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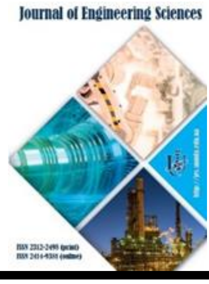

Automation of Optimization Synthesis for Modular Technological Equipment

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Abstract. Technological equipment design based on functionally modular methods is widely used in various technical fields. The designed object can be a technological machine, a production line, or a manufacturing complex. Special attention is paid to the optimization of its structure. The sequence of performing all stages of the optimization synthesis problem is presented in the article. To find a solution to this task, the developer should apply the complete or directed search of acceptable structure options and determine the best one using some optimization criteria to evaluate their quality. It can be simple enough if the designed technical system structure consists of no more than several elements. For example, if the number of alternative elements options is several dozen, it takes much time to accomplish the search correctly. Thus, the greater the number of components considered, the more difficult it is to do all the necessary calculations manually. In this case, machine resources should be involved. This scientific work aims to identify procedures of optimization synthesis that can be automated. Also, appropriate software has to be developed. Our computer program is based on the algorithm of a complete search of all options of the technical system structure. It can process an extensive array of input data and produce all possible and logically permissible results in the form the designer can analyze using the Pareto method to choose the best one. This software can be used for any technical system with a modular structure.

Keywords: equipment structure, optimization problem, software, industrialization, innovation, productivity.

1 Introduction

Modern technological equipment is a set of unified nodes, which designers often classify as a technical system with a functionally modular structure. Also, the same principle can be used for the equipment that structurally makes the production line or manufacturing complex.

It is effective enough to apply classical methods of synthesis and analysis, optimization, and predicate logic, when the object is considered from the point of view of its discrete structure with functional relations between components.

The idea of a modular approach to considering the structure of technological equipment is determined by production requirements. The technological process is divided into elementary technological operations. Then the functional module type for each operation's implementation can be selected. The functional module here is a functionally independent and structurally complete set of mechanisms that are united by a mutual functional purpose [1, 2].

If a machine implements the technological process, functional modules include assembly units, mechatronic systems, and transport mechanisms.

If a production line implements the technological process, functional modules include machines, conveyors, manipulators, systems for accumulating workpieces, and semi-finished products.

Based on the modular approach, the following essential tasks have been solved.

Structural and parametric optimization for synthesizing technological layout structures during multi-tool processing is considered in [3].

The definition of the maximum period of use of unified nodes (modules) is proposed in [4].

The research work [5] proposes an approach to machine tool frames that can be reused and adapted multiple times is presented.

Geometric requirements from the selected scenarios of the use of machine structures are determined by dividing the structures into their ideal mechanical equivalents [6].

This article uses the modular principle for applying optimization synthesis as a kind of technological equipment design. It implies creating options of the technical system structure by combining functional modules of the necessary nomenclature in a specific order according to the technological process.

The subject of this investigation is a technical system such as a technological machine, production line, or manufacturing complex, the elements of which can be represented as a set of functional modules connected by functional relations.

The object of the study is the optimization synthesis methods, which help to determine the best option of the technical system among possible alternatives during its development. Particular attention focuses on identifying tasks that can be automated because the optimization is very time-consuming in general, so its execution using machine resources is in demand.

The aim of the study is the analysis of various optimization synthesis methods for the determination of the procedures, which can be carried out by computer. The obtained results became the basis for software development that implements our idea of partial automation of the optimization synthesis problem of modular technological equipment.

2 Literature Review

In modern industry, the choice of equipment for various purposes is so large that several options can represent each functional module. They may have different construction and are characterized by various technical and economic parameters, affecting the system's efficiency [7]. Of course, choosing those functional modules with the best parameter values is justified, but often the improvement of some of them is accompanied by a worse performance of others.

To include one alternative functional module in the designed system's overall structure, it is necessary to solve the optimization synthesis problem [8]. That means the designer should consider all possible combinations of functional modules, evaluate their quality and choose the best one [9-11].

In general, the optimization synthesis of any technological equipment is divided into the following stages (Figure 1) [1, 12].

The designer should formulate the design task at the "Problem formulation" stage. The functional purpose of the system and which quality characteristics will be evaluated should be considered.

The stage "Decomposition of the technological process" aims to divide the technological process into technological operations that should be implemented.

The decomposition algorithm of the technological process into operations was described in detail in the previous research work [1].

