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TOPICAL ISSUE

Models of Equipment Selection for Modernization of Enterprises with Conveyor Assembly of Products

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Abstract—The article deals with problems of equipment selection and replacement arising during modernization of machine-building enterprises, where the assembly of manufactured products is carried out on conveyors. The author proposes methods for these tasks, which allow to determine types and quantity of equipment, which should be purchased and which it is expedient to get rid of during modernization of enterprises.

Keywords: modeling, mathematical models, linear programming, processing equipment, components, conveyor, assembly, product, modernization

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1. INTRODUCTION

In recent years, there has been a marked increase in competition, which affects virtually all areas of production activity and leads to a significant reduction in the life cycle of manufactured products. This in turn leads to the need to update manufactured products more frequently and, accordingly, to modernize production facilities to produce them.

This situation is particularly noticeable in the automotive industry, as almost all automotive manufacturing companies update the car models they produce at least every two to three years, resulting in the need to update and modernize the production facilities where these models are produced.

Successful choice of equipment in the process of modernization of enterprises allows to create profitable and competitive production, and the elimination of errors and miscalculations associated with the choice of equipment, already in the process of operation of enterprises can require very significant additional costs.

Sufficiently effective methods and models have been developed to select equipment for production systems and sites during their creation and modernization [1–3]. However, these methods proved to be unsuitable for equipment selection in enterprise modernization due to high dimensionality and complexity of the arising problems. Therefore, it is necessary to create special models and methods of equipment selection for enterprise modernization.

The article proposes methods of equipment selection for modernization of enterprises with conveyor assembly of manufactured products. These methods make it possible to determine the equipment which it is expedient to acquire for the enterprise and to exclude from its composition. The proposed methods use work schedules of formed schemes of modernization of enterprises. Such work schedules will allow to check and evaluate the operability of each received scheme of modernization of the enterprise during execution of test orders, and to choose the most suitable from them.

2. PROBLEM STATEMENT

Let's consider the statement of the problem of equipment selection for modernization of enterprises with conveyor assembly of manufactured products.

The work of conveyors is carried out in a sequential scheme and the modernization of the enterprise does not require the formation of new production units and the creation of new conveyors.

Suppose an enterprise has M production units. They produce components for the assembly of products on R conveyors. After modernization on the rth conveyor of the enterprise is expected to produce L_r $(r = 1, \dots, R)$ batches of products of different types, some of which are new to the enterprise. Some of the components can be purchased on the side. The composition and quantity of equipment located in all units of the enterprise before modernization is known. The types of equipment suitable for the manufacture of all components for new products and available for purchase by the enterprise are also known.

On each conveyor, only the "own" products are assembled in batches. The size of the assembled batch of l-type products on the rth conveyor $(l = 1, \dots, L_r)$ must not exceed the value of $\tilde{N}_{lr}$. Such limitations are due to the significant time it will take to manufacture large quantities of components, as well as the need to create and maintain large-volume warehouses to store them.

During the assembly of products on conveyors, the production units manufacture components for the assembly of products of the next batches. Conveyors are readjusted if they will be used to assemble other types of products. If some conveyors will continue to assemble products of the same type, their readjustment is not required.

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Productivity of each conveyor and the number of workplaces for assembly of the types of products produced on it are known. Time of readjustment of each conveyor for assembling on it the produced batches of products is also known, that allows to calculate duration of assembling of any batch of products.

There is a set of typical production tasks J, which, if possible, should contain the orders awaiting the enterprise after modernization in the conditions of real work. Model jobs j $(j = 1, \dots, J)$ contain batches of product types that belong to the set L. Different jobs contain batches with different numbers of parts N_l $(l = 1, \dots, L)$.

To produce jobs from this set J may require modernization of the enterprise with the purchase of additional equipment of the types available at the enterprise and equipment of such types that were not previously available at the enterprise. Some of the existing equipment may no longer be needed.

The problem requires selecting the equipment that should be purchased to modernize the enterprise, and getting rid of unnecessary equipment of the enterprise so that, given the funds allocated to modernize the enterprise D, each production task j $(j = 1, \dots, J)$ of a given set can be produced in a time not exceeding $\hat{T}_j$.

It should be noted here that it is extremely difficult to determine the values of $\hat{T}_j$, D, and production tasks j in advance, so that with the funds D allocated for enterprise modernization, production tasks j $(j = 1, \dots, J)$ can be completed in a time not exceeding $\hat{T}_j$. However, these values can provide a good preliminary target for selecting the scheme of the enterprise to be modernized. The values of $\hat{T}_j$ $(j = 1, \dots, J)$ and D will most likely have to be repeatedly reviewed and adjusted in the process of selecting equipment for plant modernization.

3. FORMATION WIREFRAME SCHEDULES

Let's first consider the principles of construction of plans and schedules of work for the production of incoming orders at enterprises with conveyor assembly of manufactured products.

The study of principles and methods of construction of such schedules and turns out to be very important. This is due not only to the fact that with the help of built schedules of work on the production of standard tasks on the schemes of the modernized enterprise can be checked whether these tasks are performed in the allotted time. Such work schedules allow to understand more clearly and distinctly the task of modernization of enterprises and to outline ways of its solution, as well as to choose the most suitable scheme for modernization of the enterprise. It should be noted here that the following peculiarity related to the designed objects and products was noticed during the design of various objects and products.

