information technology, technological equipment, design, synthesis, structure

Bogdan PALCHEVSKYI[*]

INFORMATION ASPECTS OF OPTIMIZATION SYNTHESIS OF FUNCTIONAL-MODULAR STRUCTURE OF TECHNOLOGICAL EQUIPMENT

Abstract

The paper presents the information approach to the design of equipment with functional-modular structure. The advantages and drawbacks of various technologies of synthesis are shown.

1. INTRODUCTION

The production cycle in machine building companies, which is the time that parts, components and finished goods spend in the shops, is only 1% of the total time from design to finished goods production. The other 99% fall on the research and development, design and technological preparation of production. Automation and computerization of these phases significantly accelerates the design process.

The most important trend in the development of methods for designing technological equipment is the creation and development of technology design with use of modern information technologies. The value of information technology in designing great – it creates the information foundation for the development of corresponding sphere of science and its applications.

[*] Lutsk National Technical University, 75 Lvivska str., 43018 Lutsk,
tel.: +380 (332) 767395, e-mail: pac@tf.dtu.lutsk.ua

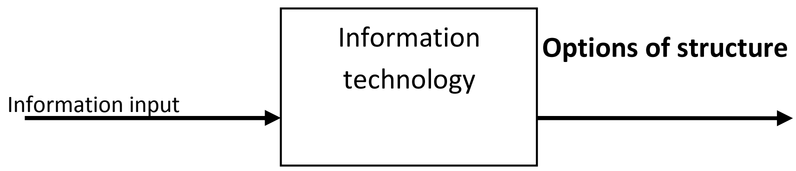

Fig. 1. The scheme of the information technology
[source: own study]

Information technology in the design – a combination of methods, processes, programming and technical means combined into a chain that provides collection, processing, storage and display of information in order to reduce the complexity of the processes of designing.

2. INFORMATION-AIDED DESIGN OF TECHNOLOGICAL EQUIPMENT

The peculiarity of using the information technology in the design of technological systems is to use them for modelling of technological equipment and workflow in it. Informational technologies in design are perfectly suited to meet the information needs in creating projects of technological equipment. It is necessary to solve the basic problem of designing – to determine dependences between the structure of the designed object and characteristics of its effectiveness.

Having some idea of the object of design (conceptual model), a person acquires background information and comparing thereafter the object with its representation forms the design action I_y.

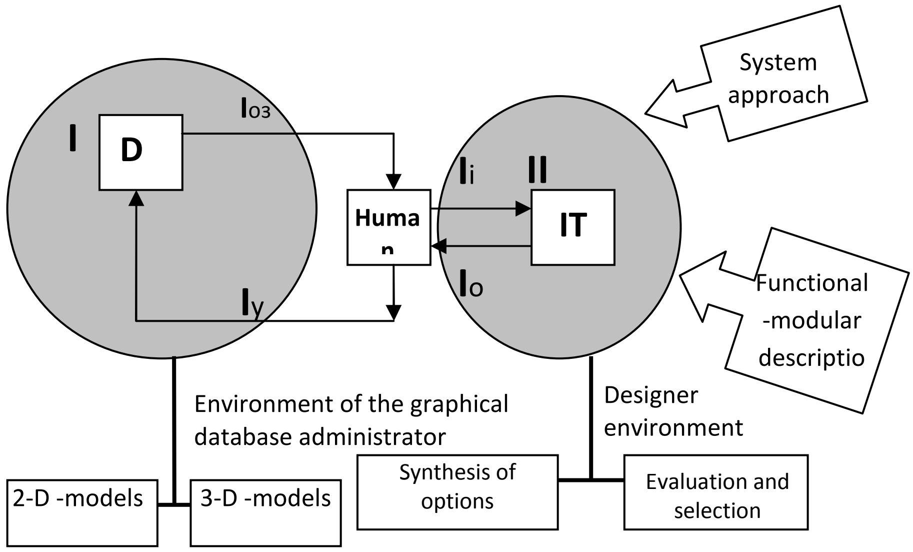

Fig. 2. Information system of computer-aided design [source: own study]

It is seen that circuit of information processing stands out, it is separated from the circuit of processing graphical information and becomes independent. The information technologies that convert input information I_{in} the product in the form of background information I_{out} are highlighted in the system. Depending on the human role in the chain $I_{ip} - I_{in} - I_{out} - I_y$ the manual computer-aided, automated and automatic design is distinguished.

