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Modeling and Optimization of Material Flows in a Section for Machining in the Presence of Alternative Technological Processes

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***Abstract*— An important factor in increasing productivity and optimal use of resources in mechanical engineering production is the effective organization of material flows. Under the conditions of the modern production systems, alternative technological processes for machining parts often exist, which creates opportunities for more flexible production planning, complicating, at the same time, material flows and equipment load management.**

The present article examines the possibilities for material flows optimization in a section for machining, in order to increase the efficiency of the production system. It analyzes the peculiarities of the organization of production in the presence of multiple technological routes and different types of machine tools and proposes an approach for modeling the production area by representing the technological processes as a graph and a matrix of the material flows between the individual workplaces. A multi-objective optimization problem is formulated, aimed at minimizing the transport distances, technological times and volume of the work in progress.

***Keywords*— alternative technological processes; machining; material flows; production optimization; technological routes.**

I. Introduction

The methods, developed so far for optimal placement of objects (technological equipment) in production areas, are based on the so-called rigid calculational model, which assumes that the technological processes (i.e. sequence of operations) for manufacturing productsя (parts and assembled units) are pre-defined at the stage of technological preparation of production. Alternative technological processes are not allowed in this case. For each operation, only the technological equipment on which it can be performed, is specified in advance.

The rigid calculational model is not appropriate to be used for solving problems, related to selecting the optimal placement of equipment for production cycles in which alternative technological processes can be applied.

Instead, the so-called flexible calculational model can be used for solving optimization problems, related to optimal placement of objects in production areas. The model specifies for each operation a list of equipment on which it can be performed, and, in addition, allows to apply alternative technological processes for manufacturing the same product.

The flexible calculational model is based on several assumptions [1]:

- equipment can only be placed on fixed sites with a known location;
- the number of machines equals the number of sites;
- the list of products to be manufactured in a section is known, and so is their manufacturing schedule;
- for each product a technological route is set, which contains a list of all necessary operations for its production;
- for each operation, a list of machines on which it can be performed is specified;

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- for each operation, the time for its execution is determined;
- each machine has its own time pool, which limits the time for its operation, and hence the number of operations, which can be performed on it.

The flexible calculational model differs from the rigid one in that with this model for each of the operations a list of machines, on which it can be executed, is specified [2]. The rigid computational model is a special case of the flexible one, in which case the list of equipment on which the respective operation can be performed contains only one machine. In addition, with the flexible model, the use of alternative technological processes is allowed, which means that in order to manufacture the same product, the workpieces may undergo a different sequence of technological operations.

II. MATERIALS AND METHODS

In order to solve the task to optimally place objects in a production area, it is necessary to formulate the task as a problem, belonging to the class of optimization problems [3]-[6]. For problems of this type, the following must be determined:

- model parameters, which are changeable;
- constraints on parameter values;
- dependence of the objective function on the model parameters;
- search criteria.

A. Model parameters

In optimization problems, related to placing objects in pre-fixed positions, the mathematical concept of "permutation" is used as a parameter [7], [8]. A permutation is a concept from combinatorics, describing the number of ways in which a finite number of elements can be arranged. The order of the elements is of essential impotance in permutations. Each permutation has its length, expressed by a natural number. A permutation of length k is a sequence of natural numbers from 1 to k, each of which occurs in this sequence only once. An example of a permutation of length 4 is (1, 4, 3, 2), (3, 4, 1, 2) and (4, 1, 2, 3). From combinatorics it is known that a total of k! permutations of k length can be formed. The permutation of the equipment allows to unambiguously determine the correspomdence between the number of a machine and the position, at which it is located. For example, the permutation (3, 5, 2, 1, 6, 4) means that the machine number 3 is located at position 1, machine number 5 is located at position 2, and so on.