The design of products and objects is more successful when several variants of this product or object are designed and their advantages and disadvantages are compared and analyzed. On the basis of comparison and analysis of their characteristics, a new variant can be formed, in which, if possible, the identified disadvantages are eliminated and the existing advantages are strengthened. After that, the best option is selected from the available options on the basis of analysis and comparison of their parameters and characteristics.

In this regard, when modernizing enterprises it is advisable to form several schemes of modernized enterprises and on the basis of comparison and analysis of their performance on the implementation of test orders, a new variant of the scheme of the modernized enterprise can be formed and the best of the available schemes is selected.

In order to understand the tasks of modernization of enterprises and to verify the fulfillment of test production tasks in the allotted time, it is necessary to build coordinated schedules of work at the enterprise level. Such schedules are understood here as schedules in which all subsequent operations for processing each batch of components should begin only after the completion of the previous operation specified in the technology of its production.

The principles and methods of constructing such schedules are described in [3, 4]. According to these principles, special groups are formed from the components manufactured for the assembly of manufactured products. Each group is formed so that in the process of its manufacturing all components included in the group would arrive for processing to the production units of the enterprise in the same order. Nevertheless, each component of any group can be processed according to "its" technological route in all production units to which this group is delivered.

Then the schedule of processing of such groups is built, which defines the order of processing of each group in the used production unit of the enterprise. To build such schedules it is necessary to determine the processing times of each formed group of components in those production units of the enterprise, in which this group is processed. The order of processing of such groups in the production unit of the enterprise is known from the principles of their formation. To determine the time of processing of a group of components in the corresponding production unit of the enterprise the schedule of processing of components of this group on the equipment of the production unit can be built. The time of processing of each group of components in a production unit is taken as the time of completion of processing of the last component group on the equipment of this production unit. The construction of work schedules in production units can be performed with the help of traditional methods [5–7], which were developed specifically for the construction of such schedules and allow to construct them quite quickly and well.

The scheduling of component groups in the production units is built according to the same rules as the usual schedule of parts processing on machines in production systems. According to these rules, only one group of components can be processed at a time in one production unit of the enterprise and one group of components can be processed at a time in only one production unit.

The order of processing of groups of components in the production units of the enterprise should be chosen in such a way that the total time of their processing would be as short as possible.

In [1], the processing schedules of component groups formed according to such principles in the production units of the enterprise were called “frame” schedules. It should also be noted that with the help of a “frame” schedule it is possible to quickly enough form a variant of the work schedule for the enterprise, called a deployed “frame” schedule.

In the Gantt chart of the extended “framework” schedule, a separate abscissa axis is allocated for each processing equipment of any production unit, along which the processing times of components manufactured on this equipment in this production units are plotted.

Processing schedules for all groups of components in the production units where these groups are processed were already built and should be, since their processing times were determined by these schedules. These times were used to build a “frame” schedule.

The available diagrams of schedules of processing of groups of components in production units are placed in the diagram of the unfolded “frame” schedule on those positions which correspond to the positions of these production units and their equipment.

The diagrams of schedules of processing of such groups are placed on the corresponding positions in the order obtained during the construction of the “frame” schedule. Placing the schedule of the next group of components at the positions of each production unit in the unfolded diagram can be performed only when the processing of the last component from the previous group is completed. Therefore, the completion times for the “frame” and “unfolded” schedules will coincide.

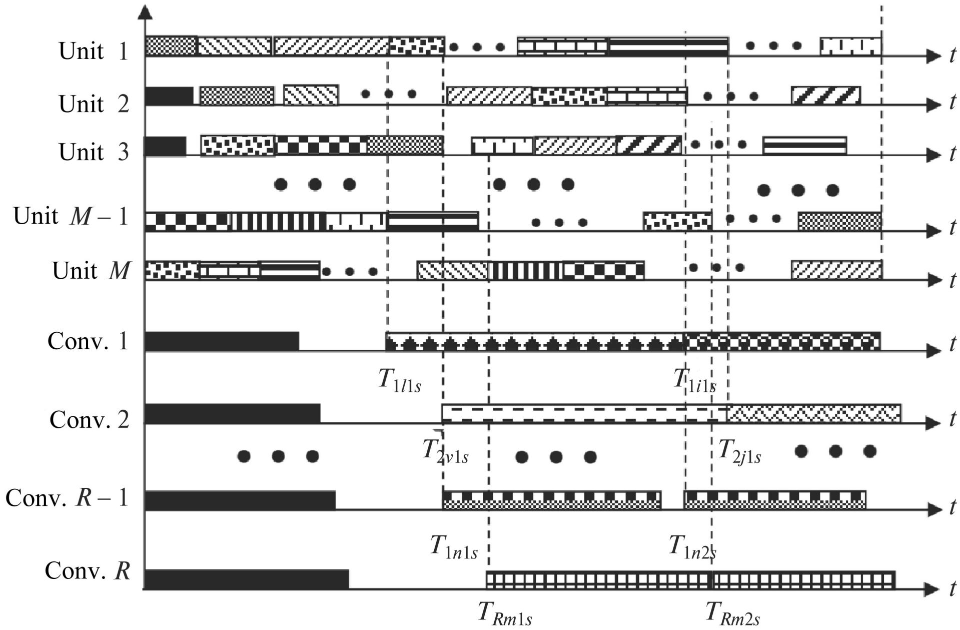
The thus constructed deployed “frame” schedule is a coordinated schedule at the enterprise level. Indeed, in such a schedule the processing of each component by time will be started on any used equipment only after its processing is completed on the previous equipment according to its manufacturing technology. However, this variant of the work schedule at the enterprise will not be quite successful, because it has a lot of “unforced” downtime of the equipment in the places of “contact” schedules of processing of adjacent groups of components in each production unit. To reduce these down times the operation of “gluing” of schedules is performed, when the equipment released in the production unit from processing of components of the processed group is immediately used for processing of components of the next group. The time of work completion under such a schedule is noticeably reduced.