The environment of graphical database administrator allows creating and editing drawings and geometric models as well as it is designed to run on hierarchical image databases. Most CAD is reduced to drafting of the already finished technical solution with use of computer programs.

The designer environment provides a solution of all complex tasks of technological equipment designing needed to build the structural, functional and schematic diagram, carry out of necessary calculations, modelling and design. Thus, the design process includes the following stages:

- The components of technological process of packaging are distinguished – technological operations that can be conveniently called functions. These functions arrange the structure of technological process, while several types of functional modules are put in line for each of them.
- The optimal set of functional modules to perform a given task is searched for.

- Next comes the allocation of the functional modules in a certain sequence and establishing connections between them, namely to form spatial layout and functionality for material, information and energy flows in the machine.

The interaction of the defined environments is carried out by using a set of models of object that are divided into two distinctive groups.

1. The first group of models describe the functioning (working) of the future equipment and its component functional modules and processes occurring in it. These models allow us to identify the characteristics of workflows and assess their impact on the technological characteristics of the machine (its performance, reliability and other characteristics).
2. Models of the second group describe the spatial structure of the machine. They allow to determine its size, area, volume, mass and strength under loading.

Models of the first group are usually called functional. The second group of models is based on geometric proportions. They are usually referred as geometric or spatial models.

3. KEY INFORMATION TECHNOLOGIES OF TECHNOLOGICAL EQUIPMENT DESIGN

Arguably, the level of CAD automation is defined by the designer environment. Applying of the information technology in this case should allow obtaining the technical solutions for further comprehensible graphic representation. Therefore, systematic approach that involves presenting of technological equipment as a system that performs a given utility function and functional modules acting as the elements of its structure should be put as the basis for the designer environment. It allows to synthesize the equipment versatile in composition and functions from a limited set of standardized functional modules (FM).

The task of informatization of the part of the technological equipment design process is stated and solved as optimization synthesis of the equipment structure from a unified set of functional modules, i.e. on the basis of functional modularity of design.

Functional-modular principle of technological equipment design has the following features:

1. Technological machines of the same purpose perform about the same amount of technological functions.

2. The general utility function of any technological machine is performed by the finite set of functional modules, each executing a complete part of the overall service function of the machine.
3. The structure of technological machine is created by ensuring the functional and spatial connections between the functional elements.

A combination of information technology of synthesis and information technology of optimization (analysis) must be put in the basis of the information process of designing the technological equipment with functional-modular structure.

The design process of manufacturing equipment is customary split into stages (functional and technical, systematic and structural, design). Proceeding from such partition, it is a natural requirement the CAD system to support all phases and levels of the design in full. Unfortunately, in practice this approach is not fully realized.

Information process of design has a set of elementary operations – procedures, which quantity is limited. The main ones are the synthesis procedure and the procedure for selecting options. Of these various combinations of design stages are composed, while the information process of design is composed of the stages combinations.

In developing the methodology of technological systems designing is important to differentiate the process of solutions synthesis (generating options) and the procedure of limiting the diversity of solutions for selecting the best (analysis, evaluation, selection, optimization).

Direct generating of options of the machine structure can lead to their redundancy. Let the facade of 10-storey building have 24 windows on each floor. In the evening, each window can be lit or shaded, that is remain in one of two states. By defining a set of possible states of the building façade, where windows different by their location on the facade whose total number is 10 • 24 = 240 are in one of two states, we obtain:

$$N = 2^{240} \approx 10^{73}$$

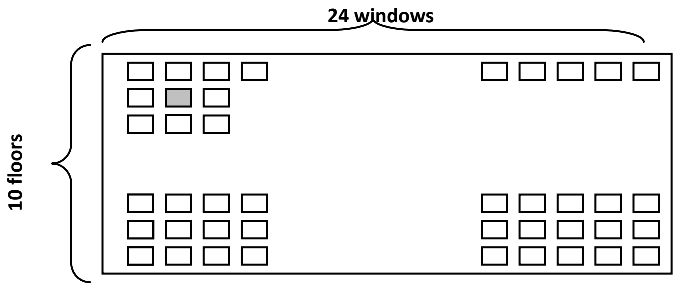

Fig. 3. Determining the number of options [source: own study]

The resulting number is extremely large; it corresponds to the number of atoms in the visible universe, which is also equal to approximately 10^{73}.

