DIGITALIZATION OF ECONOMIC SYSTEMS
ЦИФРОВІЗАЦІЯ ЕКОНОМІЧНИХ СИСТЕМ

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SYSTEM OF MODELS FOR AUTOMATED PLANNING, DESIGN AND MANAGEMENT OF DISCRETE PRODUCTION

The functioning of an industrial enterprise of discrete production is considered as a set of interconnected production and design processes and managing them. Computer modeling of processes is used to review options for enterprise activity plans and choose the best one for its implementation. Variants of model structures and corresponding modeling algorithms are obtained as a result of generalization of enterprise processes. The parameters of the models (list of works, standards of consumption time, materials, etc.) are established on the basis of the experience of performing the relevant activity for the industry and are adjusted based on the conditions of the given enterprise and the generalization of its specific experience.

Keywords: *model of production processes, aggregation, decomposition, calendar plan, inventory management, system optimization.*

Introduction

In addition to production processes, the planning of which takes place using models of the theory of schedules and inventory management, the enterprise management system includes the processes of designing, as well as the processes of analyzing and correcting models, which are used both for planning and for designing.

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Aggregated production models represent processes in a simplified form, which allows planning for long periods of time, taking into account only significant circumstances that can affect current decisions and also divide the planning task into several weakly dependent detailed ones of smaller dimensions. Detailed models are used for close-term planning and may have a specific structure. Constructed detailed plans require coordination among them and can be used as an initial state for the prolongation of aggregated plans.

Aggregated models of constructions and technological processes are used in design tasks with a similar goal — decomposition of a complex project into subsystems. In addition, the product manufacturing project in an aggregated form allows you to start planning its production even before the detailed project is completed. This shortens the time from the beginning of the project development to the production of the product.

The purpose of the article is to analyze and develop a system of models and algorithms, that can be used to automate planning, design and management processes at all stages and levels of production management. The ultimate goal is to create an integrated computer control system that can function without the use of paper media and with the maximum possible release of the manager, designer, technologist, as well as the equipment operator from routine functions.

1. Automation of Production Management — Current State

Modern systems of automated production management have gone from simple MRP, MRPII, which plan only material resources, to more sophisticated ERP and ERPII, which are focused on quick adaptation of the entire management system to changes in internal and external conditions. Next in this section we consider their accepted classification [1].

1. Material Requirement Planning (MRP) proceeds from the plan for the release of commercial products and the description of technological processes for them.

2. Manufacturing Resource Planning (MRPII) complements MRP by planning the need for equipment, labor, energy, etc. Disadvantages of MRP and MRPII are the difficulty of restructuring plans taking into account new circumstances that emerge during the execution of plans within the enterprise and among its partners.

3. Enterprise Resource Planning (ERP) complements MRPII in terms of prompt adjustment of plans, as well as creation of an infrastructure for electronic data exchange with suppliers and consumers.

4. Customer Synchronized Resource Planning (CSRP) complements ERP with the possibility of participation and influence of the consumer on the quality of goods through complaints, wishes and ordering the necessary, and also provides warranty and post-warranty service.

5. Enterprise Resource and Relationship Processing (ERPII) complements CSRP with expanded opportunities for cooperation with stakeholders: industry project organizations and competitors (mutually beneficial exchange of experience and its generalization); state bodies (labor, tax legislation); public organizations (waste management, ecology, etc.).

Companies that implement these automated systems have ready-made software modules and subsystems that are combined depending on the needs of the enterprise. The process of implementing automated systems begins with the developer's study of the company's processes and coordination of the developer's positions with the company's staff. Selected modules of the future automated system are supplemented, corrected, tested on control examples and filled with data of a specific enterprise.

Next, models and algorithms that can be used to design software modules of future automated systems are considered.

2. Models of the Theory of Schedules and Inventory Management

2.1. The Basic Structure of the Production Process Model. The model is a simplified description of the subject area in the form of a list of specific objects and processes and the values of their parameters (properties and relations). The structure of the model describes only the classes of objects and processes, and also indicates their parameters without specifying values; certain relationships are established between parameter values. Building a model based on a certain structure consists in defining a list of objects/processes defined by the structure and some of their parameters; other parameters remain undefined. The modeling algorithm provides for the determination of unspecified parameters based on the relationships specified by the structure. If these ratios are not sufficient to unambiguously determine the values of the parameters, then it is necessary to set an evaluation criterion for each possible (compatible with the given ratios) option. Further, these concepts will be used to describe the structure of the ***p****roduction* ***p****rocess* ***m****odel* (PPM).