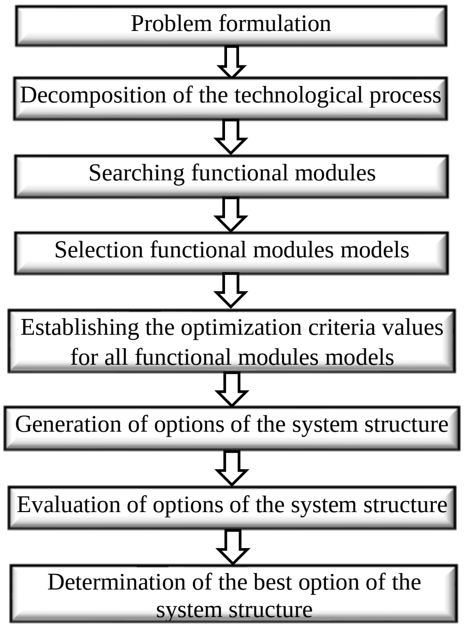


Figure 1 – Stages of optimization synthesis of modular technological equipment

"Searching functional modules" leads to finding the technological machines, devices, and mechanisms types that should perform all operations from the previous stage. It should be noted that depending on the design, some functional modules can perform two or more operations. Therefore, the number of operations is not always the same as the number of devices that implement the technological process.

"Selection functional modules models" means that any number of functional modules of the same functional purpose can be selected for further consideration.

"Establishing the optimization criteria values" lies in the determination of numerical values of technical or economic parameters, which were accepted as optimization criteria in the 1st stage and can be used for the efficiency evaluation of the entire system.

The formed set of equipment models with numerical values of the optimization criteria is the necessary initial data for solving the optimization problem.

The above stages represent an intellectual task, which implies searching and processing the array of data for compliance with the requirements.

They may be executed by one specialist, such as a design engineer, or by a group of experts (for example, to select optimization criteria, if the task is complex, and if it is more efficient to involve more than one point of view).

The next step is solving the structural optimization problem, as the most essential and complicated procedure of optimization synthesis.

Structural optimization aims to find the best option for the system structure among all alternatives obtained while solving the problem. The optimal solution is determined by finding the extremum of the objective function.

The stages "Generation of versions of the system structure", "Evaluation of versions of the system structure", and "Determination of the best version of the system structure" are implemented using the appropriate known methods of structural optimization.

There are two groups of methods for this purpose: complete search and directed search [10-16].

The formalization of optimization synthesis procedures is performed according to one of the following principles:

1) one-stage optimization synthesis, which suggests the synthesis of possible versions of the object's structure without their intermediate evaluation. Next, all received options are evaluated, and the best (optimal) is selected. One-stage optimization synthesis characterizes the methods of complete search. As a rule, these are methods of combinatorics that allow forming all the possible combinations of elements among themselves [10]. Often a genetic algorithm is used too as a tool for solving various combinatorial optimization problems, including the modular design problem [13];

2) multi-stage optimization synthesis. According to it, the increase in the number of elements within the generated options alternates at each step with its evaluation. This principle characterizes the methods of directed search, which are based on the evaluation of intermediate structures, and if they do not satisfy the task conditions, they are rejected. Eliminating unpromising initial parts of options from further consideration saves computational costs. Thus, sequential algorithms make it possible to reduce a large-dimensional problem to a set of small-dimensional problems [14, 15].

The choice of the most acceptable method for solving the specific task depends on the dimension of the problem and the designer's knowledge and capabilities.

In general, it is best when the method satisfies two main requirements:

1) makes it possible to select a set of dominant alternatives from all the results;

2) excludes the possibility of exclusion of potentially more effective options compared to those accepted for the final choice.

If the dimension of the problem is small, the designer can make the necessary conclusions empirically without using complicated mathematical algorithms. In the opposite case, the more the initial data of the problem, the more difficult it is to get the correct calculations. In this case, computer resources should be used.

Many engineering problems can be solved using appropriate software for designing various technological equipment.

In particular, designers can widely use CAD, CAM, and CAE technologies to create 3D models of equipment and its elements or execution of some standard calculations of equipment parameters [16, 17].

Specialized programs such as Mathcad or MATLAB can be used for complex mathematical calculations [18, 19].

There are also program tools for solving local problems of limited application, such as automatic tool path generation [20], digital twin development of robotized manufacturing systems [21], reverse digitizing for entire part geometry [22], obtaining optimal parameters of the milling process [23], determination of the relationship between the technological regimes and operational characteristics of materials [24], and developing mathematical models of device operation [25].

These programs can be applied to some optimization tasks, but none is acceptable for solving the problem of optimization synthesis.

We considered it expedient to develop such software based on a functionally modular approach, which would perform the mathematical part of the structural optimization task.

Two main factors determine the relevance of this task. Firstly, today's modern assortment of technological equipment is extensive and provides great opportunities for engineers to choose different equipment to implement the same technological process. Therefore, much of the time is spent on data search and analysis. The more information the engineer accepts as the initial data of the problem, the more complex the optimization task becomes.

Secondly, optimization synthesis methods are mathematically complicated enough for manual calculations.

Methods of directed search help to reject part of the results without their analysis and decrease the range of possible alternatives, but there is a risk that the optimal result will be mistakenly rejected as unpromising. The complete search methods avoid this problem and are algorithmically simpler but require much more calculations quantitatively. However, automation of these calculations can improve the efficiency of obtaining results, both from the point of view of their accuracy and saving time and resources.