This example shows that with significant number of structure elements the set of options becomes very large, and the review and evaluation of all possible structures is impossible. For this purpose the special methods of synthesis, a feature of which is to impose additional conditions on the obtained structure, are used.

In practice, during the design process the space of solutions is restricted by studying only certain combinations of elements. As a result of selection only those options remain that have “better” value of the optimization function compared to the previous iteration. In order not to miss the best solution in the design process one need to include the information synthesis procedure reducing capacities of sets obtained at different stages, namely:

1. Technology of the directed synthesis. The design process is an analysis of the product and determining the sequence of the formation of components. The result is a sequence of technological operations, which specifies the sequence of functional modules during the synthesis of structure.
2. Synthesis technology with limited set of options based on typical mathematical models which allows to consider a number of restrictions for the options of structure.
3. Synthesis technology with limited set of structure options by using the "and-or" tree. This tree contains technical solutions in a compact form of information about a specific, pre-formed set of options for the structure of a technical system.
4. Technology of stepwise synthesis and optimization. The design process is an alternation of procedures for forming subsets on different hierarchical levels and their evaluation to select the best one.

5. Technology of hierarchical synthesis. The design process is an aggregated representation of the workflow so that every bigger technological operation can be qualitatively assessed using quality measures for its implementation. Each larger function is associated with a block of functional modules that implements the function. Then when combining options modular structure the set of options considered is much smaller.

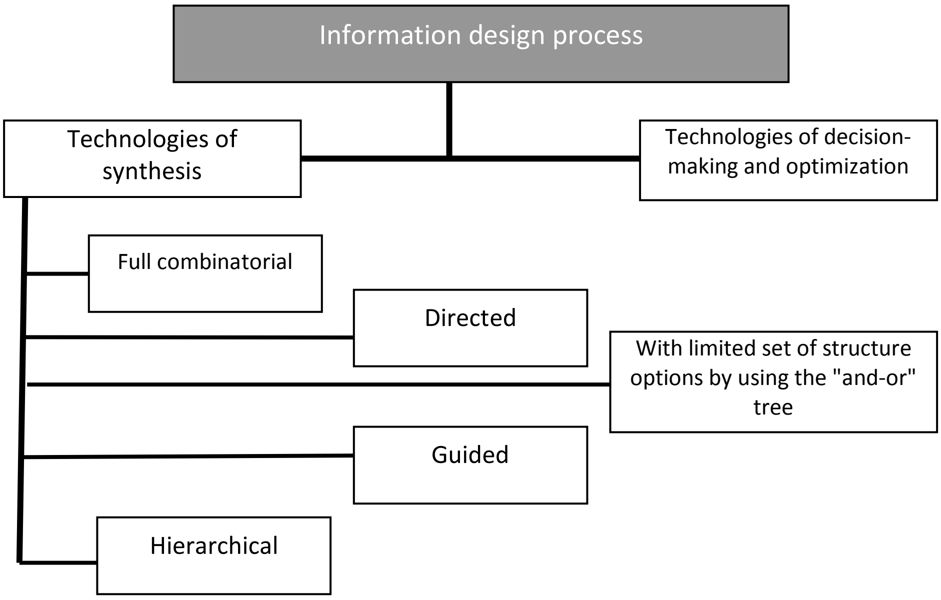

Fig. 4. Specialized methods of the synthesis procedure [source: own study]

4. TECHNOLOGY OF THE DIRECTED SYNTHESIS

It is advisable to improve design technology in a direction that every step taken from concept to finished project was an information procedure on multiple models of the object design. It creates conditions that, starting with the first and ending with the last stage of the project, all information on the results of one phase is used in the following stages during the design. Every previous model actually specifies the additional restrictions that reduce the number of options obtained with combinatorial synthesis on the next step (Figure 5). In this case, the process of structural synthesis enables the "top-down" design and gets the optimal structure that fits in the above specification and boundary conditions.

The sequence of steps of the workflow defines the product design, analysis of which allows to set the sequence of the forming its components. As a result, a sequence of technological conversions that form a workflow is determined. The structure of a workflow defines a sequence of functional modules in the structure of the machine.