One of the assumptions with the flexible calculational model is that the number of machines and the number of positions, where they can be placed, are equal [9], [10]. If the number of machines exceeds the number of the sites, then the Dirichlet priciple comes into effect, according to which two machines will have to be placed on at least one of the sites, which is unacceptable [11]. At the same time, another option is entirely possible, in which the number of positions is greater than the number of equipment. This means that some of the sites will remain vacant. Such a task can be reduced to the standard one, where the number of machines and the number of positions are equal. For this purpose, "fictitious machines" are added to the task, thus equalizing the number of work sites and the number of equipment. Moreover, the list of machines, on which the operations will be performed, must not include fictitious equipment.

It can be concluded from what has been stated so far, that the equipment placing options can be used as variable parameters of the model.

B. Objective function

The objective function is used to compare different options for deploying equipment, i.e. to compare the values of the variable parameter. The search criterion (max or min) shows the best combination of parameters – the one, which pprovides the minimum or maximum value of the objective function. The optimization problem consists in finding such values of the model parameters, for which the objective function will have an extreme value. One of the most frequently used objective functions in problems, related to production logistics is the material flow capacity in the production system [12], whose value is determined by the formula:

$$C = \sum_{i=1}^{n}\sum_{j=1}^{n} Q_{i,j}.r_{i,j} \qquad (1)$$

where n is the number of machines and sites for their placement; i, j – inventory numbers of the equipment; $Q_{i,j}$ – mass of the load to be moved from the i^{-th} to the j^{-Th} piece of equipment; $r_{i,j}$ – distance between the i^{-th} and j^{-th} machine.

The value of the parameter $Q_{i,j}$ depends on the production route [13]-[15], while the parameter $r_{i,j}$ is determined by the option for placing the machines. If no loads are moved from the i^{-th} to the j^{-th} machine, then $Q_{i,j} = 0$.

If a rigid model is used for calculation, in which the production routes are unambiguously determined by the technological ones, then it is possible to determine the parameter $Q_{i,j}$. When using a flexible model, this parameter cannot be determined, since only the equipment placement and technological routes are known. Only at the stage of operational and calendar planning does it become known which equipment will perform which operations, and accordingly, only then the production routes also become known. In other words, the capacity of the material flow in the production system will be determined not only by the location of the equipment at the workplaces, but also by the distribution of the work between the machines. Therefore, in the flexible computational model the objective function will have two parameters, instead of one as it is in the rigid model.

To find the value of the objective function for a given arrangement (permutation) of the equipment, it is necessary to formulate a problem for finding the minimum value of the material flow for a fixed placement of the equipment, and the found value will be the objective function.

Let m be the permutation of n machines and F be some mathematical object, describing unambiguously the production routes in a section. Then, the load flow capacity C is a function of m and F: C(m, F). If this function is considered for a constant value of the variable m, then the the load flow capacity C is a function of only one variable $C_m(F)$. In this case, the minimum value of the function can be written as $\min(C_m(F))$. The optimization problem for placing equipment in a production area, respectively, can be formulated in the following way: find the permutation m, which provides a minimum of the function $\min(C_m(F))$:

$$\min(C_m(F)) \rightarrow \min. \quad (2)$$

With such a representation of the problem, it is not necessary to find the vector F, which provides the minimum capacity of the load flow. However, it is possible to present the problem differently – as an optimization of a function with two variables [16]. In this case, it is necessary to find both the vector F and the permutation m – the two elements, which give the function C(m, F) a minimum:

$$(C(m, F)) \rightarrow \min. \quad (3)$$

The capacity of the load flow in the production system is traditionally used as a function in material flow optimization [17], [18]. This parameter, however, does not always accurately reflect the costs, related to moving objects in the course of a production process. Sometimes the transportation of relatively light details with large dimensions turns out to be more expensive than moving heavy parts with small dimensions. In this regard, it is relevant to use the total mileage of the vehicle as an optimization criterion. It can be found if the size of the transport batch for each manufactured product is known [19] and can be calculated by the formula:

$$G = \sum_{i=1}^{n} \sum_{ab=1}^{w} \frac{N_{MS\,i}}{N_{TBS\,i}} l_{abi}, \text{ m/year}, \quad (4)$$

where n is the number of the types of products moved per year (or other unit of time); w – number of operations for manufacturing the i^{-th} product; l_{abi} – distance from the a^{-th} to b^{-th} position, along which the i^{-th} type of product is moved, m; $N_{MS\,i}$ – manufacturing schedule for the i^{-th} type of product, pcs/year; $N_{TBS\,i}$ – size of the transport batch for the i^{-th} type of product, pcs.

When there is no information about the size of the transport batch it is expedient to use the capacity of the load flow as a target function.

A. Algorithm for solving the optimization problem of placing objects in a production area

The first step toward solving the optimization problem is to construct a technological route graph, by means of which the technological routes for manufacturing the products are defined.

Fig. 1 presents a diagram of the way of synthesizing a technological route graph.

Two types of elements can be seen in the graph in Fig. 1: vertices and edges. Each of the vertices corresponds to some beginning of the production system flow (input), or to its end (output), or to one of the machines to be positioned in the production area [20]. Each technological route is a sequence of records, starting with “input” and ending with “output”, and between them – the sequence of execution of the operations is recorded [21]. An example of a technological route is: "input - operation 1 (machines 2, 3, 5) - operation 2 (machines 1, 4) - operation 3 (machine 6) - output".

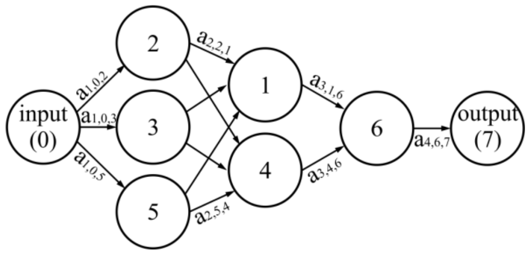

Fig. 1. Graph of the technological route

The second important element of the graph is the edges, connecting its vertices. With the help of the edges, all vertices, located on adjacent levels. are connected in pairs. Each of the edges corresponds to a part of a possible manufacturing route, i.e., there will be movement of workpieces from one machine to another. After the corresponding operations on one of the machines have been completed, the workpieces are moved to the next machine to undergo the next operations.

The definition of each edge of the technological route graph is done by means of a number, equal to the number of workpieces, moved along it – $a_{i,j,k}$. This number has three indices, defining it. The first of them, i, determines the level of the graph, at which the vertex of the corresponding edge is located (the operation, after the execution of which the workpiece is moved to the next machine, is indicated). The second index j serves to denote the inventory number of the machine, on which the corresponding operation is performed, i.e., it indicates the specific vertex, from which the edge emerges. The third index k defines the inventory number of the machine, toward which the workpiece is directed after the operation is performed, i.e., the vertex in the graph, where the edge ends.

In the event of manufacturing different types of products through different technological processes in the production system, then it is necessary to synthesize a technological route graph for each of these processes. The level numbers in each graph in this case must be unique.

The variable $a_{i,j,k}$ determines the number of workpieces, moving along the edges of the technological route [22], [23]. The term edge flow is used to define it. As an illustration to the exposed above let us consider the following example. A request to manufacture 42 items has been received. A decision has been made at the stage of operational and calendar planning to distribute the first operation among the machines as it follows:

- 15 workpieces are processed on the second machine;
- 17 workpieces are processed on the third machine;
- the remaining 42 – 17 – 15 = 10 workpieces are processed on the fifth machine.