3 Research Methodology

To implement the idea of partial automation of the process of solving the optimization problem, we developed the software "OptiTech". It can process an array of parameter values of functional modules (input data), produce all possible and logically permissible results (output data) according to the complete search algorithm and present them conveniently for further processing.

It is necessary to start using the program when the results of the first five optimization synthesis stages described above (Figure 1) have already been carried out.

The sequence of solving the structural optimization problem is fully illustrated below by a practical example.

Suppose a task is to collect a production line for packing liquid products (e.g., water and juice) in glass bottles.

At the initial design stage, optimization criteria for evaluating the quality of structural elements of the line and the result of its structural synthesis should be selected. Anyone or two can do it, but no more than three characteristics that are most important from the developer's point of view. It is important to note that each parameter must be additive since the program determines the sum of values of each criterion for each generated option of the structure.

From the point of view of saving cost, workshop space, and energy resources, we have chosen the following quality criteria respectively:

1) price (P, USD);
2) area (S, m^2);
3) energy consumption ($E, \frac{kw \cdot s}{pc}$).

Energy consumption is determined by considering the power of the equipment, as below:

$$E_i = P_i \cdot T_i, \tag{1}$$

where E_i – energy spent by the functional module during time T, MJ; P_i – the power of the functional module, kW; T_i – the time required to produce a unit of a product.

At $1\ kW \cdot s = 1000\ W \cdot 1\ s = 1\ MJ$

$$T = \frac{1}{Q}, \tag{2}$$

where: Q_i – productivity of the functional module, pc/s. Then

$$E_i = \frac{P_i}{Q_i}. \tag{3}$$

The values of these parameters should be as small as possible. It means that we need to solve a multicriteria minimization problem:

$$F(X) = (f_1(X), f_2(X), f_3(X)) \to min,$$

where $F(X)$ – the general objective function; $f_i(X)$ – the partial objective function [1].

As a result of the decomposition of a technological process of packing liquids into glass bottles, we got a list of main operations (Table 1).

Table 1 – Compliance of functional modules with operations

Technological operation	Code	Functional module	Code
Cleaning and disinfection of bottles	O_1	Bottle washing machine	FM_1
Product bottling	O_2	Dosing machine	FM_2
Capping of bottles	O_3	Capping machine	FM_3
Labeling	O_4	Labeling machine	FM_4
Marking the date of manufacture	O_5	Marking machine	FM_5

Auxiliary operations (input empty bottles, inspecting them after washing, moving between working positions of the equipment, checking tightness after capping, and removing finished products and their packaging in transport containers) are not included in the optimization synthesis in this case. We accept that the appropriate equipment is presented in a single quantity so that it may be added to the main structure of the line after its optimizations.

The next step is data formalization.

The plural of implemented operations will be:

$$O = \{O_1,\ O_2, \dots,\ O_n\} = \{O_1,\ O_2,\ O_3,\ O_4,\ O_5\},$$

where O – technological operation; n – the sequence number of the operation in the technological process.

To perform the specified operations, applying appropriate functional modules – technological machines is necessary. They are shown in Table 1.

Thus, the technological process is realized by generalized structure X of the production line:

$$X = \{FM_1,\ FM_2,\ FM_3,\ FM_4,\ FM_5\}.$$

The set of the models of machines will be:

$$FM_\mathrm{n} = \{E_{nm}\},$$

where: m – the sequence number of the model of n^{th} functional module.

The alternative models of defined functional modules are presented in coded form (Table 2). The manufacturers of the equipment set the values of optimization criteria.

Table 2 – Base of initial data of the problem of structural optimization of the production line for packing liquids

Functional module	Functional module model	Price P, USD	Area S, m^2	Energy consum-ption E, kW·s/pc
Bottle washing machine	E11	21700	24.5	13.2
	E12	20100	25.8	15.3
	E13	19300	27.4	14.1
Dosing machine	E21	15300	10.1	7.8
	E22	14800	13.7	8.5
	E23	16100	12.5	7.1
	E24	15400	11.6	7.6
Capping machine	E31	8700	9.8	6.4
	E32	9100	8.7	6.7
	E33	8200	9.1	6.2
Labeling machine	E41	5400	4.2	5.6
	E42	6300	3.6	5.9
	E43	6800	5.2	6.1
Marking machine	E51	750	1.6	3.8
	E52	900	1.2	4.2

So, we accept that the technological process includes five operations, which are implemented by five separate types of technological machines.

The next stage is generation of possible options of the structure of the entire production line.

Iteration is executed in the order from E11 to E52 with the step-by-step addition of the next element within FM_n to the formed structure until the complete set of modules is completed.