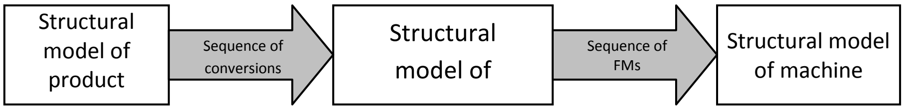

Fig. 5. Sequence of the system models use in the directed synthesis [source: own study]

The design begins with the analysis of the product. Analysis of the structure of traditional machining processes, for example, shows that the sequence of creating surfaces of a detail is chosen in most cases purely arbitrary. This sequence is set by a designer's intuition and is far from optimal. If an elementary technological conversion is put in line with the creation of each elementary surface, then it can be assumed for any a single conversion that the conditions for its realization will depend on some previous conversions. On the other hand, this technological conversion, in turn, can affect the implementation of the following ones. That is the surface created on the step is necessary to implement some of the next conversions. Thus, each conversion is characterized by technological input and output cause-ties of in the scheme of machining and therefore should occupy an appropriate place in the structure of processing. In the most general case, the functional, design and technological limitations affect the sequence of surface processing, that can distinguish three groups of contradictions namely:

- functional connection of precedence imposed by the conditions of functioning parts (auxiliary surfaces at first, next the functional surfaces);
- design connection of precedence imposed by the terms of spatial arrangement of surfaces in parts (datum references are processed initially);
- technological connection of precedence imposed by the conditions of part machining.

To determine the logical sequence of processing the functional, geometric and technological precedence ratio that are imposed on the surface details can be written in the form of a precedence matrix.

The surface to be processed previously						
П –the processed surface	П1	П2	П3	П4	П5	**Bo** Level of dependence of the surface
П1						0
П2	1					1
П3	1					1
П4		1	1			2
П5				1		1
Level of following of the surface	2	1	1	1	0	

In this matrix, each connection of precedence between two surfaces is marked as 1. Through formalized procedures developed by A. Kaufmann, a sequence of technological conversions of processing the surfaces of a part is derived divided into 4 stages of processing (Fig. 6).

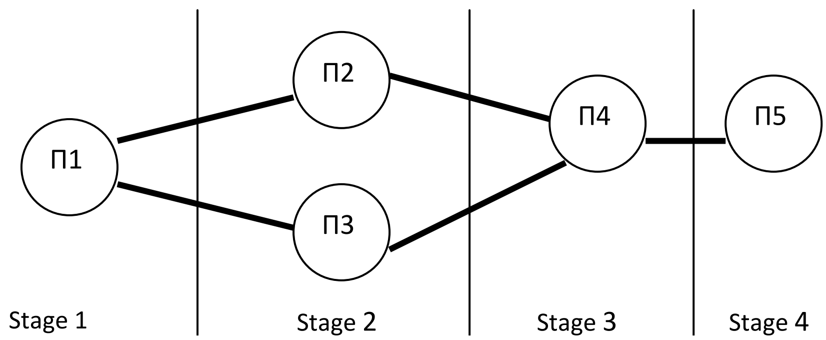

Fig. 6. Graph of precedence connections for processing the П1-П5 surfaces [source: own study]

The function of the equipment that performs technological operation implements complex technological transformation that includes a number of simple conversions performed by individual functions and subfunctions φ_i:

$$F \rightarrow \{\varphi_1 \cdot \varphi_2 \cdot \varphi_3 \cdot ......\}$$

A subfunction generally consists of two or more elementary functions. The advantage of this method is that for the required performance function several alternative models of workflow can be developed and selected for their optimal suitability at a relatively small cost of time. The structure of the workflow, shown in Figure 6, defines partially ordered sequence of formation of the product, for example, by processing blanks with the state S (0) to the final state S (P5):

$$F = C_0(0)\varphi_1 C_1(\Pi 1) \left. \begin{array}{l} \nearrow \varphi_2 C_2(\Pi 2) \\ \searrow \varphi_3 C_3(\Pi 3) \end{array} \right\} \varphi_4 C_4\ (\Pi 4)\varphi_5 C_5(\Pi 5)$$

This record of a workflow structure means the following. Originally the workpiece transferred by means of transition φ1 from the state C0 to state C1 (P1) by processing the surface P1. Next a conversion φ2 or φ3 is possible. A part is shifted into a state C4 (A4) with the φ4 conversion and so on down to a final state C5 (P5). One can see that the order of conversions φ2, φ3 is not regulated. Because even this simplified scheme can build several options of processing that differ by type of machining equipment, degrees of processing concentration, parallel or serial execution of certain operations, the next step is to search for the optimal structure of the part machining process, but the estimated number of options will be significantly reduced.