In addition, plant-level schedules can be used to determine the start and end times of all component manufacturing operations for each product on all enterprise equipment in use, from the first to the final operation. It is also possible to know the start and completion times of assembly of each batch of products.

Let’s consider the principles of building “frame” schedules using the rules described above for processing of components in the production units of the enterprise and assembling of order items from them on conveyors.

First, groups of components are formed for all products of the order according to the above rules. For products of each type the groups are formed independently from products of other types. After determining the processing time of the formed groups of components for all products of the order in the relevant production units of the enterprise, a “frame” schedule of processing of these groups at the enterprise is built.

The construction of such a schedule starts with the construction of a schedule for the processing of groups of components used to assemble batches of products from the received order, which will be assembled on the conveyors of the enterprise in the first place. For its construction traditional methods of schedule construction can also be used, because the dimensionality of the “frame” schedule due to the association of components into groups and equipment into subdivisions is not significant.



Gantt diagram of a “frame” schedule for manufacturing components and assembling products from them on conveyors.

When the construction of such a schedule is completed, the construction of its next part begins. This part includes the schedule of processing of groups of components from which products will be assembled on each conveyor of the enterprise in the next turn. The previously built part of the schedule cannot be changed, and the new part of the schedule starts to be built from the moment of releasing the enterprise production units from processing of component groups of the already built part of the schedule.

After completion of processing of the last group of components of each batch of products in the enterprise production units, the manufactured components are transferred to the corresponding conveyor for assembly. This process continues until the completion of processing of component groups for the last batch of products to be assembled on the enterprise's conveyors from the received order.

The transfer of manufactured components to the corresponding conveyor does not affect the work of production units and the “frame” schedule for the manufacture of components.

For better understanding of the processing of components and assembly of products from them at enterprises, it is convenient to visualize them in the form of a “framework” schedule, an example of which for an enterprise with M production units and R conveyors is shown in figure.

In figure, the first five axes of abscissas on which mark the start and end times of processing of component groups in the production unit that corresponds to this axis. On the axes labeled as “Unit 1”, “Unit 2”, ..., “Unit M” axes indicate the start and end times of processing of component groups in the first, second, ... and Mth production units, respectively. The axes labeled “Conv. 1”, “Conv. 2”, ..., “Conv. R” mark the completion times of the assembly of products on the first, second, ... and R conveyors, respectively. In this diagram, through T_{1l1s} is the time of completion of processing of components for assembly on the first conveyor of the first batch of products l-type from sth order, through T_{Rq2s} is the time of completion of assembly of the second batch of products q-type on the third conveyor from sth order. The rectangles shaded in black on this diagram mark the lead times and completion times from the previous job.

As can be seen from this Gantt chart on the axes labeled as “Unit 1”, “Unit 2”, ..., “Unit M” actually represents a “frame” schedule of processing components for assembling products from the incoming order. As components are ready for assembly of any batch of products, these components are transferred to the appropriate conveyor. This, as already noted, does not affect the work of production units and the “frame” schedule of work.

If some scheme of modernization of the enterprise to perform, for example, sth typical task will be formed, then the Gantt diagram representing the “frame” schedule of this task will have a form similar to the one shown in figure. In addition, from such a diagram it is possible to determine the time of task execution with a fairly good accuracy.

The diagram of this schedule shows that in order to complete the sth task in a time not exceeding $\hat{T}_s$, the time for manufacturing components and assembling the task items from them must not exceed certain values.

Let’s estimate the time $\tilde{T}_s$, not later than which the components for assembly on conveyor belts should be manufactured for the products from sth production task, so that the time of fulfillment of sth task does not exceed $\hat{T}_s$. To fulfill this requirement, the value of $\tilde{T}_s$ is determined by the following relationship

$$\tilde{T}_s = \hat{T}_s - \max_r T_{rns},$$

where T_{rns} – assembly time on the rth conveyor of the last batch of products from the sth job.

However, the work schedule of the enterprise cannot be built without knowing the equipment of this enterprise. Therefore, it is proposed to preliminarily the equipment for the scheme of the modernized enterprise and build a work schedule for it to perform the production task. After analyzing this schedule, the selected equipment is adjusted to form a more suitable scheme for the enterprise to be modernized. This process will be described in paragraph 4 and will continue until the most suitable scheme of the plant to be modernized is obtained.