For example,

$X_1 = \{\mathrm{E11},\ \mathrm{E21}, \mathrm{E31}, \mathrm{E41}, \mathrm{E51}\}$;
$X_2 = \{\mathrm{E12},\ \mathrm{E21}, \mathrm{E31}, \mathrm{E41}, \mathrm{E51}\}$;
$X_3 = \{\mathrm{E13},\ \mathrm{E21}, \mathrm{E31}, \mathrm{E41}, \mathrm{E51}\}$;
$X_4 = \{\mathrm{E11},\ \mathrm{E21}, \mathrm{E31}, \mathrm{E41}, \mathrm{E51}\}$;
$X_5 = \{\mathrm{E11},\ \mathrm{E22}, \mathrm{E31}, \mathrm{E41}, \mathrm{E51}\}$, and so on.

In the described case, the number of such sets will be:

$$N = 3 \cdot 4 \cdot 3 \cdot 3\ \cdot 2 =\ 216.$$

The last solution should be represented by the set:

$$X_{216} = \{E13, E24, E33, E43, E52\}.$$

However, we consider that the model E43 of the labeling machine can mark the product's date of manufacture (the notches, which are made on the labels, indicate the date of production). That is, E43 can implement operations O_4 and O_5. Therefore, it should not be combined with elements E51 or E52 in the same structure.

The sequence of work with the program using the received information is described below.

4 Results

4.1 Description of the software

Work with the program "OptiTech" starts with creating a new document (Figure 2). To view an already created database, it can be loaded into the program using the command "Open" in the same menu.

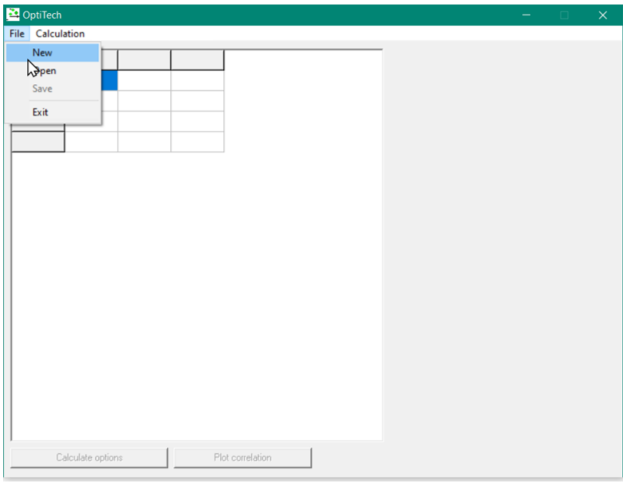


Figure 2 – The main program window

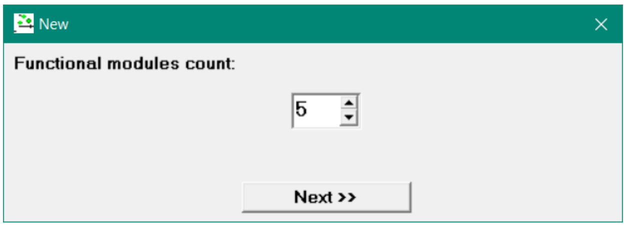
Next, the functional modules count (Figure 3a), models of each module count (Figure 3b), the optimization criteria count (Figure 3c), and the names of these criteria (Figure 3d) should be entered at the request of the program.

Then, it is necessary to fill in the table on the screen (Figure 4) with the appropriate criteria values for each element.

The next action is to specify the logical relations between elements. A logical relation should be understood as a condition that excludes the possibility of having more than one module that performs the same operation in the object structure. To mark that the element E43 should not be combined with element E51 or E52 in one structure the following actions should be done:

1) select the "Calculation - Logical relations" menu item;

2) using the drop-down lists, select the elements that are incompatible with each other (Figure 5).



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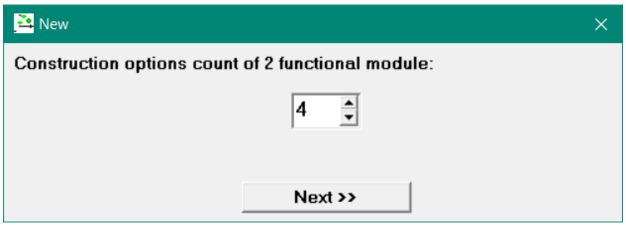

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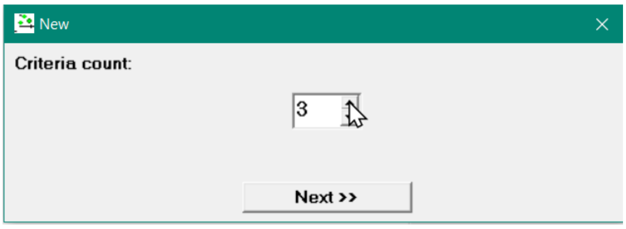