Under the procedure of constructing the system model of the process is to be understood such activities that are necessary to ensure that workflow in equipment is provided by a structure derived from subfunctions or elementary functions that meet the technological conversions at various levels of complexity.

Functional modeling is a key moment of forming the structure of technological machine because the function model serves like a roadmap that helps designers to reach the desired layout of the machine.

The design process is based on the presence of a design scheme, with alternating design procedures of two types – synthesis and optimization of technical solutions (Fig. 7). Structural design is a combination of possible combinations of technology machine's FMs, getting set of layouts and their evaluation for choosing the best. The applied here method of directed search (as the machine workflow defines the sequence of FMs) provides consistent consideration of each of the options structure during sorting.

Consider, as an example, the structural design of the technological machines for the packaging of loose substances.

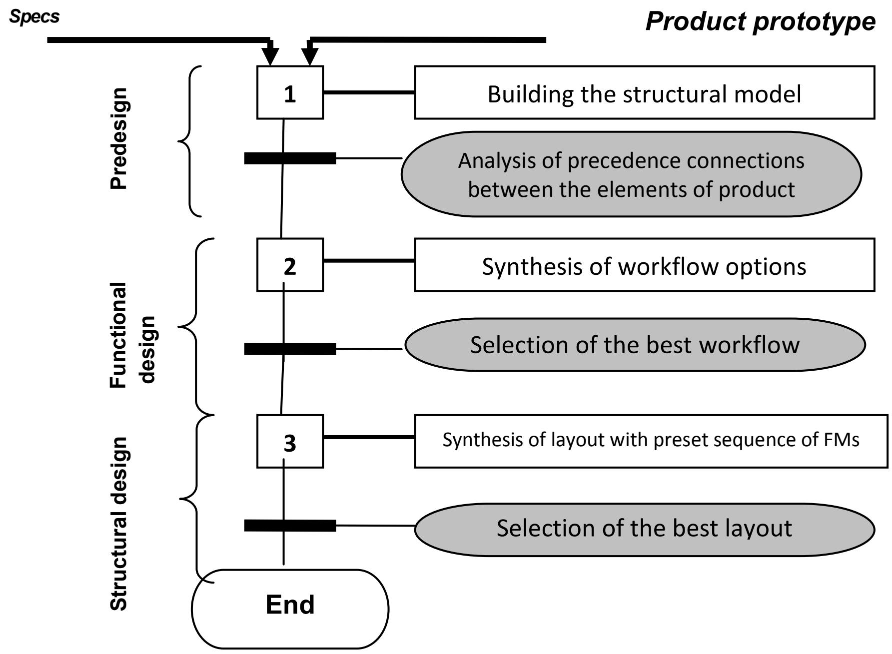

Fig. 7. Algorithm for the directed synthesis of technological equipment [source: own study]

Technological packaging operation includes technological transitions (x1 – x5) sequence of which can be considered as given:

- forming a tube blank of the package from the polymer film (x1);
- dosing the mass of substance (x2);
- longitudinal welding of package (x3);
- transverse welding of package with a dose of substance in it (x4);
- pulling a tube blank of the package (x5).

Since the implementation of each conversion makes possible the use of FM differing by design and characteristics (reliability, speed, energy consumption, cost, etc.), the problem of packing machine structure synthesis becomes multivariate. Methods of directed search are based on the possibility of gradual rejection of unpromising directions finding the optimal solution (Fig. 8). The process of designing is reduced to finding a way (1 – n) on the model that provides the best value of the machine quality. Problems that hidden behind such a simple algorithm become evident while increasing the number of FM in the structure of the machine.

