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The Design of Modern Process Equipment

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ABSTRACT

Expert system is a methodology to adapt algorithm of successful decisions in one sphere of scientific and practical activity into another. Widespread information technology is an identical intelligent computer program that contains the knowledge and analytical skills of one or more experts in the field of application and is able to draw logical conclusions based on this knowledge, thereby solving specific problems in designing the process equipment without the presence of an expert (a specialist in a specific problem area). The expert system allows to solve problems in a narrow subject area. The modern realities of introduced automated production do not provide a quality result, because all design decisions are made on the basis of subjective knowledge and intuitive feelings. One way to solve this problem is to develop formalized human-machine design methods in the early stages of creating a project of process equipment.

This study describes the process of developing an expert system, which is aimed at solving problems of product modeling, optimization synthesis of the process operation structure and layout of the process machine. In the study, the author identifies the stages of process equipment designing, identifies the components of the expert system, and describes the procedural model of the design process. The result of the paper is the developed structure of software and information support of the automated information system for the design of process equipment. The developed system will speed up the decision-making process in the design of process equipment and receive competent advice. The expert system will serve as a basis for the introduction of intelligent production and smart consumption, which confidently goes hand in hand with the Fourth Industrial Revolution.

Key words : expert system; product modeling; information system; process equipment; procedural model.

1. INTRODUCTION

The design of modern process equipment requires automated initial design stages. One of the options for solving this problem is to develop an expert system to solve the problems of product modeling, optimization synthesis of the technological operation structure and layout of the technological machine.

Like any other artificial intelligence system, the expert system includes a knowledge base that contains information for the A knowledge base from the experience of designers is being formed. In the system of automated decision-making, the concept of “knowledge” corresponds to the integration of information that characterizes the objects of the subject area, with information that describes the basic patterns in this area [1].

2. LITERATURE REVIEW

In paper [2], the elementary expert system is described as “one of the simplest computer programs developed in terms of programming”. When developing an expert system, it is only necessary to ask a number of questions; enter answers; have a series of IF-THEN statements to eliminate any inconsistencies that do not correspond to the data provided; and draw conclusions that have not been remedied.

In his works, E. Feigenbaum [3] laid the foundations for the development of expert systems and introduced the concept of “knowledge engineering”, which later became the basis for solving informal problems, which include tasks with one (or more) of the following characteristics: the task cannot be represented in numerical form; initial data and knowledge about the subject area have ambiguity, inaccuracy, contradiction; goals cannot be expressed through a clearly defined objective function; there is no unambiguous algorithmic solution to the problem; an algorithmic solution exists, but it cannot be used due to the large size of the solution space and resource constraints (time, memory).

In papers [4], [5] the authors describe the general structure and functions of expert systems, their purpose, importance, and necessity in their creation. The work of J. Liebowitz [2] considered the application and future trends of expert systems. In turn, Earl Hunt [6] in his study considers the problem of pattern recognition, machine proof of theorems, machine perception of the surrounding physical world and, finally, machine understanding of natural language, which the author of this article emphasizes in the development of intelligent production system [7].

To implement the design of process equipment, the main unresolved problem is the automation of the initial design stages and the use of simulation results in the synthesis process [8].

The development of expert systems for designing manufacturing systems has also been the focus of attention of D. Ardayfio [9] and P. Norman [10] who in their works considered the possibility of applying computer programs in the process of selecting technological samples for the prototype equipment within three different software environments. Another important approach to process equipment design is the use of genetic design [11] simulating evolutionary development of nature empowered by Artificial Intelligence techniques [12]. This approach enables engineers to interact with the algorithms for the development and assessment of hundreds of potential projects. The role of an engineer is to introduce into the system project's goals and limitations. These goals and limitations may include such parameters as operational or special requirements, materials, manufacturing methods, price limitations etc. Due to special iterative procedures, computer programs explore all possible permutations and quickly generate several alternative projects while monitoring their efficacy during every single iteration. This approach seems to be promising; however, not all functional points can always be effectively combined. Their effective combinations can be offered and evaluated by human experts.