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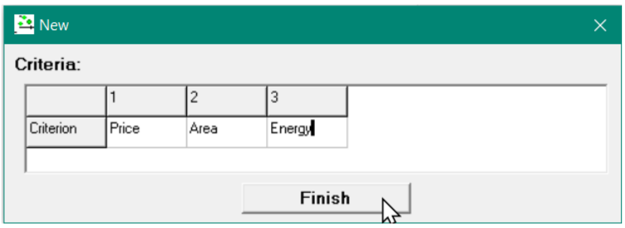
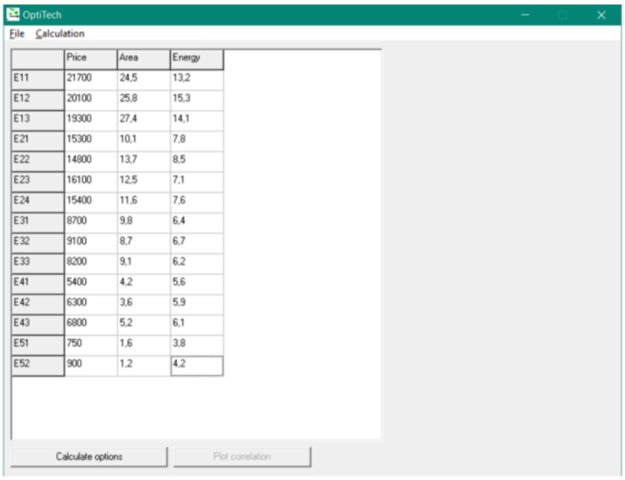


d

Figure 3 – The program window for entering data: a – functional modules count; b – the model of each module count; c – count of optimization criteria; d – names of optimization criteria



	Price	Area	Energy
E11	21700	24,5	13,2
E12	20100	25,8	15,3
E13	19300	27,4	14,1
E21	15300	10,1	7,8
E22	14800	13,7	8,5
E23	16100	12,5	7,1
E24	15400	11,6	7,6
E31	8700	9,8	6,4
E32	9100	8,7	6,7
E33	8200	9,1	6,2
E41	5400	4,2	5,6
E42	6300	3,6	5,9
E43	6800	5,2	6,1
E51	750	1,6	3,8
E52	900	1,2	4,2

Figure 4 – The program window for entering criteria values

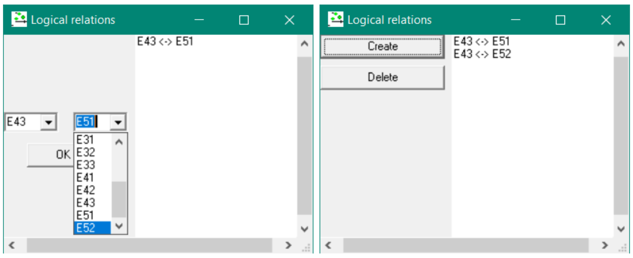
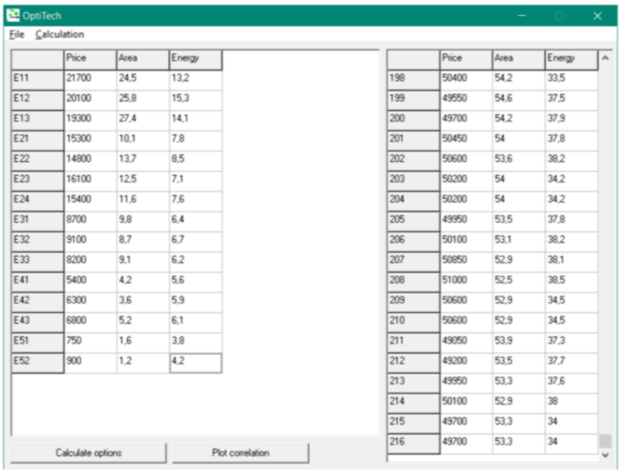


Figure 5 – The program window for entering the logical relations between functional modules

In this case, the program will count the criteria values for such modules in the same structure one by one, and the values of the alternative module will be counted as zero.

After clicking the “Calculate options” tab, a table with all the calculated results will appear in the right part of the program window (Figure 6), the sums of values for each criterion appropriate to a specific option of the problem solution.

In order to display the results of the calculation, it is necessary to click “Plot correlation”. The window that opens coordinate axes should be marked with the criteria names. For this purpose, drop-down lists placed in the upper left (axis Z), lower left (axis X), and lower right (axis Y) corners of the program window are used.