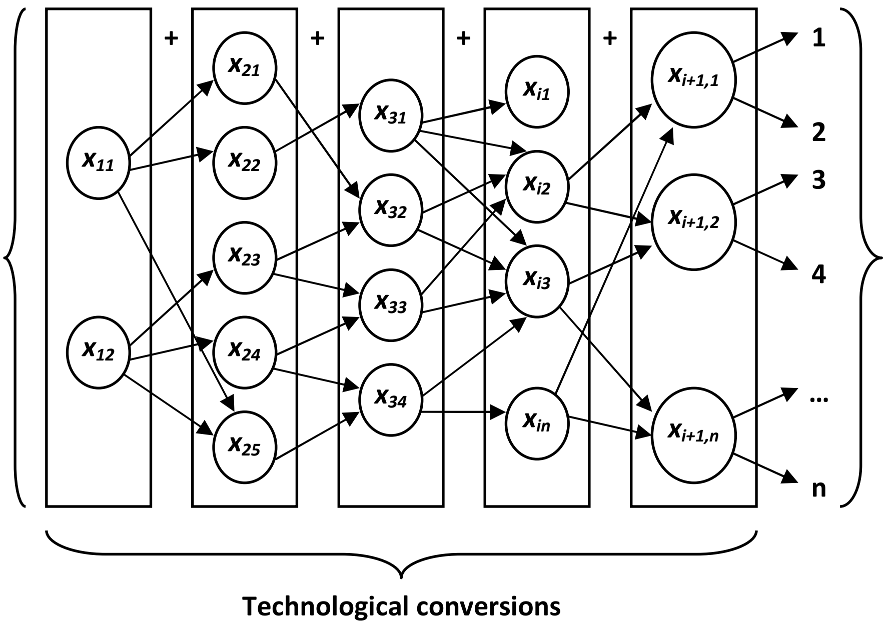

Fig. 8. Model of optimization synthesis of a packaging machine of functional-modular structure with preset sequence of FMs [source: own study]

5. SYNTHESIS TECHNOLOGY WITH LIMITED SET OF OPTIONS BASED ON TYPICAL MATHEMATICAL MODELS

It allows to take into account a number of constraints on the existence of options structure. The following characteristics of differences between versions of the structure are taken into account:

1. qualitative composition of elements, ie, possible variations of elements that create the object. This feature of the mathematical model is denoted as FE;
2. number of elements that create the object of synthesis. This attribute of the model is denoted as FN;
3. the order of elements in the structure of the object of synthesis. This attribute model is denoted as Fp.

If the content of elements of all the options while generating the structure is the same, then FE = 1 else – that FE = 0. If all the options of structure have the same number of elements, then FN = 1 else FN = 0. If a sequence of combining elements in the structure of all the options is the same, then fp = 1 else – Fp = 0.

Depending on the generated object with certain features of differences between the structure options, the following classes and subclasses of standard mathematical models (Table 1) are used.

Tab. 1. Classification of mathematical models used for generating the options of structure

Model			Characteristic of generating the option of structure		
Class	Subclass	Name	F_E	F_N	$F_П$
Conjunctive	0	MS01	1	1	-
		MS02	0	1	-
		MS03	0	0	-
Organizing	Table – 1	MS11	1	1	1
	Network – 2	MS21	0	1	1
		MS22	0	0	1
	Permutation 3	MS31	1	1	0
		MS32	0	1	0
		MS33	0	0	0

Let us consider example of a typical model MS31 to generate variants of the technological process of assembling the product. Technological operation of assembly is associated with installation of one of the components (Figure 9).

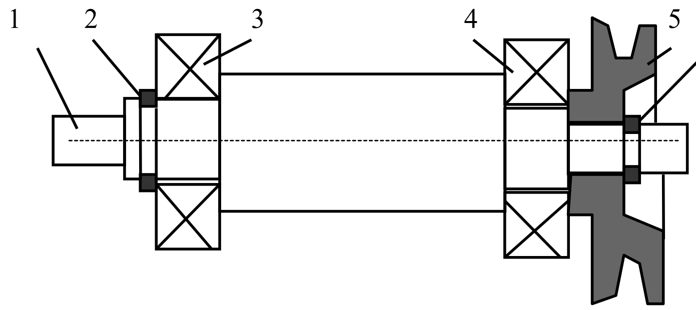

Fig. 9. Drive mechanism
1 – shaft, 2,6 – retaining rings, 3,4 – bearings, 5 – pulley
[source: own study]

All possible sequences of combinations of parts are described completely by graph on six vertices. Each of the options of assembly process is set by a covering tree of this graph. Total number of covering trees and thus options of assembly sequence is determined by Cayley's theorem and is:

$$n_{TП} = p^{p-2} = 6^4 = 1296,$$

where: p – is a number of vertices.