Expert system offered in this research paper will make it possible to select and modify process equipment at the stage of design. This will improve qualitative and quantitative design parameters, reliability of the designed equipment, as well as its future modifications to meet the needs of the related manufactures. For developing the sample of the expert system, the authors based their research on the technological equipment for packaging liquids. This process equipment can be used for producing and packaging food and non-food products. In addition, we have also considered the possibility of the quick modifications of adjustments of the equipment depending upon products specifications.

Modern world's changing conditions offer new challenges to manufactures, which need to quickly adapt to new market conditions and social reality. Covid-19 pandemic pointed out lack of changeability and adaptability in modern manufacturing business. The authors have suggested the possibility of using expert system for quick modification of process line for packaging liquids and for designing new technological equipment. However, the developed system has its limitations due to construction specifications of process equipment and types of products (mainly liquids). Still, the mail research objective was designing the general sample of the system and making it adaptable for different types of manufactures. For this reason, the authors extracted special conditions for process equipment interaction, preliminary project design and procedural model that are universal but may be adapted for different manufactures. However, these works are, to some extent, a review. The author tries to solve the applied problem by developing the structure of software and information support of the automated information system for the design of process equipment.

3. MATERIALS AND METHODS

The purpose of the study is to improve the designing of process equipment by developing an expert system to solve problems of product modeling, optimization synthesis of the technological operation structure and layout of the technological machine. To achieve this purpose, the following tasks have been solved:

- The analysis of stages of process equipment designing has been allocated and carried out;
- The approach to formation of information - logical models of technical objects has been offered;
- The model of technical object structure and layout of software and information support of the automated information system for designing of the process equipment has been developed.

3.1 Stages of process equipment designing

The designing of process equipment consists of the following main stages. The basic initial data for the design of process equipment (PE) is the Design specification (DS) which describes the functions of PE, the conditions of its interaction with the ambient and working environment, restrictions on its parameters [13]. Design specification can be presented as follows (1).

$$DS = (L, Fa, Q1, Q2, Q3, Q4)\,. \tag{1}$$

where ***L***- is the main dimension of process equipment;
Fa = {fa} - means many functions of the designed equipment;
Q1 - is conditions for interaction with the working environment (interaction between units and functional parts, their compatibility);
Q2 - is conditions for interaction with the ambient environment (speed of reaction and adaptability of manufacturing to the changes in the world. Adaptation to pandemic and economic crises);

Q3 - is conditions for interaction of the equipment with a person (requirements to service and safety);
Q4 - is additional requirements and restrictions (for example, restrictions on overall dimensions).
The functions of the equipment will be presented in the form of (2):

$$Fa = (D, G, H)\ . \tag{2}$$

where *D* - is the mentioned actions, equipment;

G - is a indication of the object to which the action is directed. *H* - is an indication of special conditions and restrictions under which the action is performed. The result of the design is a detail design (DD) (3).

$$DD = (DD_k), k = 1,2,...9\ . \tag{3}$$

where DD1 - is an assembly drawing of equipment;
DD2 - is assembly drawings of individual pieces of equipment;
DD3 - is drawings of all equipment parts;
DD 4 - is specifications;
DD5- is equipment passport;
DD6 - is technological calculations of processes taking place in the equipment;
DD7 - is strength calculation;
DD8 - is operating conditions;
DD9 - is technological documentation.

To present the stages of the process equipment designing and information flows present in the design, we will use the methodology of functional design IDEF0. The context diagram of the upper level, which reflects the relationship of the modeling object with the ambient environment, is presented in Figure 1.