	Price	Area	Energy
E11	21700	24,5	13,2
E12	20100	25,8	15,3
E13	19300	27,4	14,1
E21	15300	10,1	7,8
E22	14800	13,7	8,5
E23	16100	12,5	7,1
E24	15400	11,6	7,6
E31	8700	9,8	6,4
E32	9100	8,7	6,7
E33	8200	9,1	6,2
E41	5400	4,2	5,6
E42	6300	3,6	5,9
E43	6800	5,2	6,1
E51	750	1,6	3,8
E52	900	1,2	4,2

	Price	Area	Energy
198	50400	54,2	33,5
199	49550	54,6	37,5
200	49700	54,2	37,9
201	50450	54	37,8
202	50600	53,6	38,2
203	50200	54	34,2
204	50200	54	34,2
205	49950	53,5	37,8
206	50100	53,1	38,2
207	50850	52,9	38,1
208	51000	52,5	38,5
209	50600	52,9	34,5
210	50600	52,9	34,5
211	49050	53,9	37,3
212	49200	53,5	37,7
213	49950	53,3	37,6
214	50100	52,9	38
215	49700	53,3	34
216	49700	53,3	34

Figure 6 – The program window with the calculated results

After performing the specified actions, a set of calculated results (solutions) will be displayed on a 3D graph (Figure 7).

For convenient work with the results, the program can show the projections of these points in the Cartesian coordinate system.

To divide the three-dimensional graph into planes with the possibility of viewing each of them, it is necessary to remove the 3D mark in the upper part of the window.

Next, it is possible to switch the marker in the upper left part of the window to the desired pair of axes.

The obtained results are presented in Figure 8. In particular, it can be seen, how the result window looks like for a point (Figure 8a). It shows information about the set of functional modules for this option of the structure and the total values for each criterion. To see it just click on any point.

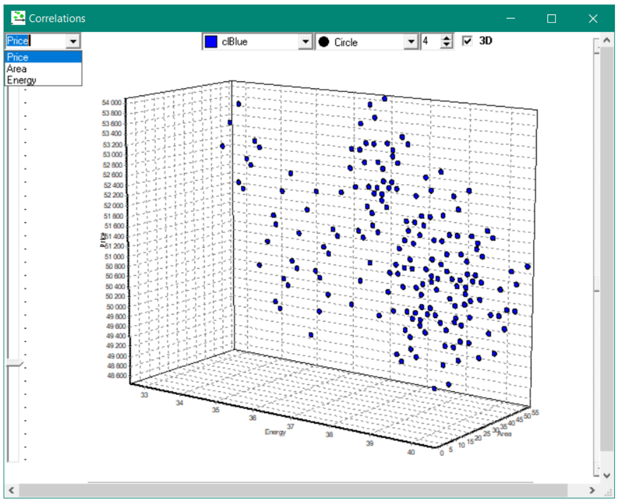
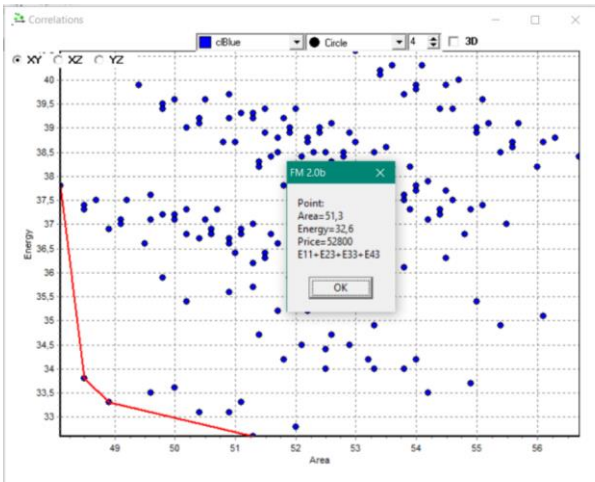


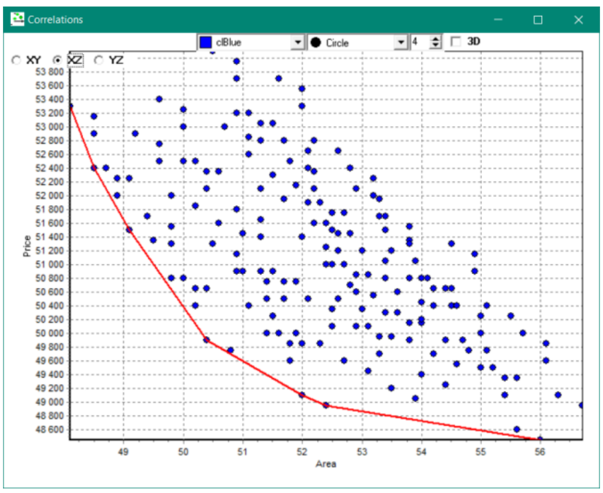
Figure 7 – 3D correlation graph of optimality criteria

Next, we highlight the Pareto set in the program.