4. EQUIPMENT SELECTION MODEL

Let’s consider the principles of building a model for preliminary selection of equipment to solve the simplest problem of modernizing an enterprise with M production units and R conveyors for assembling manufactured products.

Pre-selected equipment can be used to build a “skeleton” schedule for processing components. This will allow the selected equipment to be refined and adjusted.

For preliminary selection of the types and quantities of necessary equipment, we use balance constraints for groups of equipment of each type in the enterprise’s production units by time.

Balance constraints for the equipment available at the enterprise, on which components with a single processing route are processed, can be presented in the following form:

$$\sum_{l=1}^{L} \left\{ \sum_{v \in V_{jm}^l} N_l n_{vl} t_{vj}^{lm} \right\} \leqslant (y_{mj} + \tilde{y}_{mj} - \bar{y}_{mj}) \left(\tilde{T}_s \eta_j^{ml} - \sum_{l=1}^{L} \sum_{v \in V_{jm}^l} \tau_{vj}^{lm} \right) \mu_{jm}, \quad j \in G_m, \tag{4.1}$$

where L is the number of product types in the sth production task, V_{jm}^l is the set of component types of the lth product that can be processed on the jth equipment of the mth production unit, N_l is the number of products of the lth type ($l = 1, \ldots, L$) in this task, n_{vl} is the number of components of the vth type in the lth product, t_{vj}^{lm} is the processing time of the vth component of the lth product on the jth equipment of the mth production unit, η_j^{ml} is the coefficient that determines the resource of the time of use of the jth type of equipment during the time interval of its operation, μ_j^{ml} is the utilisation coefficient of the jth equipment from the mth production unit, τ_{vj}^{lm} is the changeover time of the jth equipment from the mth production unit for the production of the vth batch of components of the lth product, y_{mj} is the number of units of the jth equipment that was in the mth production unit before modernization, $\tilde{y}_{mj}$ is the number of units of the jth equipment that should be purchased during the modernization process for the mth production unit, $\bar{y}_{mj}$ is the number of units of the jth equipment that should be disposed of during the modernization process of the mth production unit.

The enterprise may also have equipment that processes components using less than ideal technological processing routes. Other technological routes may be developed for such components using both existing and newly acquired equipment. The model requires selecting the most suitable of these routes.

However, it should be noted here that developing a technological route requires time and money, and not always small ones, especially when checking the route and debugging it for use in a constantly operating production facility.

Balance constraints for the types of equipment available at the enterprise that can process components with several processing routes are as follows:

$$\sum_{l=1}^{L}\left\{\sum_{i\in\tilde{V}_{jm}^{l}} N_l n_{il} t_{ij}^{lm} + \sum_{v\in V_{jm}^{l}}\sum_{k\in K_{vj}^{l}} \theta_v^{kl} N_l n_{vl} t_{vj}^{klm}\right\}$$
$$\leqslant (y_{mj}+\tilde{y}_{mj}-\bar{y}_{mj})\left(\tilde{T}_s\eta_j^{ml} - \sum_{l=1}^{L}\sum_{v\in V_{jm}^{l}} \tau_{vj}^{lm}\right)\mu_{jm}, \quad j\in G_m, \tag{4.2}$$

where θ_v^{kl} are integer variables of type $[0,1]$.

The value of θ_v^{kl} in constraints (4.2) is equal to 1 if the vth component of the lth product is manufactured on the jth equipment via the kth process route, and zero otherwise.

The balance constraints for newly acquired equipment, on which components can be processed via several process routes, can be represented as follows:

$$\sum_{l=1}^{L}\left\{\sum_{i\in\tilde{V}_{jm}^{l}} N_l n_{il} t_{ij}^{lm} + \sum_{v\in V_{jm}^{l}}\sum_{k\in K_{vj}^{lm}} \theta_v^{kl} N_l n_{vl} t_{vj}^{klm}\right\}$$
$$\leqslant y_{mj}\left(\tilde{T}_s\eta_j^{ml} - \sum_{l=1}^{L}\sum_{v\in V_{jm}^{l}} \tau_{vj}^{lm}\right)\mu_{jm}, \quad j\in\tilde{G}_m. \tag{4.3}$$

The balance constraints for newly acquired equipment, on which components are processed along a single process route, have almost the same form as constraints (4.3). The difference is that on the left-hand side of the constraint, due to the presence of a single processing route for components, the term $\sum\limits_{v\in V_{jm}^{l}}\sum\limits_{k\in K_{vj}^{lm}} \theta_v^{kl} N_l n_{vl} t_{vj}^{klm}$ is missing.

The choice of process routes for manufacturing components is made using the variables θ_v^{kl}, on which the following constraints are imposed:

$$\sum_{k=1}^{K_v^l}\theta_v^{kl} = 1, \quad m=1,\dots,M, \quad v\in\tilde{V}_m^l, \quad l\in\bar{L}, \tag{4.4}$$

where $\tilde{V}_m^l$ is the set of components of the lth product that have changes in their design or manufacturing technology and for their manufacture in the mth production unit it is necessary to select a manufacturing process route from the K_v^l routes developed for processing this component, $\bar{L}$ is the set of products from the formed task that have changes in their design or manufacturing technology. The remaining designations are defined above.