In accordance with this decision, the value of the three edge flows of the technological graph can be determined:

$$a_{1,0,2} = 15; \qquad a_{1,0,3} = 17; \qquad a_{1,0,5} = 10.$$

After having the first operation completed, the workpieces are directed to the corresponding machines for the second operation. Assume that the following decision was made during planning: 17 of the workpieces, processed during the first operation on machine 3, should be distributed as it follows: 8 of them - to be processed on machine 1 (second operation), 9 of them - to be processed on machine 4 (second operation 2). This allows to define two more edge flows:

$$a_{2,3,1} = 8; \qquad a_{2,3,4} = 9.$$

It can be seen that the set of all variables $a_{i,j,k}$ uniquely determines the production routes, along which the objects are moved in the production area, and thus the routes can be regarded as object F.

In order to unambiguously define all production routes, it is both necessary and sufficient to indicate the value of the flow along each edge of the graph for those of the technological routes, which lead to manufacturing products. It means that if the values of the variable $a_{i,j,k}$ in the production system are known, the capacity of the load flow (the material flow) can be determined.

B. Constraints on model parameter values

At the stage of choosing an option for placing the equipment, it is possible to consider some limits, within which the values of the edge flows may change. Multiple constraints are possible to be imposed on their values and the constraints can be divided into 3 groups:

- *First group of constraints*

The constraints, belonging to the first group, can be written, taking into account the peculiarities of the technological route graph. From this it follows that at all vertices of the graph, excluding "input" and "output", the total input flow is equal to the total output flow. An equation, relating the edge flows incident on a given graph vertex, can be written based on this [24]. The number of equations will match the number of vertices. The equation has the form:

$$\sum_{i=0}^{n+1} a_{k+1,l,i} = \sum_{j=0}^{n+1} a_{k,j,l} \,, \qquad (5)$$

where k is the operation number or the graph level; n – number of machines in the production area; l -number of the machine, on which the k-th operation can be performed; j – number of the machine, on which the (k – 1)th operation can be performed; i - number of the machine, on which the (k + 1)th operation can be performed.

To illustrate the limitations of the first group, the diagram in Fig. 2 is presented [20].

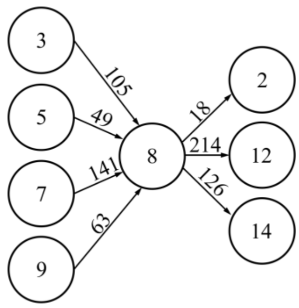

Fig. 2. An example of the first group of constraints

Here the equation is written for machine number 8, on which operation number 3 will be performed. The previous operation (№2) can be performed on machines numbers 3, 5, 7, 9. The next operation (№4) can be performed on machines 2, 12, 14.

The meaning of the first group of limitations is that the number of workpieces, directed toward machine 8 from machines 3, 5, 7 and 9 (on the left side of the graph), must be equal to the number of workpieces, which will be moved to machines 2, 12 and 14 (on the right side of the graph). The equation can be written in the following way:

$$a_{3,3,8} + a_{3,5,8} + a_{3,7,8} + a_{3,9,8} = a_{4,8,2} + a_{4,8,12} + a_{4,8,14}.$$

In Figure 2 this constraint is met: the total input flow is equal to 105 + 49 + 141 + 63 = 358 workpieces, and the output flow is also equal to 18 + 214 + 126 = 358 workpieces.

It is important to note that all constraints from the first group are of the first degree, i.e., linear equations, forming together a system of linear equtions [24].

- *Second group of constraints*

This group connects the size of the edge flows with the manufacturing schedule of the products. If all the flows, which go out of the "input" vertex are summed, the result will be the total number of products, manufactured following a specific technological process. The flows, incident on the "output" vertex, can be similarly summed up. Having in mind the first group constraints, it is sufficient to write equations only for one vertex (input or output), since they provide the same value of the input and the output flows for each level of the graph. The following rule can be formulated from here: the sum of the edge flows, incident on the "input" vertex, is equal to the manufacturing schedule of the product, following the corresponding technological process.