We will start from the concepts used in machine and instrument construction; other types of discrete production are to a large extent similar and simpler. For PPM elements, we will introduce abbreviations and indicate them in italics. The main element of PPM is the model of production of ***g****oods and provision of* ***s****ervices* (*G&S*). As the basic level of the production model of the *G&S*, we will accept the ***d****esign and* ***t****echnological* ***s****pecification* (*DTS*), which is the result of the design of the *G&S* and the design of its manufacturing technology. Components of the *DTS* are ***p****arts and* ***a****ssemblies* (*PA*) with the relationship "*PAx* is included in *PAy*". For each *PA*, the manufacturing method is specified in the form of ***t****echnological* ***p****rocess* (*TP*) — sequence of ***t****echnological* ***o****perations* (*TO*); *G&S* is the final *PA* or their set. Each *TO* consume ***n****on-renewable* ***r****esources* (*NR*): materials, blanks, components, etc. and takes the time of the operator and the renewable resources used by him: equipment, tools, equipping, etc., which are not completely consumed during one *TO*, but may require periodic: repair, adjustment, sharpening, etc. The operator (one or several workers) and the renewable resources assigned to him will be called the ***p****er****f****ormer* (*PF*). The maintenance process is determined during the design of the *TP* in a language that is understandable for an operator with the appropriate qualification. The same *TP* is used for the production of many copies of *PA*, and therefore *G&S*.

PPM, in addition to the production model of the *G&S*, includes: a ***time scale*** (*TS*) with a certain discreteness of measurements, which continues as needed; available *PF*s, with possible intervals of inoperability; the stock and receipts of *NR* tied to the *TS*, which can be used during the production of *TO*.

Below are the simplifications and clarifications of the concept of *TO*, adopted by us — the real process may differ slightly.

1. *TO* lasts a certain continuous time and ends with a certain change in the *PA*. *TO*s are related by the "previous-next" relationship, if the result of the previous *TO* is used as the *NR* for the next one. *NR*s are consumed at the beginning of the performing *TO* and allow accumulation for the next use, which allows you to match the rate of their receipt with the rate of consumption.

2. The *PF* is usually capable of performing several different *TOs* over different *PA*s. Identical processing of several identical *PAs* in a row at one *PF* is performed with minimal time spent on reconfiguration — switching to processing other *PAs* requires more time, which depends on the previous and subsequent *TO*. Transfer of *PA*s between *PF*s generally occurs in batches of several pieces. Increasing the batch size reduces equipment set-up costs as well as transportation costs, but at the same time waiting for readiness of the entire *PAs* batch to transfer between *PFs* has a negative effect on the level of ***work in progress*** (WIP) and the duration of *G&S* production. Therefore, the size of the *PAs* batch should be determined on the basis of a compromise between the specified factors.

3. In most cases, the *PF* is fully loaded by one *TO* over the *PAs* batch during its entire execution period. But there are *PF*s that can simultaneously perform *TO* over several, possibly different, *PAs*. Examples are thermal and galvanic treatment, cutting, transportation, etc. Simultaneous processing of a certain set of *PAs* for the given examples is more efficient than individually. In order to take into account the above features of the *PF*, the planning algorithm should provide for the accumulation of a sufficient number of *TO*, before starting on this *PF* with the same performance parameters.

PPM can be adapted to describe a wide class of production processes, particularly when: the position of not only the equipment, but also the *PA* (houses, airplanes on the runways, etc.) can be fixed — the operator and the processing tool (*PF*) move between the elements of the processing object (*PA*); one operator serves several units of equipment — considered as several *PFs*, etc.