If the vth batch of components of the lth product can be manufactured only by one technological route, then the variables θ_v^{kl} and constraint (4.4) are not included in the model.

If individual parts of this batch can be manufactured by different technological routes, then the following constraints are imposed on the variables $0 \leqslant \theta_v^{kl} \leqslant 1$, and the value θ_v^{kl} shows what part of this batch of components is processed by the kth technological route. Usually, for previously produced components, technological routes for processing components for which already exist and these routes do not cause serious complaints, new routes are not developed.

The funds required to purchase additional equipment, taking into account the funds received from the sale of unnecessary equipment, should not exceed the funds allocated for modernization. Therefore, the following constraint is included in the model:

$$\sum_{m=1}^{M}\left(\sum_{j\in\Omega_m}\tilde{d}_j\tilde{y}_{mj} - \sum_{j\in G_m}\bar{d}_j\bar{y}_{mj}\right) \leqslant D + p_1, \tag{4.5}$$

where $\Omega_m = G_m \bigcup \tilde{G}_m$, $\tilde{d}_j$ is the cost of acquiring equipment of the jth type, $\bar{d}_j$ is the cost of selling unnecessary equipment of the jth type, p_1 is an auxiliary variable that is minimized in the functional.

The functional J, the minimum of which is determined in this model, has the form

$$J = \min\left\{\alpha_1\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{j\in\tilde{G}_m}\sum_{v\in V_{jm}^l}\sum_{k\in K_{vj}^{lm}}\left(\theta_v^{klm}N_l n_{vl}\breve{c}_{vj}^{klm}\right) + \alpha_2\sum_{m=1}^{M}\sum_{j\in\tilde{G}_m} b_{mj}T.y_{mj} + \alpha_3 p_1\right\}, \tag{4.6}$$

where α_1, α_2 and α_3 are weighting coefficients, $\breve{c}_{vj}^{klm}$ is the cost of manufacturing a component part of the vth type for a product of the lth type along the kth process route on the jth type of equipment in the mth production production unit of the enterprise, b_{mj} is the cost of ensuring the operation and maintenance of the jth type of equipment from the mth division during a unit of time. The remaining designations are defined above.

The calculations of model (4.1)–(4.6) are reduced to solving an integer linear programming problem [7, 8].

However, when calculating this model, there is no need to obtain an exact integer solution. This is due to the fact that the equipment selection model (4.1)–(4.6) for upgrading real enterprises with conveyor assembly of products, as a rule, has a very significant dimension. Obtaining an exact integer solution for problems of such a dimension using existing methods will take a very long time.

On the other hand, some of the initial data in the calculations is approximate. In addition, the data on the amount of equipment purchased and excluded from the enterprise, even if an exact solution is obtained, cannot be used to make a decision on purchasing or excluding equipment at the enterprise. The fact is that optimization models cannot take into account the times of forced equipment downtime and waiting for the start of component processing during their manufacture. Such downtime almost always occurs during the processing of parts and tasks [5–7] and can significantly increase the time of component manufacturing. The times of forced downtime can only be determined after constructing component manufacturing schedules at the enterprise.

As a result of the model calculation, the amount of equipment $\tilde{y}_{mj}$ that must be additionally purchased in addition to what is available at the enterprise, as well as the amount of equipment $\bar{y}_{mj}$

that it is advisable to get rid of, is determined. In addition, the amount of equipment of new types $\tilde{y}_{mj}$ that must be purchased for the enterprise is determined.

If the model (4.1)–(4.6) at given and $\hat{T}_s$ has a solution at p_1 equal to zero, then we check whether the given task is fulfilled in the allotted time. For this purpose, the schedule of processing components and assembling the items included in the task from them is built.

If the built work schedule for manufacturing of components and assembling of the task items from them is completed in time T_s, which is less than the allotted time $\hat{T}_s$, then the obtained scheme of the modernized enterprise is placed in the scheme check group.

Very often, as an acceptable solution to the problem of equipment selection for modernizing enterprises, not only the solution in which the manufacturing time of the order will be completed not earlier than the allotted time, but also the solution with some excess of this time is chosen. Usually the manufacturing time of s-order in this case can belong to the given interval $\left[\hat{T}_s + \Delta T\right]$, where ΔT defines such a time interval.

However, if the model (4.1)–(4.6) for a given D has a solution in which the value of p_1 is different from zero, then a check is performed.

If the value of p_1 is less than the given value of ΔD, then the processing schedule is constructed according to the scheme described above and the time of manufacturing sth job $\breve{T}_s$ is determined by this schedule.

If this time is less than the specified time with an acceptable delay ΔT_s, i.e. $\breve{T}_s \leqslant \hat{T}_s + \Delta T_s$, then the generated schema of the enterprise to be modernized is included in the verification group.

However, if the model (4.1)–(4.6) for a given D has a solution in which the value of p_1 is different from zero and is greater than a given value ΔD, then a very complicated situation arises.