Only one limitation of this type is written for each technological route as follows:

$$\sum_{i=0}^{n} a_{b,0,i} = n_b , \qquad (6)$$

where b is the number of the first operation of the technological process; n – number of machines in the production area; i – inventory number of the machine, on which the first operation of the technological process can be performed; n_b –number of products, which must be manufactured following this specific technological process (manufacturing schedule).

To illustrate this limitation, the diagram in Fig. 3 is presented [20].

In this specific case, 1500 parts must be manufactured, following a given technological process. The first operation of the process can be performed on machines with the following inventory numbers: 3, 8, 9, 23. Then an equation can be written, connecting the edge flows and the incident input:

$$a_{8,1,3} + a_{8,1,8} + a_{8,1,9} + a_{8,1,23} = 1500.$$

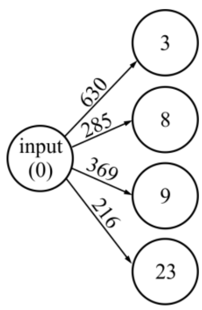

Fig. 3. Example of the second group of constraints

The constraints, belonging to the second group, are also linear equations. Together with the constraints from the first group, they form an indeterminate (i.e., having multiple solutions) system of linear equations, which limits the allowable values of the edge flows of the graph.

- *Third group of constraints*

Production routes are determined not only by the route of movement of the workpieces in a production system, but also by the load on the technological equipment. The greater the number of operations to be performed on a machine, the more time it will take to complete its assigned tasks [25]. If the limitation of the working time pool is not taken into account, it is possible to have production routes, in which some of the machines will be overloaded and others will not be occupied.

The flexible computational model introduces the assumption that the time, spent by the equipment for completion of the assigned tasks, depends linearly on the number of products to be manufactured. In reality, this is not entirely true [27], as additional time is required, associated with re-adjusting the machine for the new batch of parts, replacing worn or broken tools, periodic equipment maintenance, etc. Nevertheless, the use of linear dependencies is adequate. On the one hand, it is convenient from the point of view of solving optimization problems, based on this mathematical model, and, on the other hand, it adequately reflects the manufacturing processes.

The third group of constraints are inequalities, limiting the load on the machine, which must not exceed its working time pool. The inequalities have the form:

$$\sum_{b=1}^{m} \sum_{i=0}^{n+1} a_{b,l,i} \cdot t_b < T_i , \qquad (7)$$

where b is the number of those operations, which can be assigned to the machine; n – number of units of equipment in the production area; m – number of operations, performed in the production area; l – inventory number of the machine, on which an operation, preceding operation b, can be assigned; T_i – effective time pool for operating a machine; t_b – time, required to execute operation b.

It is important to understand the difference between the limitations, belonging to the first and third groups. In both cases they concern one of the machines. In the first case, several constraints can be set on the machines, one for each operation they can perform. According to the third group of constraints, one inequality is formulated for each machine. This means that the number of inequalities matches the number of machines in the production area [28], [29].

The diagram in Fig. 4 illustrates the third group of constraints [20].

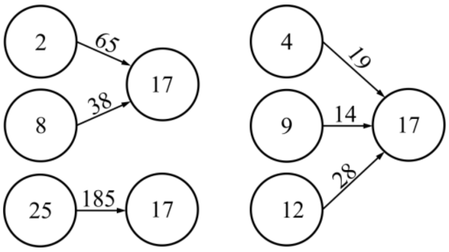

Fig. 4. Example of the third group of constraints

According to the technological process, on the machine with inventory number 17 operations with numbers 2, 9, 15 are allowed. The time for performing these operations is known - 12, 25, 45 minutes. It is also known that the preceding operations can be performed on the following equipment: operation 1 (precedes operation 2) – on machines 2 and 8; operation 8 (precedes operation 9) – on machine 25; operation 14 (precedes operation 15) – on machines 4, 9, 12.