Obviously, the set of assembly processes obtained by formal enumeration of graphs include many unrealistic and absurd choices, the analysis of which is unnecessary. Therefore, the use permutation model which significantly limits the number of options eligible for consideration, greatly simplifies the process of optimization synthesis. First of all, only the variations of the process, starting from the operation of setting the part 1 (basic part of the mechanism) are taken into account. When considering the possibilities to access other parts the number of options process will be reduced to ten (Table 2). In Table 2 the following notation is used: 1 – install the shaft 1 in the assembly device; 2 – install retaining ring 2; 3 – install the bearing 3; 4 – install the bearings 4; 5 – press the pulley 5; 6 – install retaining ring 6.

Tab. 2. Options of the drive mechanism assembly process

№	Assembly sequence	№	Assembly sequence
1	1-3-2-4-5-6	6	1-4-3-5-6-2
2	1-3-4-5-6-2	7	1-4-3-5-2-6
3	1-3-4-2-5-6	8	1-4-5-3-6-2
4	1-3-4-5-2-6	9	1-4-5-3-2-6
5	1-4-3-2-5-6	10	1-4-5-6-3-2

6. TECHNOLOGY OF THE STEPWISE OPTIMIZATION SYNTHESIS

The methods controlled search are based on the possibility of gradual rejection of unpromising directions while finding the optimal solution. The design process is the successive addition of the specific functional elements to the machine at each stage and the evaluation of the result. The assessment procedure is shown as a logical transition to the next stage of design (Fig. 10).

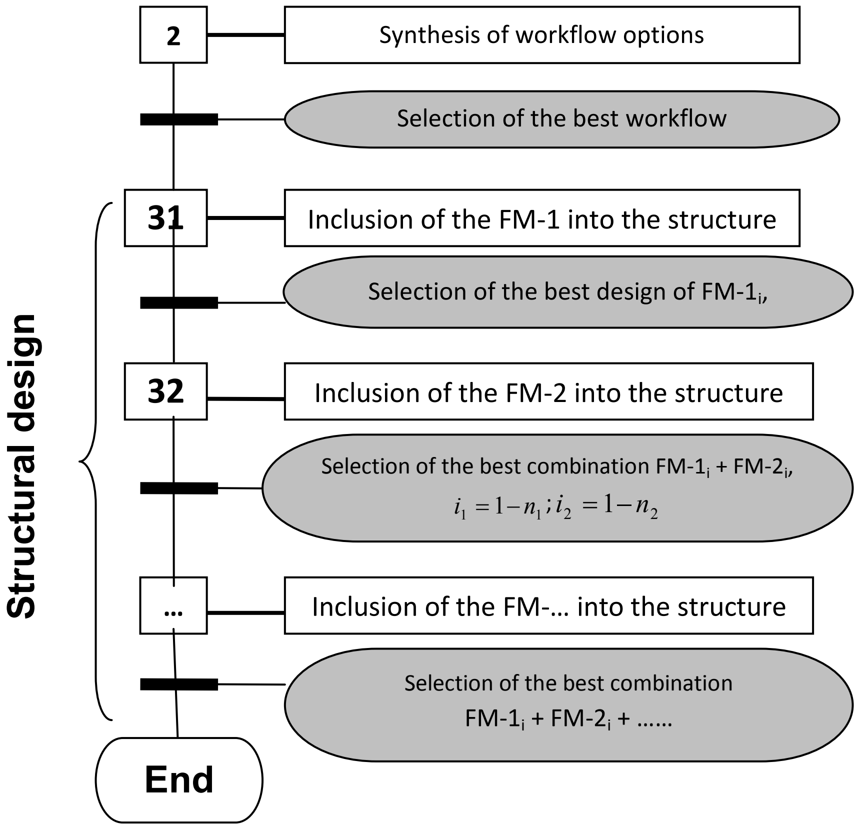

Fig. 10. Algorithm for the stepwise directed synthesis of technological [source: own study]

The peculiarity of this synthesis is additivity of the criterion for evaluation and selection of layout design at each step. These criteria include the cost of FM, its weight, energy consumption, etc. It should also be noted that the sequence of joining FMs to a machine can be both direct, i.e. starting from first technological conversion FM and reverse when step by step synthesis starts from the last (terminal) FM.

7. TECHNOLOGY OF HIERARCHICAL SYNTHESIS

To facilitate the search for proper layout and accelerate virtual search extensive libraries on the principle of building blocks performing the most complicated part of the machine workflow, are currently being formed.