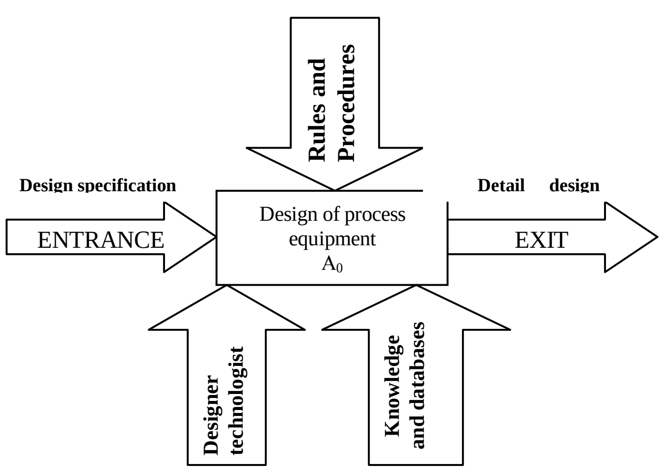

Figure 1: Context diagram of the upper level A_0

The function of the block on the diagram A0 is the design of the technological object. At the entrance of this block is a design specification, at the exit there is a detail design. A designer and a technologist provide control over the operation of the intelligent information system. They are the “decision makers” in matters of choice. The system requires different databases and knowledge bases.

3.2 Procedural model of the process equipment designing

Procedural model of design process (FM) is necessary to develop the control program of the automated information system (AIS) on its basis for process equipment designing. The function of the procedural model is to convert the information flow defined by the design specification DS into the information flow of the detail design DD (4):

$$FM\ : TЗ \xrightarrow{M, M^g, M^t} РП \tag{4}$$

where *M* - is the information-logical model of the designed object;
M^g - means models of processes occurring in the equipment;
M^t - is a technology model for manufacturing a technical object.
The FM procedural model applied to *M*, M^g and M^t should allow to obtain the DD working documentation on the basis of the design specification DS.
We present the procedural model in the system of formulas (5):

$$FM = \langle F_1, F_2, F_3, F_4 \rangle,$$

$$F_1 : F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{z1} \xrightarrow{M^s} I_1,$$

$$F_2 : L \cup Q_1 \cup Q_2 \cup Q_4 \cup I_1 \cup I_{z2} \xrightarrow{M^g M^p} (I_2 \cup I)_7 \vee I_6,$$

(5)

$$F_3 : L \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_1 \cup I_2 \cup I_{z3} \xrightarrow{M^p M^r} I_4 \cup I_3,$$

$$F_4 : Q_1 \cup Q_4 \cup I_3 \cup I_{z4} \xrightarrow{M^t} I_5.$$

where F_1 - is a procedure for determining the structure of process equipment;
F2 - is a procedure for performing technological calculations of equipment;
F3 - is an equipment design procedure;
F4 - is a procedure for developing the equipment manufacturing technology;
M^s, M^p, M^r - are components of the information-logical model M of the designed object.
Let us consider the components of the procedural model.

The procedure for determining the equipment structure (F_1) consists of the following components (6):

$$F_1 = \langle F_{11}, F_{12}, F_{13}, F_{14} \rangle,$$

$$F_{11} : F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{z1} \xrightarrow{M^s} I_{11},$$

$$F_{12}: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{11} \cup I_{z1} \xrightarrow{M^s} I_{12},$$
$$F_{13}: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{12} \cup I_{z1} \xrightarrow{M^s} I_{13},$$
$$F_{14}: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{13} \cup I_{z1} \xrightarrow{M^s} I_{14}. \quad (6)$$

where F_{11} - is the procedure for determining the presence of equipment functional elements.