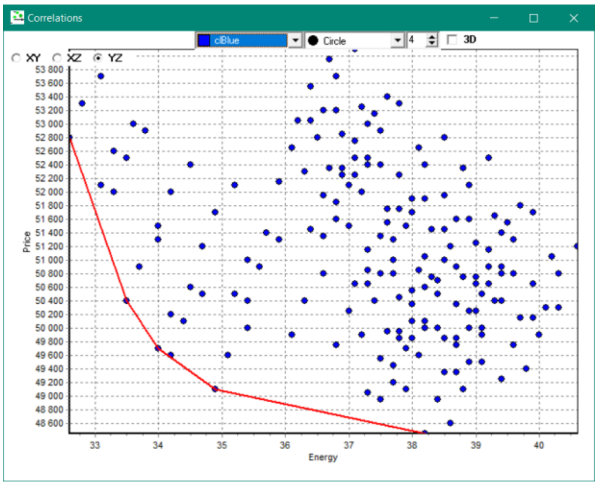
To connect the desired points on each graph, it is necessary to select the “Add line” item with the right mouse button, click on the desired points, open the menu again and select the “Finish” item. An explanation of which points should be selected is given below



a



b



c

Figure 8 – Projection of points on planes: a – "Energy-Area" (XY); b – "Price-Area" (XZ); c – "Price-Energy" (YZ)

4.2 Program results interpretation

Further on the concept of criteria space $\{F\}$, which has dimension s (according to the optimal criteria count) and is formed by s orthogonal axes on which the values are marked $f_k(X)$, $k \in [1, s]$ is used.

We are using the language of predicate logic for description [26].

The priority relationship $\succ$ should be determined on the set D_X. Then, under conditions $F(X) \to min$ and $f_k(X^1) \leq f_k(X^2)$, $k \in [1, s]$ vector $X^1 \in D_X$ has priority over the vector $X^2 \in D_X$, which we denote as $X^1 \succ X^2$. Similarly, we define the dominance relation $\lhd$. If $X^1 \succ X^2$ vector optimality criterion $F(X^1) \in D_X$ dominates over $F(X^2) \in D_X$, that is $F(X^1) \lhd F(X^2)$.

The defined relations of priority and dominance are transitive. That is, if $X^1 \succ X^2$ and $X^2 \succ X^3$, then $X^1 \succ X^3$. Similarly, if $F(X^1) \lhd F(X^2)$ and $F(X^2) \lhd F(X^3)$, then $F(X^1) \lhd F(X^3)$.

So, we can define the set D_X a subset of points $D_X^* \in D_X$, for which no points are dominating them. The indicated set D_X^* is the Pareto one. Accordingly, the value of any partial optimization criteria can be improved only by worsening the other.

All the specified criteria must be minimized, so the Pareto set will be a set of points located in the extreme left lower position in the graphs.

In Figure 8a, the Pareto set includes the following solutions (options for the production line structure):

$$X^1 = \{E_{11}, E_{21}, E_{32}, E_{42}, E_{52}\};$$
$$X^2 = \{E_{11}, E_{21}, E_{32}, E_{43}\};$$
$$X^3 = \{E_{11}, E_{21}, E_{33}, E_{43}\};$$
$$X^4 = \{E_{11}, E_{23}, E_{33}, E_{43}\}.$$

In Figure 8b, the Pareto set includes the following solutions:

$$X^1 = \{E_{11}, E_{21}, E_{32}, E_{42}, E_{52}\}$$
(the same as in the plane "XY");

$$X^5 = \{E_{11}, E_{21}, E_{33}, E_{42}, E_{52}\};$$
$$X^6 = \{E_{11}, E_{21}, E_{33}, E_{41}, E_{52}\};$$
$$X^7 = \{E_{12}, E_{21}, E_{33}, E_{41}, E_{52}\};$$
$$X^8 = \{E_{13}, E_{21}, E_{33}, E_{41}, E_{52}\};$$
$$X^9 = \{E_{13}, E_{21}, E_{33}, E_{41}, E_{51}\};$$
$$X^{10} = \{E_{13}, E_{22}, E_{33}, E_{41}, E_{51}\}.$$

In Figure 8c, the Pareto set includes the following solutions:

$$X^4 = \{E_{11}, E_{23}, E_{33}, E_{43}\}$$
(the same as in the plane "XY");

$$X^{11} = \{E_{13}, E_{23}, E_{33}, E_{43}\};$$
$$X^{12} = \{E_{13}, E_{24}, E_{33}, E_{43}\};$$
$$X^{13} = \{E_{13}, E_{22}, E_{33}, E_{43}\};$$
$$X^{10} = \{E_{13}, E_{22}, E_{33}, E_{41}, E_{51}\}$$
(the same as in the plane "XZ").

4.3 Determination of the optimal solution

The results show that some points of the Pareto set are projected onto two planes at once, so we get 13 solutions that dominate the rest of the 203 in terms of quality.

The total numerical values of the optimality criteria are summarized in Table 3.

We conclude that the program does not give a single solution to the problem, and the Pareto method only narrows the search circle but does not give a final result.

The designer's task is to choose the best (optimal) solution by going through the points belonging to the Pareto set. We should proceed to mathematical calculations of the integral optimality criterion for this.

In this case, it is the simplest to search for the values of the additive criterion [15].