Practically all types of enterprises have, in addition to the main units, engaged in direct production of *G&S*s, auxiliary units (create conditions for others) similar to those that are the main ones in mechanical engineering: equipment repair; production of specific equipment, etc. Similar models are used for their planning, but since their processes are weakly dependent and somewhat specific, the planning of the processes of auxiliary units takes place separately with subsequent coordination between themselves and with the plans of the main units.

2.2. *Basic Algorithm of Calendar Production Planning.* Further, in the text of this and the following paragraphs, the algorithms are described schematically — their transformation into programs requires additions and specification.

The development of technologies takes place in the direction of both the complication of the *TO*s themselves and the unification of several *TOs* within the

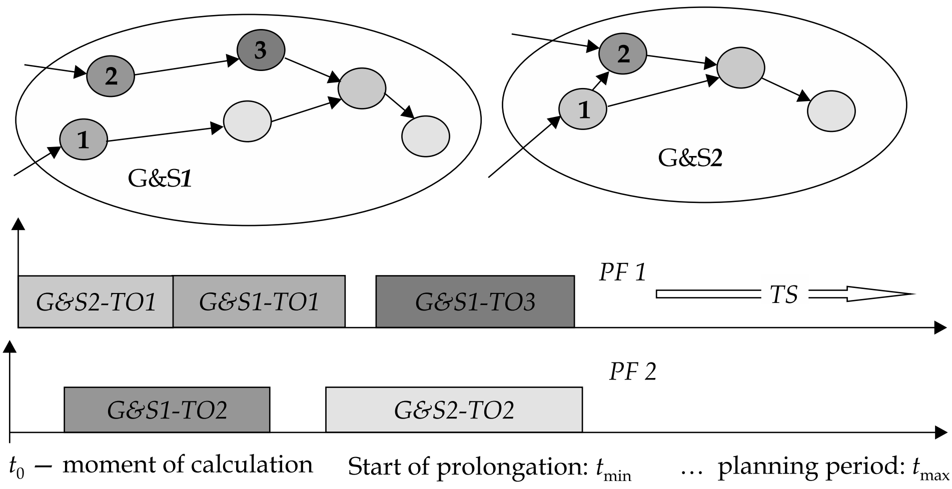

Fig. 1. Simplified PPM-B

framework of comprehensive one. The management of the *TO* execution process is increasingly automated — the operator is removed from the influence on the object of processing and is engaged in the analysis and influence on increasingly general parameters of the *TO* execution. But the principle of structuring production at the enterprise on *G&S*, which are performed according to the pre-designed *DTS*, consisting of a set of interconnected *TO*s, remains unchanged. Therefore, our further considerations, based on the indicated production process presented, will not lose their relevance. Described in item 2.1 PPM will be accepted as the basic (PPM-B); it will be used:

— to explain the basic principles of production planning — in this section;

— for building aggregated PPMs — in section 3.

The simplified PPM-B is shown in Figure 1. The figure does not show *PA*s, which are usually present in the information base of the *DTS* description; as a result, the structure of the model became simpler without losing essential features.

In Figure 1, from above: *G&S* production model in the form of a DTS-graph: graph vertices — *TO*; arcs — the relationship between *TO*: the result of the previous one (which is at the beginning of the arc) is used as a subject of processing for the next one (which is at the end of the arc); arcs from the outside of the *DTS* graph indicate that the *TO* requires other *NRs* in addition to the results of previous *TOs*). From below: distribution of *TO* on *TS* and on *PF*.

In addition to those depicted in Fig. 1, PPM-B also contains other parameters:

• for *PF*, periods of forced downtime associated with equipment repairs and operator absence are indicated on *TS*;

• for *TO* specify the parameters;

— for "previous-next" relations between *TOs*, indicate the number of results of the previous *TO*, which is used for the next one;

— *PF*s that can perform it and the duration of set-up, depending on the previous *TO*;

— specific equipping and *NR*;

— norm of time for execution, etc.

Thus, PPM-B describes the possible options for the production of *G&S* — it leaves the executors and terms of execution of the *TOs* undefined. The application of the structure described above for modeling the production process is also known as models of ***c**alendar **p**lanning* (CP) [2—5]. Next, we will present one of the variants of the CP algorithm, which simulates the variants of the production process and looks for the best among them according to the given criterion.