The design process is an aggregated representation of the workflow of equipment so that every bigger technological operation or conversion can be assessed using quality measures for its implementation. Each enlarged function is associated with a correspondent block of functional modules. Thus, when combining the modular structure the set of options considered becomes significantly smaller.

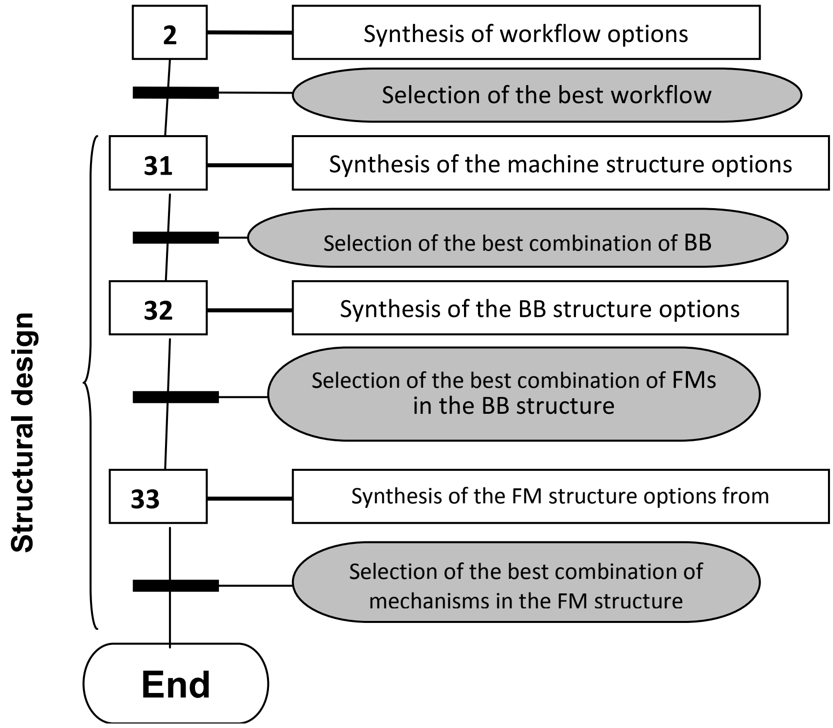

Fig. 11. Algorithm of hierarchical synthesis [source: own study]

Applying the hierarchical synthesis of functional-modular structure allows presenting a packing machine as a combination of three units: BB-1 – a dosing unit, BB-2 – package forming unit and BB-3 – auxiliary functions unit (Fig. 12).

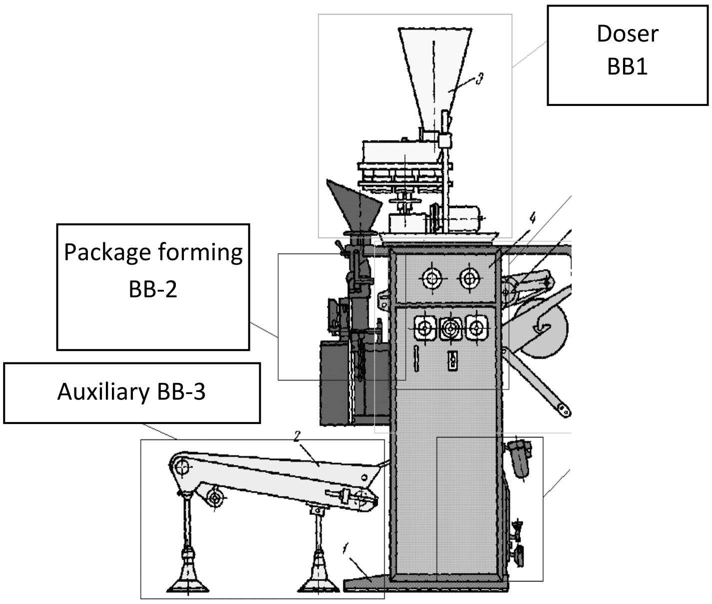

Fig. 12 Packaging machine design of three BBs [source: own study]

A distinctive feature of the use BB is as follows:

1. Few parts in BB can be developed more thoroughly using the methods of analysis and modeling that are inaccessible to a large array of connections. This allows to obtain more reliable results.
2. Second, a smaller number of structural units facilitates combinatorial processes.

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