When applying the additive criterion, the objective function is obtained by summing up the normalized values of the partial criteria.

Table 3 – Values of optimization criteria for options of the production line structure

Criterion / Solution	Price *P*, USD	Area *S*, m²	Energy consum-ption *E*, kW·s/pc
X^1	53300	48.1	37.8
X^2	52900	48.5	33.8
X^3	52000	48.9	33.3
X^4	52800	51.3	32.6
X^5	52400	48.5	37.3
X^6	51500	49.1	37.0
X^7	49900	50.4	39.1
X^8	49100	52.0	37.9
X^9	48950	52.4	37.5
X^{10}	48450	56.0	38.2
X^{11}	50400	54.2	33.5
X^{12}	49700	53.3	34.0
X^{13}	49100	55.4	34.9

The objective function is:

$$F(X^j) = \sum_i^k C_i \frac{f_i(X^j)}{f_i^0(X^j)} = \sum_i^k C_i f_i^*(X^j) \to min, \quad (4)$$

where: j – the number of points in the Pareto set; C_i – weight coefficient of the i-th partial criterion; $f_i(X^j)$ – the value of the j-th partial criterion; $f_i^0(X^j)$ – i-th normalizing divisor (minimum) value of i-th criterion; $f_i^*(X^j)$ – a normalized value of the i-th partial criterion.

Thus, we assigned the weighting coefficients C_i for each value of the partial criteria (Table 4). We did it according to the principle of increasing values of partial criteria since we have a minimization problem for all optimization criteria.

Table 4 – Evaluation of options of the production line structure by weighting coefficients

Criterion / Solution	Price P, USD	Area S, m^2	Energy consumption E, kW·s/pc	The value of the additive criterion $F(X^j)$
X^1	12	1	10	25.8
X^2	11	2	4	18.2
X^3	8	3	2	13.7
X^4	10	6	1	18.3
X^5	9	2	8	12.9
X^6	7	4	7	17.4
X^7	5	5	13	25.9
X^8	3	7	11	22.9
X^9	2	8	9	21.1
X^{10}	1	12	12	29.0
X^{11}	6	10	3	20.6
X^{12}	4	9	5	19.3
X^{13}	3	11	6	22.1

So, substituting the relevant data in (4), we get:

$$F(X^1) = 12 \cdot \frac{53300}{48450} + 1 \cdot \frac{48.1}{48.1} + 10 \cdot \frac{37.8}{32.6} = 25.79;$$

...

$$F(X^{13}) = 3 \cdot \frac{49100}{48450} + 11 \cdot \frac{55.4}{48.1} + 6 \cdot \frac{34.9}{32.6} = 22.13.$$

The results of all calculations are listed in Table 4.

The optimal option of the structure of the designed production line among all possible is X^5 because its additive criterion is the smallest.

5 Discussion

Many scientific works are aimed at improving the equipment at the design stage. Solving engineering problems based on a modular approach is widespread [2, 4-7, 9, 17]. Structural optimization issues are also well investigated [3, 8, 10-12, 14, 15, 18].

Some studies are devoted to automating various design tasks [16, 19-25].

A review of these studies confirms that structural optimization is one of technological equipment design's most essential and challenging stages. Mistakes made in its early stages irreversibly affect the quality of the object and the efficiency of its operation. Therefore, the development result should be technically rational and economically justified as possible.

Regardless of the effectiveness of the chosen optimization method, the quality of the solution depends directly on the accuracy of calculations. So special attention should be paid to its correctness.

In this article, we offer to increase the efficiency of solving the optimization problem by software to automate its stages.

As can be seen from the presented materials, our software "OptiTech" has a few features:

– does not limit the number of elements (models of the equipment) of the designed system structure;

– executes the combinatorial part of the optimization task;

– determines problem solutions with high mathematical precision;

– is suitable for a wide range of equipment with a discrete structure regardless of its functional purpose.

Based on the above results, it can be stated that the research aim is completely achieved.

6 Conclusions

In the article, an analysis of optimization synthesis methods to determine the procedures which computer resources can carry out is conducted. The obtained results became the basis for software development that implements the idea of partial automation of the optimization synthesis problem of modular technological equipment.

The suggested software "OptiTech" is developed using the complete search algorithm. It generates all logically admissible options of the system structure, counts the values of selected criteria, and visualizes the set of all solutions. The obtained correlation is convenient for applying the Pareto method. The optimal option is determined using the generalized optimality criterion.

The efficiency of this research is confirmed by the presented optimization synthesis of a production line for packing liquid products in glass bottles. Automation of the calculation procedures ensures adequate accuracy of results. The dimension of the data to be calculated manually is reduced significantly. For the presented task, the number of solutions, which should be processed at the final stage, decreased from 216 to 13 (by 16 times).

Software "OptiTech" is acceptable for structural optimization of any technical system with a functionally modular structure (technological machines, production lines, or manufacturing complexes) regardless of its functional purpose.

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