Since the components of functional elements that can be included in the process equipment is known, we need rules that determine the need for each of these elements. Such rules can be quite simple, for example, if DS has a "heat" function in the list of equipment functions, then a heat exchange device shall be present. So, we can identify all the basic elements included in the process equipment;

F_{12} - is a procedure for determining the type of each functional elements. Here the rules are not clearly defined, they are based on the experience gained in the field of design, on the advantages of the manufacturer, on the special requirements of the customer, i.e., DS. For example, it is known that for bulk working media, the preferred type of bottom is conical, or for viscous media is preferred mainly screw device;

F_{13} - is a procedure that pre-assembles functional elements. For example, the location of the mixing device is determined or the location of various fittings is determined, etc.;

F_{14} - is a procedure that determines the presence and types of connecting elements of equipment. It defines the types, dimensions and other properties of connecting elements, such as welds, flanges, keyways, couplings, and others.

The procedure for performing technological calculations (F_2) consists of the following components (7):

$$F_2 = \langle F_{21}, F_{22} \rangle,$$
$$F_{21}: L \cup Q_1 \cup Q_2 \cup Q_4 \cup I_1 \cup I_{z2} \xrightarrow{M^p} I_{21},$$
$$F_{22}: L \cup Q_1 \cup Q_2 \cup Q_4 \cup I_{11} \cup I_{21} \cup I_{z2} \xrightarrow{M^g} (I_2 \cup I_7) \vee I_6. \quad (7)$$

where F_{21} - is a procedure that determines in advance the basic dimension of the functional elements of the equipment, necessary for technological calculations;

F_{22} - is a procedure that performs material and thermal calculations;

At technological calculations, the basic dimensions are specified or they are changed so that the set material loadings, a thermal mode in the equipment are provided. If it is impossible to provide the necessary material and thermal modes for the selected parameters of the equipment, it is possible to change the types of its components or the type of equipment.

The equipment design procedure (F_3) consists of the following component procedures (8):

$$F_3 = \langle F_{31}, F_{32}, F_{33}, F_{34}, F_{35} \rangle,$$
$$F_{31}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{z3} \xrightarrow{M^p} I_{31},$$
$$F_{32}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{31} \cup I_{z3} \xrightarrow{M^p} I_{32},$$
$$F_{33}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{32} \cup I_{z3} \xrightarrow{M^p} I_{33}, \quad (8)$$
$$F_{34}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{33} \cup I_{z3} \xrightarrow{M^p} I_{34},$$
$$F_{35}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{32} \cup I_{z3} \xrightarrow{M^p} I_{35}.$$

where F_{31} - is a procedure that determines the basic dimension of the functional elements of the equipment in advance, not defined previously in F2;

F_{32} - is a procedure that calculates the strength. It includes a simplified design calculation to determine the thickness of the elements loaded with pressure, or to determine the thickness according to the general recommendations;

F_{33} - is a procedure that performs a simplified layout. It determines the exact positioning of all elements relative to each other;

F_{34} - is a procedure that determines previously undefined parameters of equipment elements;

F_{35} - is a procedure that performs a preliminary calculation of strength.

Preliminary calculation of strength includes the following calculations of strength, in general:

- Preliminary calculation for strength and resistance to internal and external overpressure for all loaded equipment elements;
- Adequacy calculation of strengthening the holes from the excess pressure and external loads on the fittings;
- Test calculation of equipment flange connections from excess pressure and external loadings;
- Durability check of the elements undergoing basic and sling loadings;
- Checking the fatigue strength of elements subjected to cyclic loads;
- Check of vibration resistance, rigidity and durability of rotating elements.
- Depending on the specifics of the particular device, the list of required strength calculations may vary. According to the results of strength calculations, it is possible to return to procedure F34 and change the size of elements.

Procedure for developing the equipment manufacturing technology (F_4). The input data for the development of manufacturing technology are design documentation, namely, assembly drawings of equipment and its individual components and drawings of all parts, which indicate all dimensions, types of welding, material and type of work piece that are necessary for the manufacture and assembly. At the exit we have technological routes for the manufacture of equipment parts and assembly.