In this situation, with the funds D allocated for the modernization of the enterprise, it is impossible to purchase the equipment that will allow the enterprise to perform sth task in the time $\hat{T}_s$. Therefore, it is necessary to make a decision either to change the values of D and $\hat{T}_s$, or to stop work on modernization of the enterprise at this stage of the enterprise's activity and, possibly, to postpone it for better times.

5. CORRECTION OF EQUIPMENT COMPOSITION

Consider the situation when a decision is made to proceed with the formation of a suitable scheme of the modernized enterprise at new values of D and $\hat{T}_s$.

In this case it is required to choose such a value of the time of production of components for the assembly of sth job, so that at a given $\tilde{D}$ it is possible to form such a scheme of the modernizing enterprise, on which sth job will be produced for the shortest time T_s. The value of $\tilde{D}$ is determined by the capabilities of the enterprise and therefore does not change.

The algorithm that allows to determine such time T_s for manufacturing sth job, as well as the equipment for modernization of the enterprise can be represented by steps as follows.

Let us denote by $\bar{T}_{sr}$ the time of manufacturing components for assembling sth job at rth iteration of the algorithm. When r=1, the time $\bar{T}_{s1} = \tilde{T}_s$.

Step 1. The time $\bar{T}_{sr+1}$ during which the $(r+1)$th iteration of the algorithm needs to produce components is calculated using the relation $\bar{T}_{sr+1} = \bar{T}_{sr} + \Delta\bar{T_{sr}}$, where $\Delta\tilde{T}_r$ is the incremental value. The transition to Step 2 follows.

Step 2. In the model (4.1)–(4.6), the value $\tilde{T}_s$ is replaced by the value $\bar{T}_{sr+1}$ and its calculation is performed. As a result of model calculation the new composition of equipment for the considered scheme of the modernized enterprise is determined. The transition to Step 3 follows.

Step 3. Verification is performed. If the variable p_1 in the obtained solution turns out to be equal to zero, then the difference $\Delta\bar{T}_{sr+1} = \bar{T}_{sr+1} - \bar{T}_{sr}$ is calculated and proceed to Step 4. Otherwise, we assume $r := r + 1$ and the transition to Step 1 follows.

Step 4. If the value $\Delta\bar{T}_{sr+1}$ is greater than the given value $\Delta\tilde{T}_1$, then the parameter $\bar{T}_z$ is assigned the value $\bar{T}_{sr}$ and the value $\bar{T}s = \frac{\bar{T}_{sr+1}+\bar{T}_z}{2}$ is calculated. The transition to Step 5 follows. Otherwise, proceed to Step 7.

Step 5. The model (4.1)–(4.6) is calculated, in which the value $\tilde{T}_s$ is replaced by $\bar{T}s$. As a result of the calculation, the variable p_1 and the new composition of equipment for the considered scheme of the modernized enterprise are determined. The transition to Step 5 follows.

Step 6. If the variable p_1 is greater than zero, the difference $\Delta\bar{T}_{sr+1}$ is calculated. $\Delta\bar{T}_{sr+1} = \bar{T}_{sr+1} - \bar{T}s$, and proceed to Step 4. Otherwise, $\bar{T}_{sr+1}$ is assigned to $\bar{T}s$, and the difference $\Delta\bar{T}_{sr+1} = \bar{T}_{sr+1} - \bar{T}_{sr}$. Then the transition to Step 4 follows.

Step 7. For the newly selected equipment composition of the scheme, the production schedule of the given production job is constructed. Based on the constructed work schedule, the manufacturing time of this job $T_{s(r+1)z}$ and the component manufacturing time $\bar{T}_{sr+1}$ are determined. The computation stops.

6. OTHER TASKS OF MODERNIZATION OF ENTERPRISES

Let's consider briefly the possibilities of using the proposed methods to solve other problems of equipment selection.

In the second paragraph of the work it was assumed that the modernization of the enterprise does not require the formation of new production units and the creation of new conveyors. However, these assumptions are not fundamental. The equipment selection models and work schedule construction methods proposed in the paper can be used in equipment selection without performing them.

Moreover, with their help it is possible to solve the problems arising at the considered enterprises, which can be called "what will happen if" problems. In these tasks it is required to determine "what will happen if" changes in the structure and activities of the enterprise occur or are introduced, and to evaluate the results of such changes.

Among such tasks we can single out the tasks of changing the structure of the enterprise, in which the creation of new or elimination of inefficient production units, merger or division of existing ones, change in the number of conveyors for assembly of manufactured products at the enterprise are considered. In addition, such tasks include tasks related to the increase, reduction or changes in the composition of output products, tasks to determine and change the funds allocated for modernization.

These tasks also include the tasks of redistribution of equipment between production units, the tasks of replacement and replenishment of equipment of enterprise production units.

To solve these problems using the proposed methods, the structure of the modernized enterprise is determined, including the selected number of production units and the number of conveyors with the purpose of products assembled on them. For newly mastered products are determined components that can not be processed on the equipment available at the enterprise. Types of equipment that will provide their necessary processing are selected, and these types are distributed among the existing or created production units of the enterprise.

Then for the components of the newly mastered products the technological routes of their processing are formed taking into account the existing and purchased equipment in the production units of the enterprise. For components of manufactured products, alternative technological routes of processing are formed in case of problems with the existing equipment.

