to technological design, it consists in the normalization, which defines the norms of per-piece and preparation-closing time.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А | 2170 Штамповка | ИО 37.104.52.182-84
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Условие | #Zago# = "круг"
А | 4286 Фрезерно-отрезная | ИОТ 37.104.0060-91
Конец условия
А | 5010 Отжиг | ИОТ 37.104.52.0652-8
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Fig.18. The fill-in form for the diagram of processing cylindrical tooth gears

In parametric synthesis, knowledge bases are usually not related to the time parameter. To represent conceptual models in this case, it is advisable to use the IDEF0 standard [15, 16].

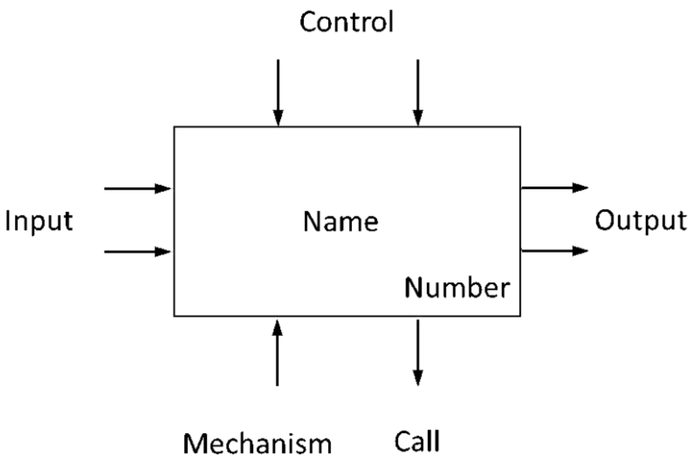

Fig.19. IDEF0 diagram

Fig.19 gives the external representation of the object function in the IDEF0 standard.

The IDEF0functional model can be considered as an equivalent of the condition-action rule: controls define condition, and action lies in conversion of inputs into outputs by using a mechanism or by calling appropriate software.

In expert programming [9, 10], the production rule has the name “knowledge module” (KM). The mechanisms of knowledge modules should ensure the implementation of all the functions that may be required in the formation of knowledge bases. These include the following basic functions: formula evaluation (including assignment of values to variables), definition of values by tables, selection of values from databases, update of values in databases, entry of values to databases, calculation of values with subprograms, calculation of values with the methods generated from knowledge modules, calculation of values with using the executable exe-modules or dll-libraries generated by other systems.

There is a developed appropriate mechanism for the generation of 3D models [14].

Knowledge modules, which are elementary generating systems, are combined into structured generating systems that carry KM models. The model of structured generating systems, from the AI point of view, is semantic networks. The KM semantic network is an acyclic oriented graph (Fig. 20). Acyclicity is required for the semantic network to perform its functional purpose – to ensure the determination of output variable values by the given input variables.

In expert programming, KM ranked semantic networks are generated automatically [16]. This means the realization of the first element of the structured programming basic set "sequence". The second element of structural programming is provided by the presence of KM preconditions. The third element (associated with cycle generation) is provided with the help of the selected FinCalc variable. Its appearance starts a cycle ensuring the repeated execution of a KM set until the value of this variable is changed.

From the point of view of the IDEF0 standard, a KM ranked semantic network implements a process consisting of the operations performed by KM. The actions to convert the information model properties are carried out by KM mechanisms.

In fact, the KM semantic network, formed automatically, contains an algorithm for converting information, eliminating the non-programmers from the need to form this algorithm themselves.

Knowledge modules may be considered as frames. Thus, expert programming integrates all ways of knowledge representation.

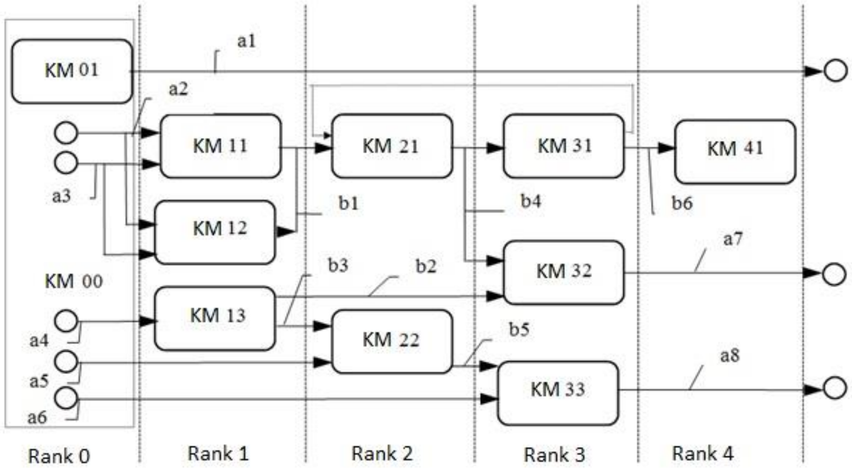

Fig.20. KM ranked semantic network

The synergetic system of knowledge generation is divided into three levels of knowledge: mathematical, clear and fuzzy [19]. The core for building the AI synergetic system is the clear knowledge of classical AI. Mathematics, using only numerical information, does not contain explicit semantics of its models. The same mathematical models can be applied in a variety of application areas.