Table 1: Summarizes the above composition and functions of the procedural model

Procedure	Operation
FM	$FM: T3 \xrightarrow{M, M^g, M^t} P\Pi$
F_1	$F_1: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{z1} \xrightarrow{M^s} I_1$
F_{11}	$F_{11}: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{z1} \xrightarrow{M^s} I_{11}$
F_{12}	$F_{12}: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{11} \cup I_{z1} \xrightarrow{M^s} I_{12}$
F_{13}	$F_{13}: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{12} \cup I_{z1} \xrightarrow{M^s} I_{13}$
F_{14}	$F_{14}: F_a \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_{13} \cup I_{z1} \xrightarrow{M^s} I_{14}$
F_2	$F_2: L \cup Q_1 \cup Q_2 \cup Q_4 \cup I_1 \cup I_{z2} \xrightarrow{M^g M^p} (I_2 \cup I_7) \vee I_6$
F_{21}	$F_{21}: L \cup Q_1 \cup Q_2 \cup Q_4 \cup I_1 \cup I_{z2} \xrightarrow{M^p} I_{21}$
F_{22}	$F_{22}: L \cup Q_1 \cup Q_2 \cup Q_4 \cup I_{11} \cup I_{21} \cup I_{z2} \xrightarrow{M^g} (I_2 \cup I_7) \vee I_6$
F_3	$F_3: L \cup Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_1 \cup I_2 \cup I_{z3} \xrightarrow{M^p M^r} I_4 \cup I_3$
F_{31}	$F_{31}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{z3} \xrightarrow{M^p} I_{31}$
F_{32}	$F_{32}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{31} \cup I_{z3} \xrightarrow{M^p} I_{32}$
F_{33}	$F_{33}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{32} \cup I_{z3} \xrightarrow{M^p} I_{33}$
F_{34}	$F_{34}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{33} \cup I_{z3} \xrightarrow{M^p} I_{34}$
F_{35}	$F_{35}: Q_1 \cup Q_2 \cup Q_3 \cup Q_4 \cup I_2 \cup I_{32} \cup I_{z3} \xrightarrow{M^p} I_{35}$
F_4	$F_4: Q_1 \cup Q_4 \cup I_3 \cup I_{z4} \xrightarrow{M^t} I_5$

As it has been found above, to perform the functions defined by the procedural model, it is necessary to have an information-logical model of the designed technical object M, models of processes occurring in the machine Mg, and a model for manufacturing technology of technical object M^t.

Information - logical model of the technical object reflects it in the form of a set of elements and connections between them and allows to generate possible variants of its design that satisfy the initial data defined by the design specification. Information-logical modeling describes the structure of technical objects at different levels: abstract, object and specific. The approach to the formation of information - logical models is presented in Figure 2.

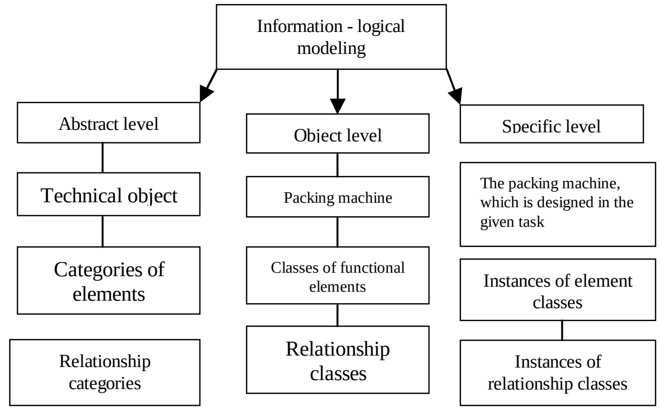

Figure: 2 Information - logical models

The set of structural units of the object level is formed on a system of structural units at the abstract level. The set of structural units of a specific level is based on a system of structural units at the object level and reflects the current information state of its elements.