Planning is carried out periodically, with a period τ; we extend (prolongate) the plan as the previously planned *TOs* are fulfilled so that the period of existence of the current plan exceeds the minimum permissible value of $t_{\min}$. The time until which the plan is extended — $t_{\max}$ is distant from $t_{\min}$ by the period — τ, for which calculations are made ($t_{\max} = t_{\min} + \tau$). In case of violation of the current plan, it may be necessary to make an extraordinary adjustment, which can be carried out:

— by using the A1 prolongation algorithm by restructuring the previously prepared plan from the moment the violation was detected;

— by a special algorithm, similar to the usual prolongation, but with a possible partial exemption of the *PF* from planned *TO*, when they turn out to be less priority.

***Algorithm* A1** (prolongation of CP):

1. Enter data for calculations for an additional period up to the moment $t_{\max}$:

— readiness times and *DTS* parameters of those *G&S* that are specified by the higher-level plan up to the moment $t_{\max}$. There should be no closed paths in the *DTS* graph; this is performed during the design and is necessary for the correct operation of this algorithm — none of the *TOs* located on a closed path will be able to get to the "front" of those for which the previous ones have already been planned;

— for *PF*, the time intervals of their possible use are determined;

— restrictions on the terms of possible use are determined for the specific equipping;

— for *NR*, supply plans are determined in accordance with concluded contracts. Some *NR* and equipping are always available (supplied upon request to the Store) and are not taken into account when planning (item 2.4).

2. Based on the results of preliminary planning, the following data are prepared:

— scheduled *TO*s over *PA* batches. In the absence of pre-planning data, the deadlines for the completion of currently executed *TOs*, which are received from their executors, will be sufficient;

— unplanned *TOs* of all *G&S*s that are present in the planned task and all previous ones for which are already planned or executed — "front" of unplanned *TOs* that are ready to be inserted into the plan;

— terms of release of *PFs* from execution of previously planned *TOs*. In the absence of preliminary planning data, the *PFs* release term is obtained from its operator.

3. A *PF* with a minimum release term and the possibility of loading a new *TO* (taking into account the possible incapacity of the *PF*) is selected. A *TO* is selected from the "front", which is a priority for execution on the selected *PF*, and we put it in the plan: its start and end terms are determined.

4. The "front" is supplemented by those *TOs* that follow the *TO* inserted in the previous step 3 in the plan, and for which there are no other previous *TOs* not placed in the plan.

5. Plan construction completion check: are *TOs* present in the "front"?

— if so, then proceed to step 3;

— if the *TO* "front" is empty, then the work on prolongation the plan is completed for *TOs* from the *G&S*s, the deadlines of which are within $t_{\max}$, executors and execution terms are defined.

***End of* A1**

The following are comments and additions to the A1 algorithm:

1. Preparation of *PF* work schedules is a preliminary step for CP. Changes in the composition of the *PF* (acquisition/decommissioning of equipment and recruitment/dismissal of personnel) are planned in advance at higher levels of management. At the CP level, this possibility is minimal; only equipment repairs and staff absences (vacation, training, etc.) are taken into account. Of course, the operator is attached to certain equipment and together they form a *PF*. If a situation arises when it is impossible to comply with this (one of the *PF* components is missing), then the operator's ability to work on different equipment and the availability of backup equipment are used. The formation of *PF* work schedules is not a complex task — the unit planner using equipment repair plans, in dialog mode with the computer, will allocate workers to *PF*, agreeing on situations that go beyond the usual order of distribution. Such an agreement requires interaction directly with the employee who is offered a deviation from the usual work order for a certain reward.

2. When determining the start time of the *TO,* selected in step 3, one should take into account not only the completion time of all previous *TOs*, but also the following:

— availability at this moment of all other *NR*s that are consumed by *TO* — those that will be used are removed from the available *NR*s;

— it is necessary to ensure the availability of *PF* during the *TO* execution period, as well as take into account the time for its adjustment;

— the execution of some *TOs* may require equipping, the deadline for which must be agreed with the relevant subsidiary unit.