The inequality in this case is written in the following way:

$$a_{2,2,17} \,.\, t_2 + a_{2,17,17} \,.\, t_2 + a_{9,25,17} \,.\, t_9 + a_{15,4,17} \,.\, t_{15} + a_{15,12,17} \,.\, t_{15} \leq T_{17}.$$

If the working time pool for machine 17 is 10000 minutes, then, substituting the numerical values of t and T, we obtain the inequality:

$$a_{2,2,17} \,.\, 12 + a_{2,17,17} \,.\, 12 + a_{9,25,17} \,.\, 25 + a_{15,4,17} \,.\, 45 + + a_{15,12,17} \,.\, 45 \leq 10\,000.$$

It can be verified that the values of the edge flows, shown in Figure 4, allow this constraint to be met:

$$65 \,.\, 12 + 38 \,.\, 12 + 185 \,.\, 25 + 19 \,.\, 45 + 14 \,.\, 45 + + 28 \,.\, 45 = 8930 \leq 10\,000.$$

If the initial data in the optimization problem contain too low values of the working time pool, then no distribution of the operations between the machines will satisfy the inequality and, as a result, the problem will not have a feasible solution.

If the value of the working time pool is overestimated, then it will turn out that the permissible options will have a high degree of uneven load on the equipment.

The third type of constraints are linear inequalities, which limit the throughput of each vertex of the graph by prohibiting the construction of production routes in a way, in which they all pass through a single vertex.

III. Results and Discusion

The capacity of the material flow is influenced not only by the location of the technological equipment, but also by the production routes themselves. If there are several alternative processes to manufacture a single product, then different size of the material flow will be observed with the different options. It follows from here that the choice of optimal production routes for manufacturing the products is also important.

The optimization of the material flows in a section for machining in case of presence of alternative technological processes can also be described by a technological route graph. The edge flows of this graph determine all production routes.

The technological processes themselves differ from each other only in the list of machines, on which the corresponding operations can be performed. It can be illustrated by the diagram in Fig. 5 [30].

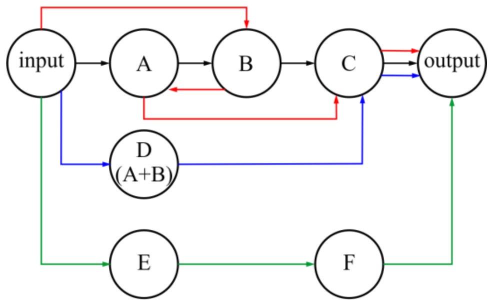

Fig. 5. Construction of a technological route graph in the presence of alternative technological processes (ATP)

Assume that there is some bsic technological process, in which operations A, B and C (ATP1) are sequentially performed. Alternative technological processes are also permissible. One of the possible variants of the alternative technological processes (ATP2) differs from the basic variant only in the sequence of execution of operations A and B: operation B is performed first and then A. In another possible alternative technological process (ATP3), operations A and B are grouped into one operation D, which is performed on a machine with higher functional capabilities (e.g. turning and milling on a machining centre). Operation D is followed by operation C. In a possible alternative technological process (ATP4), fundamentally different operations E and F may be performed.

Not individual machines but the operations in the technological process are used as vertices of the technological route graph. A special case is the situation when for each operation there is only one machine on which it can be performed.

Let all operations, except operation D, be performed on only one machine, and operation D – on one of three machining centres. In this case vertex D will be replaced by three vertices, each corresponding to one of these machines, marked in Fig. 6 as D1, D2 and D3 [30].