The main form of knowledge representation in information - logical models is the representation of knowledge in the form of products (rules). This is due to the fact that most of the requirements of regulatory documentation and existing experience in the field of design is the easiest, most accurate and natural to formalize in the form of products. Other forms of knowledge representation in information - logical models are mathematical formulas or their systems (calculation methods).

Information - logical models of the technical object at the abstract level of representation are formally represented in the form (9):

$$M = \langle E, M^s, M^p, M^r \rangle. \tag{9}$$

where $E = \{e\}$ - is many elements of the technical object;
M^s - is a structural model of the technical object;
M^p - is a model of parameters of technical object elements;
M^r - is a positioning model of technical object elements in space.

A set of technical object elements.
$E = \{e\}$ - a set of technical object elements is divided into the following element classes:

- functional elements $E^b = \{eb\}$;
- connecting elements $E^s = \{es\}$.

Each element is presented in the form $e = \langle P, Z_n \rangle$,
where $P = \{p\}$ means many properties of this element;
$Zn = \{zn\}$ - is many possible values of this element properties.
Examples of element properties are: element type, geometric and technical characteristics, manufacturing material and others. For complex elements, its structure is an important property.

4. RESULTS AND DISCUSSION

The structural model is used at the level of conceptual design of a technical object, where the main tasks are: to determine which functional elements will the designed object consist of, to determine the types of these elements, their number and relative position, and to determine the connection types between them. Using the model of the structure M^s, the following tasks are solved:

- selection from the set of possible functional elements of all technological equipment E^b of some functional element subset $E'^b, E'^b \subset E^b$, which belongs to a specific designed equipment;
- type definition for each item with E'^b ;

determination of S^p positioning relationships between elements with E'^b

- determination of a set E'^s of connecting elements of the designed process equipment on the basis of certain connections of positioning Sp between elements with E'^b .

The structure model is presented in the form (10):

$$M^s = \langle E, Y^e, Y^s, Y^t, Y^s \rangle. \tag{10}$$

where Y^e - means rules that determine the availability and number of functional elements of equipment;

Y^t – rules that determine the type of each functional element;

Y^k – rules that determine the previous arrangement of elements relative to each other;

Y^s – rules that determine the types of connecting elements of the technical object.

At the level of conceptual design, it was determined which functional elements make up the designed object, the types of these elements, their number and relative position, i.e., its structure. At the next stage, it is necessary to specify such parameters of elements as the dimensions (dimensional, connecting and others), admissible deviations of the dimensions, roughness of surfaces, material of manufacturing and technological characteristics.

The elements parameters are divided into unit and unitary. The unit parameters of an element depend on the initial data for design (technological purpose of the equipment, properties of the working environment, etc.), on the parameters of other elements or on the general parameters of the assembly unit, which this element is a part of. Unitary parameters of the element are completely determined by the unit ones (for example, the mass of the element, the geometric parameters of standard products, which are determined by their dimensions).

The model of element parameters can be formally represented in the form (11):

$$M^p = \langle E, Y^b, Y^{pp}, Y^{pe} \rangle. \tag{11}$$

where Y^b - means rules and dependencies that determine the general parameters of the equipment as a whole;

Y^{pp} – rules and dependencies that determine the values of unit parameters of elements;

Y^{pe} – rules and dependencies that determine the values of unitary parameters of elements.

The structure of AIS software and databases is presented in Figure 3.The software of the system consists of a control program that implements the procedural model (FM), individual executive modules that perform specific design tasks and are necessary for the design of databases and knowledge bases.