3. Obviously, according to algorithm A1, it is possible to build any admissible variant of the plan — each new variant can be generated by at least one decision in step 3, which will differ from what was adopted for other variants. The task of finding the optimal relative to the given criterion of the CP option for the general case (without features that could be used to reduce the selection of options) has exponential complexity depending on the dimensionality of the input data — the number of *TO*s that need to be planned and the number of *PF*s. For the conditions of real production, when the dimensionality of CP tasks is measured in thousands, the construction of an optimal plan becomes unattainable even for modern computing capacities. To solve the problems of large-scale CP, the theory of schedules offers heuristic methods that do not ensure the optimality of the plan, but only bring it closer [5] — algorithm A1 is a scheme for the application of such methods. Algorithm A1 makes it possible to sort out compact variants of CP, when each *TO* is inserted into the plan compactly — without obvious loss of time, but also does not prohibit providing unused time intervals of *PF* work in the plan, which can be used as a reserve when adjusting the plan due to deviations. The quality of the variant built by the A1 algorithm depends on step 3, namely, on the selection of the *TO* from the "front", which is supposed to be carried out according to a certain algorithm. In particular, for the implementation of step 3, a limited (by the number of steps) "branches and bounds" scheme can be applied.

In addition to the specified heuristic search, the simplification of CP tasks can be achieved in several other ways:

— allocation of *PA* from *DTS*, the task and plan for the manufacture of which can be determined separately, based on the inventory management model (item 2.4) and thus reduce the dimensions of *DTS*;

— organization of flow production lines with sequentially placed *PFs*, which can be loaded by a sequence of *TO* (***F****lexible* ***P****roduction* ***L****ines* — FPL). The list of planning objects is shortened in the CP model with FPL, and the planning model itself is slightly modified (item 2.5);

— aggregation and generalization (described in section 3), which allow you to break down the general task of CP into sub-tasks of a smaller dimension, followed by their coordination. Further, in item 2.3 describes the corresponding coordination scheme.

2.3. *Coordination Scheme of Cooperating Units.* Decomposition of a complex process into several weakly dependent ones allows reducing the dimensionality of CP tasks. The higher level of the plan, built using the aggregated model (section 3), defines a rough plan of interaction between units, which in general can be improved due to the coordination of their detailed plans. Next, a scheme of such coordination is proposed.

A rough interaction plan is used as a planning task for detailed planning of each unit. To be able to "shake" the rough plans of interaction, each of the units can use an algorithm similar to A1, but using the principle of system optimization [6]. We turn each of the restrictions in the CP model for detailed planning of the unit, established by the rough plan, into a criterion: we allow its violation and set fines, proportional to the deviation with a coefficient that can be adjusted, based on estimates of real losses in the neighbor. The general quality criterion of each detailed plan is calculated as the sum of fines for violation of each of the restrictions. The option with the minimum total fine is considered the best. The following are possible as external criteria (formed from restrictions on interaction with neighbors):

— exceeding the *G&S* execution terms set by the rough plan. For units as a *G&S*, we accept the results of their activities, which are used by other units or transferred outside the enterprise;

— exceeding the need for specific materials and components, the delivery plans of which are determined by the rough plan. There is no need to plan and coordinate widely used materials and components supplied through the Store — they are planned according to the stock level (see item 2.4);

— violation of equipment repair schedules, established in accordance with planned and preventive repairs, which are the basis for subsequent agreements between the repair unit and the unit using the equipment. Emergency repair of equipment is coordinated with the involvement of the Dispatcher, who determines the degree of responsibility of the equipment user and the repairer to determine fines;

— use of equipping in violation of agreed terms.

In addition to the specified external criteria, in the CP model we will allow internal efficiency losses:

— overtime work of *PF* (in non-working shifts) and its downtime while waiting for work;

— inconsistencies in operator qualifications and *TO* complexity;

— loss of time for setting up the equipment, which depends on the order of starting the *TO*.

Fines for the specified losses of efficiency are usually accepted as certain norms for the entire enterprise and do not require frequent adjustments. The specified violations operate only within certain limits, according to which they are considered inadmissible.

The task of the unit, defined by the rough plan and the payment for its execution, is agreed by the higher-level planner with each unit: the parties agree that the plan is feasible and the executor deserves payment depending on the intensity, which is measured by reserves of time and resources. The unit planner can calculate a detailed plan with external restrictions (maximum fines for violating external criteria), determine internal losses and thus clarify the possibility of meeting the conditions of the rough plan and payment for its implementation.