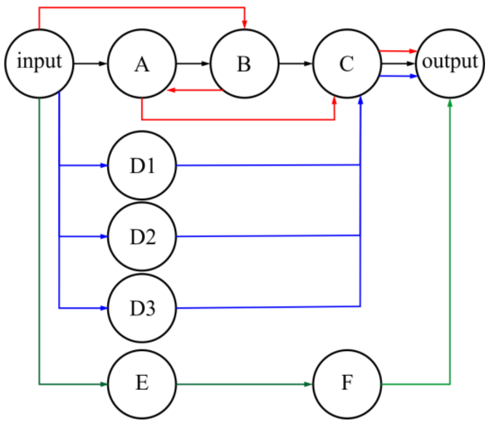

Fig. 6. Technological route graph in the presence of alternative technological processes (ATP)

The variables $a_{i,j,k}$, which characterize the edge flows of the graph, can be introduced for the technological route graph from Fig.6. The same three groups of constraints can be imposed on these variables:

- the total inflow should be equal to the total outflow;
- the sum of the edge flows should be equal to the manufacturing schedule for making the products;
- the time pool limit of the machines should not be exceeded and an even load on the equipment must be ensured.

Assume that 1000 parts need to be manufactured. One of the possible options is presented in Fig. 7.

- 250 parts are machined in the case of ATP1 (input →A → B → C → output);
- 300 parts are machined in the case of ATP2 (input →B → A → C → output);
- 100 parts are machined in the case of ATP3 (input → D1 → C → output);
- 0 parts are machined in the case of ATP3 (input → D2 → C → output);
- 150 parts are machined in the case of ATP5 (input → D3 → C → output);
- 200 parts are machined in the case of ATP6 (input → E → F → output).

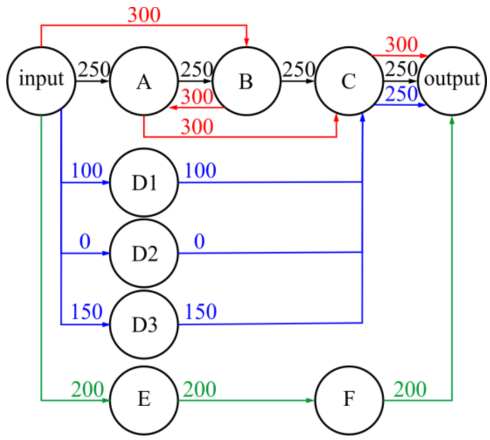

Fig. 7. Example of a production route for processing parts using alternative technological processes

From the presented example it can be seen that the total input flow (1000 parts) is equal to the total output flow, the production schedule is executed and the machines are loaded more evenly.

After imposing the constraints on the production routes, it is necessary to formulate the objective function. The capacity of the load flow is a linear combination of the edge flows:

$$C = \sum_{e=1}^{m} \sum_{f=0}^{n+1} \sum_{z=0}^{n+1} a_{e,f,z} \, . \, R_{f,z} \, . \, M_e \, , \qquad (8)$$

where e is the graph level, i.e., the number of the operation; m – total number of operations, performed in the production area; f, z – inventory numbers of the equipment; n – number of machines; $R_{f,z}$ – distance between the pairs of machines f and z; M_e – mass of the products after performing the operation.

If in the task of searching for optimal equipment placement in a production area, this function is used only for a preliminary assessment of the load flow capacity at the stage of technological preparation of production, and the quantities $a_{e,f,z}$ are only parameters of the model, when optimizing the load flow they will become variables.

The problem of minimizing the function C is a linear programming problem and therefore it can be solved relatively easily and in a short time, even when the problem is of large dimension.

IV. Conclusions

To solve optimization problems, related to optimal placement of objects in a production area, the so-called flexible calculational model can be used. The model specifies for each operation a list of equipment, on which the operation can be performed. In addition, the use of alternative technological processes for manufacturing the same products is allowed.

For each equipment placement option, a linear programming problem is formulated, and when solving it, the upper and lower limits of the production system load flow value can be found. The lower limit is recommended to be used as an optimality criterion. To formulate the linear programming problem, it is proposed to use a special graph, called a technological process graph.

In order to consider and evaluate all possible options for placement of technological equipment, a heuristic algorithm can be used, for example, simulated annealing.

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