In accordance with the AI interpretation, mathematical knowledge is clear, since fuzzy knowledge is built on the basis of linguistic variables. To fill the mathematical knowledge with semantics, you need to build a system of clear knowledge over them. At that, formal mathematical variables associated with the variables of the knowledge base dictionary receive a semantic content.

On the other hand, in order to operate with the concepts of fuzzy knowledge, we must give them clear descriptions.

The foundation for building a clear knowledge is a dictionary. A dictionary has a name and methods for sorting and searching for words, as well as importing words from text documents. A dictionary consists of words, each of which has a name-identifier, a common name and type (integer, real or symbolic). There are methods of adding and removing words, and determining the inclusion of words into knowledge modules. Words can be connected with associative lists of acceptable values. Associative lists, like words, have an identification name, a list name, and a value type. Associative lists are connected with the methods of adding, deleting, sorting and searching for a list. Lists consist of elements, each of which must have a value and can be added or deleted.

Knowledge modules are based on dictionaries. Each module has a literary name, an identifier name, a precondition name, and a version. A module is associated with the methods allowing adding, selecting an analogue module, translating and testing the module, defining the inclusion of the KM in the knowledge bases and other modules, as well as the removing the module itself.

KM has its own dictionary, which is a subset of terms from the knowledge base dictionary and includes input and output variables. In addition, KM can have a precondition that defines the scope of the module definition and contains a set of interrelated logical expressions.

A knowledge module can be compound and include other modules.

Every module has its own mechanism, by means of which the input variables are converted to the output variables. When designing products, calculations can be performed both on the basis of engineering procedures and on the basis of mathematical models [9]. Engineering procedures apply formulas, tables and databases. Mathematical models use solutions of linear, nonlinear and differential systems of equations. Geometric models form a special kind of mathematical models.

The highest level of knowledge representation is the fuzzy knowledge that can be formed with the help of clear knowledge means [19].

Below, there is an external representation of the knowledge module for calculating the cutting speed during lathe turning. This module is used in the normalization of boring cylindrical axial holes. The calculation is carried out according to the formula.

KM: "VtTok" - Calculation of the cutting speed during lathe turning

Preconditions for triggering

Name	Description	Type	Condition
NaimPer$	Step name	STRING	Bore
ElDet$	Part element	STRING	Cylindrical axial hole
So	Chip load, mm/rev	REAL	(0,)
t_	Cutting depth, mm	REAL	(0,)

Input properties

Name	Description	Type	Value
yv	Yv index	REAL	0.25
Cv	Cv coefficient	REAL	141
t_	Cutting depth, mm	REAL	0.1
So	Chip load, mm/rev	REAL	0.03
xv	Xv index	REAL	0.15

Mechanism - Formula

Vt = Cv/(t_^xv * So^yv)

Output properties

Name	Description	Type	Value
Vt	Base cutting speed, m/min	REAL	77

Results

In order to integrate the Industrial and Digital revolutions that are taking place at present, 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 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. The ontology of tasks makes a structural synthesis of products and production processes, as well as the synthesis of their parameters. The digital models of manufacturing processes are transferred to manufacturing 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 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 software matching the source texts. Business prose can be formed in any languages, and software can be generated in different programming languages.

Artificial intelligence methods allow creating semi-automated systems for products' 3D model generation using knowledge bases integrated with CAD systems. It should be possible to integrate them with various CAD systems.

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.

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.

Cloud technologies should be used for different purposes at all stages of creating integrated computer-aided systems.

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.

The systems of operational scheduling should be customizable to take into account the specific methods accepted at a particular enterprise.

For the design of products or for technological processes planning and standardization, it is necessary to use synergetic intellectual systems that allow representing mathematical, clear and fuzzy knowledge.

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 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 product models and the digital models of their manufacturing processes, generated by users in a semi-automatic mode. The Internet of Things must transmit the data on the current state of production to the Internet of Knowledge.

It is essential to use synergetic intelligent systems that allow representing mathematical, clear and fuzzy knowledge.

Conclusion

Russia possesses all necessary technologies for the 4IR realization. It should be specially mentioned that the tenth technology, the artificial intelligence 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 from 95 Russian cities.

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