After coordination with the higher-level planner, the planner of each unit has the opportunity to increase the income of his unit by reducing internal losses and providing better conditions for adjacent units. For this, he evaluates the capabilities of his partner and calculates his plan with the possibilities of violating external criteria, expecting to reduce his internal costs. The result of such a calculation is the appearance in the detailed plan of one's unit of other conditions for the neighbor, compared to the rough or previously agreed plan of interaction. Under stricter conditions for the spouse, our planner offers compensation that he pays from his fund (but not more than the savings of his fund due to the reduction of internal costs). Tougher conditions will be accepted by the spouse if they increase his internal losses no more than the proposed compensation. That is, agreement will occur if each partner benefits.

For mitigating conditions, which may also arise as a result of detailed planning — our planner can receive compensation if these mitigating conditions contribute to the reduction of the spouse's losses.

The process of reconciliation and recalculation can be repeated – each iteration leads to a decrease in total costs for a pair of interacting units, which means that it improves the plan and the "trajectory of movement" of the entire production.

In reality, a situation may arise when the unit cannot fulfill the position of the rough plan. The spouse, knowing this, may demand compensation that is excessive compared to his own losses. In order to prevent unfair benefits for one unit and losses for another, it is necessary to provide a way to resolve this kind of disputes. A higher-level Dispatcher interested in the overall efficiency of interacting units and able to understand their processes can be a judge in their disputes.

It is quite plausible to claim that the iterative process of coordination brings the overall plan of the interacting units closer to a degree of efficiency that could be achieved by solving the CP problem for all units together using the algorithm used for detailed planning.

New conditions for algorithm A1 lead to its complication: it is necessary to choose the values of constraint violations. At the same time, the need for frequent recalculation of plans based on the results of negotiations with partners requires its quick implementation. The methods of simplifying CP tasks, mentioned at the end of the previous item 2.2 become more relevant.

2.4. *Inventory Management Models.* According to the inventory management model [7, 8], it is expedient to plan such *PAs* that: will be used for a long period of time; their reserves do not increase the WIP too much, and the stock can be quickly replenished — we will call them blanks. The blanks are concentrated in the Store and can be quickly delivered to the consumer. Reserve quantities of blanks are maintained by ordering them from an external supplier or an internal manufacturer at the moment when their level drops to a certain value.

According to the inventory management model, the following are planned:

— supply of external resources of materials, components, etc., which are available on the market;

— specific *PAs* of own production, which are widely used for a long period of time, have a short production period, which means that they can be noticed in the *DTS* as those that are not planned by the general scheme;

— tool, which is partially repaired at the enterprise and requires replenishment after final wear;

— equipping manufactured at the enterprise, which is stored in the Store for reuse.

The production and repair of these resources at the enterprise are usually carried out by auxiliary units that plan their work based on orders received from the Store. The capacities of these supporting units are maintained based on their loading forecasts. The intensity of their planned tasks is evaluated and compensated by the higher-level Dispatcher, who takes part in determining the required capacity.

The Store, in turn, receives orders from units — consumers of the specified resources; the regulation establishes the deadline for order fulfillment. The consuming unit may not take into account the resource restrictions that are supplied from the Store when planning — it is enough to order the necessary in advance. A delay in the execution of an order is considered as a deviation from the normal course of production and is compensated to the customer by a fine imposed on the Store.

2.5. *Flexible Production Line (FPL) & Flexible Production System (FPS).* When the need for certain *PAs*, close in technology, increases to the level that will allow to fully load several sequentially placed *PF*s, then it is worth thinking about the organization of a FPL — serially placed equipment with a fixed order of processing a certain set of *PAs* and a close time to complete each *TO* for a given type of *PA*. The advantages are a reduction in the time required for the processing of *PAs* and in transportation costs. In addition, the dimensionality of the CP problem is reduced: several *TO*s over the *PA* batches are considered as one and several *PFs* are considered as one (Fig. 2).