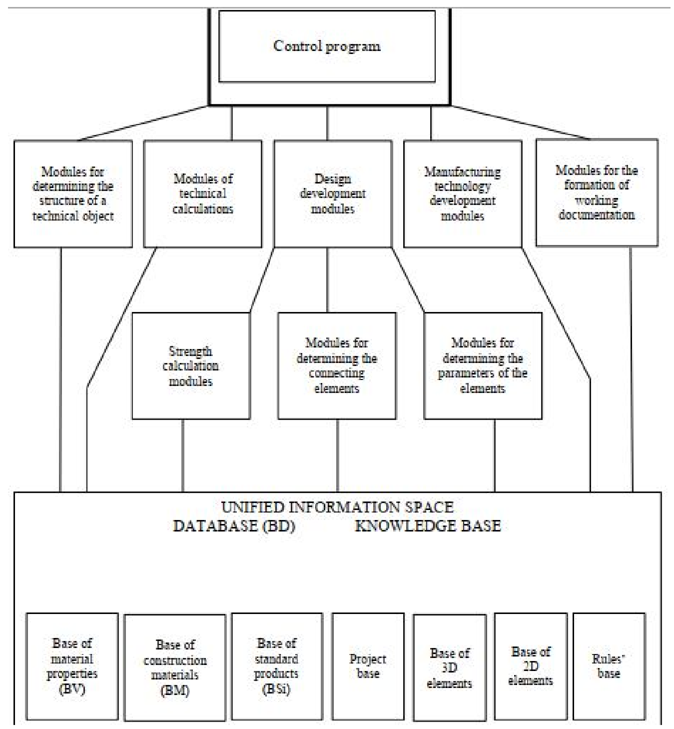

Figure: 3 The structure of software and information support of the automated information system for the design of process equipment

The control program in the automated mode calls the module which carries out a certain stage of designing. The decision-maker, who is a designer and a technologist, has the opportunity to adjust the results of the system at different stages of design.

Data exchange between modules is carried out by means of information bases, which include databases of materials and construction materials properties, standard elements, 3D elements and 2D drawings, work results of separate modules (project base) and base of rules (in the presented work, rules and dependences $Y^e, Y^t, Y^k, Y^s, Y^b, Y^{pp}, Y^{pe}$.

The database of the computer-aided design system *BD = {BV, BM,BSi}* contains:

Base of material properties *(BV)* – base of materials, is a pair of :

$$BV = \{BVN, BVS\} \tag{12}$$

where *BVN* - is a set of materials names,
BVS - is a set of material properties.

$$BVS = \{BVS1, BVS2, BVS3\} \tag{13}$$

where *BVS1* – means chemical properties of substances, such as chemical composition, corrosion resistance, etc.;
BVS2 - is physical properties (physical state, density, viscosity, etc.);
BVS3 - is other properties, such as, the tendency to precipitate.

Base of construction materials (*BM*). It includes structures, geometric characteristics of the material (14).

$$BM = \{BMN,BMS,BMP,BMPS\} \tag{14}$$

where *BMN* - is a set of construction materials names;
BMS = {BMS1, BMS2, BMS3} - is a set of structural materials properties;
BMS1 - is a set of chemical properties of materials;
BMS2 - is a set of physical properties;
*BM*S3 - is mechanical characteristics;
BMP - is a set of delivery states for each of BMN;
BMPS - is a set of properties for each BMP.

$$BMPS = \{ BMPS1, BMPS2, BMPS3 \} \tag{15}$$

where *BMPS1* - means geometric characteristics of the material (thickness, width, surface roughness, etc.);
BMPS2 - is mechanical characteristics of the material;
BMPS3 - is condition of the material (heat treated, normalized, hardened, etc.).

$$BSI = \{ RBSi, TBSi, GBSi \} \tag{16}$$

Base of standard products (*BSi*). It contains *RBSi* - a relational database of standard products, *TBSi* - text documents (passport, safety instructions), *GBSi* - graphic information, including 3D standard elements models of packaging equipment.

5. CONCLUSION

Expert systems use heuristic algorithms for optimization synthesis of the workflow in the machine, its technological scheme and layout using expert knowledge in order to build synthesis procedures and evaluate technical solutions. The developed system provides an opportunity to choose the best technical solutions. A prototype system is a version of an expert system designed to verify the correct coding of facts, connections, and expert reasoning strategies.

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