After that, the model (4.1)–(4.6) is used to determine the amount of equipment of each type that should be purchased for the relevant productions of the enterprise. Then, for the obtained scheme of the enterprise according to the rules described above, the construction of the schedule of production of a given production task is made.

According to a similar scheme with minor changes with the help of the proposed methods can be made selection of equipment for newly established enterprises.

In this case, the work of all schemes of the modernized enterprise, obtained as a result of making the changes of interest, can be checked on the performance of test tasks. According to the results of their fulfillment on the tested schemes can be collected interesting characteristics of their operation, by which it is possible to visually check the introduced or emerging changes, as well as to assess their consequences.

7. ANALYSIS AND SELECTION OF THE BEST MODERNIZATION OPTION

Let's consider the main methods of performance verification and comparison of the work of the assembled schemes of the modernized enterprise, as well as methods of selecting the most appropriate from them.

Verification of the performance of the formed schemes of the modernized enterprise is very important and necessary, because it should identify the main errors and miscalculations that may have arisen during the modernization of the enterprise. Identification and elimination of errors and miscalculations in the process of "model" verification of the performance of schemes of the modernized enterprise will require much less time and money than in the process of unsuccessfully modernized enterprises.

First, on the basis of research and analysis of the conditions of future operation of the modernized enterprise formed a sufficient number of standard orders, as well as the desired timing of their implementation. The formed orders should, if possible, be similar to the real orders that will and can come to the enterprise after modernization. It is convenient to summarize such orders into a long-term production program of one and a half to two years, an example of which is presented in the table.

Table

Order structure	Order 1st	...	Order lth	...	Order Qth
...	pieces	...	pieces	...	pieces
Batch 1	500	...	1200	...	1100
...	...	...	...	...	...
Batch r	1200	...	400	...	500
...	...	...	...	...	...
Batch L	900	...	1500	...	1200

The verification of each scheme of the modernized enterprise is done by simulating the operation of the scheme on the production of the same production program, including a large number of diverse orders. In the process of modeling the operation of each scheme, a schedule of processing orders from such a program is built and information about their performance is collected.

In the process of "model" verification of the work of all selected schemes of the modernized enterprise there is an opportunity to thoroughly check the work of each of the formed schemes. In addition, in the process of verification it is possible to collect the necessary information on the performance of schemes of different tasks, allowing to determine the different characteristics of schemes, to identify their advantages and disadvantages, and possibly to identify ways to strengthen the advantages and eliminate the disadvantages.

A very important and often successful way to enhance the advantages and eliminate the disadvantages of schemes is to replace unsuccessful fragments of the scheme successful fragments of other schemes, as well as the creation of a combined scheme on the basis of several schemes. Under the fragments of the scheme here is understood the composition of equipment of production units of the enterprise.

As the collected information can be specified the number of violations by the scheme of the time allocated for the execution of each task from the generated program, the maximum and average values of violations by the scheme of the time allocated for the execution of tasks and the total value of such violations. In addition to this information is collected information about the maximum, minimum and average load of the selected equipment of each scheme, about the cost of each task and maintenance of the selected equipment, about the idle time of conveyors waiting for components, etc.

On the basis of such a "model" check and analysis of the collected information on the performance of a significant number of tasks is assessed, tested and analyzed the performance, suitability and efficiency of the considered scheme of the modernized enterprise, to identify miscalculations and shortcomings in its work, to compare the work of different schemes, as well as the choice of the most suitable of them.

Often the comparison of the work of different versions suggests how and at the expense of what can expand and enhance the advantages of the created object and how to eliminate a significant number of its shortcomings.

One of the most important problems of choosing the most suitable version of the created object or product from the available alternatives is the problem that the values of some characteristics of some compared version are better than others, and others are worse. As a rule, it is very rare that there is a version that has all characteristics better than the others.

To solve selection problems in such cases, ideas and methods of decision making and multi-criteria optimization can be used [9].

In this case, the collected performance characteristics of different enterprise modernization schemes, from which the selection of the most appropriate scheme will be made, it is convenient to consider as criteria. The concession method [9, 10] is the most suitable for selecting the best scheme for the enterprise to be modernized. Let us briefly consider one version of this method for selecting the best scheme of the modernizing enterprise from $\tilde{L}$ schemes to be tested.

Let $\left(i = 1, \ldots, \tilde{L}\right)$ values of $\tilde{m}$ characteristics be known for each scheme i $\left(i = 1, \ldots, \tilde{L}\right)$ of the enterprise being modernized. These characteristics are collected in the circuit performance verification process described above and treated as criteria.

For each scheme, it is convenient to represent the compared characteristics of its performance in the form of vector components that define the values of the criteria in descending order of importance. The first component of this vector defines the value of the most important characteristic of the circuits. In such a vector $\vec{F}_i^T = |a_{1i}, a_{2i}, \ldots, a_{\tilde{m}i}|^T$ for the ith scheme $\left(i = 1, \ldots, \tilde{L}\right)$, which we will call the criteria vector, the jth component a_{ji} defines the jth $(j = 1, \ldots, \tilde{m})$ most important characteristic of the ith scheme under consideration.

For each criterion, i.e., component of this vector, the concession values d_j $(j = 1, \ldots, \tilde{m})$ are given.

If the value of the first characteristic is required to be smaller, the value of the concession d_1 is added to the minimum of a_{11}, a_{12}, $\ldots$, a_{1L}, i.e., to $\tilde{a}_1 = \min\{a_{11}, a_{12}, \ldots, a_{1L}\}$, and the interval $[\tilde{a}_1, \tilde{a}_1 + d_1]$ is defined.

If the value of the first characteristic is required to be larger, the value of the concession d_1 is subtracted from the value of $\bar{a}_1$, where $\bar{a}_1 = \max\{a_{11}, a_{12}, \ldots, a_{1l}\}$, and the interval $[\tilde{a}_1, \tilde{a}_1 - d_1]$ is defined.

Then those schemes whose first components of the criteria vector fall into the corresponding interval are considered equivalent and only these schemes are further compared. The remaining schemes, in which the first components of the criteria vector do not fall into the corresponding interval, are excluded from further consideration. This procedure is repeated for the following components of the remaining vectors $\vec{F}_i^T = |a_{2i}, a_{2i}, \ldots, a_{mi}|^T$ $\left(i = 1, \ldots, \tilde{L}\right)$ until there is one circuit left.

If from the generated schemes it is not possible to select a suitable scheme for the enterprise being modernized, then according to the procedure described above or by combining the already obtained schemes, or using the model (4.1)–(4.6) with other input data, new schemes of enterprise modernization are generated and the whole process of verification, correction and selection of schemes described above is repeated.

Using the methods of constructing "frame" schedules of components manufacturing and schedules of parts transportation between production units, it is possible to determine the necessary number of vehicles for delivery of parts from one unit of the enterprise to another to continue processing, as well as to determine the necessary volume of warehouses for inter-operational storage of components. However, unfortunately, the volume of the article does not allow us to even briefly describe the ideas and principles of creation and operation of these methods.

8. OTHER TASKS OF EQUIPMENT SELECTION FOR ENTERPRISES

Let's consider briefly the possibilities of using the proposed methods to solve other problems of equipment selection.

In the second paragraph of the work it was assumed that the modernization of the enterprise does not require the formation of new production units and the creation of new conveyors. However, these assumptions are not principal. The equipment selection models and work schedule construction methods proposed in the paper can be used in equipment selection without making 'these assumptions.

Moreover, with their help it is possible to solve the problems arising at the considered enterprises, which can be called "what happens if" problems. In these problems it is required to determine 'what will happen if' changes in the structure and activities of the enterprise occur or are introduced, and to evaluate the results of such changes.

Among such tasks we can single out the tasks of changing the structure of the enterprise, in which the creation of new or liquidation of inefficient production units, merger or division of existing ones, change in the number of conveyors for assembly of manufactured products at the enterprise are considered. In addition, such tasks include tasks related to the increase, reduction or changes in the composition of output products, tasks of determining and changing the funds allocated for modernization.

These tasks also include the tasks of redistribution of equipment between subdivisions, the tasks of replacement and replenishment of equipment of enterprise subdivisions.

To solve these problems using the proposed methods, the structure of the modernized enterprise is determined, including the selected number of production units and the number of conveyors with the purpose of products assembled on them. For newly mastered products are determined components that can not be processed on the equipment available at the enterprise. Types of equipment that will provide their necessary processing are selected, and these types are distributed among the existing or created production units of the enterprise.

Then, for components of newly developed products technological routes of their processing are formed taking into account the existing and purchased equipment in the enterprise's production units. Alternative technological processing routes are formed for components of manufactured products in case of problems with the existing route.

After that, with the help of model (4.1)–(4.6) the quantity of equipment of each type to be purchased for the corresponding production units of the enterprise is determined. Then for the obtained scheme of the enterprise according to the rules described above, the construction of the schedule of manufacturing of a given production task is made.

According to a similar scheme with minor changes with the help of the proposed methods can be made selection of equipment for newly established enterprises.

9. CONCLUSION

Joint use of the developed model of equipment selection and methods of construction of schedules of work of the modernized enterprise allows:

— to form and evaluate different schemes of modernization of the enterprise rather quickly on different sets of initial data;

— to present with the help of Gantt diagrams, tables and graphs “model” work of each subdivision of the formed scheme of modernization of the enterprise on performance of test tasks;

— reasonably assess the costs of equipment acquisition and the possibilities of the scheme of the modernized enterprise obtained at these costs;

— to make a thorough and comprehensive “model” verification of the performance of each selected scheme of modernization of the enterprise;

— collect information during the testing of selected schemes to analyze their performance and determine their characteristics;

— to identify in the process of inspections of selected schemes a significant number of miscalculations and errors in the selection of equipment for modernization of enterprises;

— on the basis of analysis, collected characteristics and operation of selected schemes to make a reasonable choice of the most suitable for modernization of the enterprise.

The costs of time to conduct a comprehensive verification of the performance of the selected schemes of modernization of enterprises with the help of the proposed models and methods are not very large.

However, the cost of time and especially funds for the elimination of errors and miscalculations, as well as lost profits in the process of unsuccessfully modernized enterprises is many times more expensive

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