It is possible to process several batches of different *PA*s by one FPL at the same time: batch *PA2* is started before the processing of the previous batch *PA1* is completed.

Before launching a batch of *PA*s of a certain type, the FPL is configured to process *PA*s according to their own technology. If the rate of processing of the next

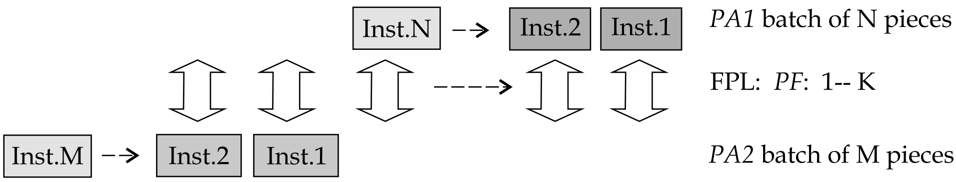

Fig. 2. Loading FPL by batches of PA

batch of *PAs* is faster than the rate of the previous one, then planning should allow for a delay before starting the next batch. The delay is calculated so that on the last *PF*, the processing of the last instance of the previous batch is completed before the start of the processing of the first instance of the next batch. Thus, the *PA* batch planning model changes slightly (in terms of determining the start of the next *PA* batch), but the sequence of steps of the A1 algorithm, in the case of its application to productions where FPL is used, remains. If the nomenclature of those *PAs* that fully load a certain FPL is within 3–5, then its planning can be carried out separately, similar to the planning of a separate unit. At the same time, simple calculations are performed to determine the order of launching several batches of *PAs*, with subsequent coordination with the plans for supplying blanks to the FPL and using its results.

The design of FPL is the selection of *PAs* with a similar *TP* and redistribution/modification of *TOs* between *PFs* so as to ensure the same sequence and duration of their execution. It is convenient to carry out the relevant calculations and search for the necessary *PAs* in dialogue with the computer [9].

FPL in many respects is similar to flow (continuous) production, which can be an element of discrete production: certain resources are supplied to the flow input in portions (discretely) and are also discharged in portions. The task of planning discrete production, which contains such "interspersions" of flow lines, is similar to planning with interspersions of FPL. The design of flow production is specific to each subject area and is not considered by us.

During the 4th industrial revolution, which began in 2011, they seek to automate as many operator functions as possible, including setting up equipment for maintenance, control over the processing process, transferring parts between *PF*-machines, etc. Due to the automation of only FPL, it is impossible to achieve the required flexibility of the production process — various routes of passing *PAs* between *PFs* are required, which means synchronization of operation of *PF*s and transportation of both *PA* and the tool for debugging *PF* is required. Appropriate approaches to the management of *PFs*-machines are developed within the framework of the theory of Flexible Manufacturing Systems (FMS).The corresponding models of calendar planning practically do not change in structure, but stricter requirements are imposed on the accuracy and speed of planning: we have more accurate, complete and operational information from equipment sensors and we need a quick and high-quality reaction to changes in the state of production — expensive equipment should not be idle and needlessly reconfigured. On the other hand, a significant reduction in the number of operators and service personnel allows to organize round-the-clock work of the enterprise without days off. This imposes additional requirements on the planning task — production processes do not stop, which means that a quick reaction to changes in the production state is required. Several levels of planning with the possibility of coordinating plans between units-automat and between planning levels, discussed in the following section 3, can be applied not only to conventional enterprises, but also to automatic ones. Approaches to planning in FMS with the use of machine intelligence are developing in the areas of Cyber Physical Production Systems (CPPS), Internet of Things (IoT), Digital Twing (DT), Artificial Intelligence (AI), Advanced Robotics [3, 9, 10], which are aimed at providing properties to automata to communicate and make intelligent decisions in real time.

3. Aggregation and Decomposition of Calendar Planning Models

Aggregation and decomposition is the most versatile and powerful approach for reducing the dimensionality of CP problems. Aggregated models are used for long-term planning with subsequent detailing (decomposition) of aggregated plans for nearer periods. Detailed plans are not needed for the long term: for relatively long periods of time, sufficient information is available on the aggregated resource requirements for the production of *G&S*, the quantity and quality of which may be somewhat uncertain.

Aggregation of PPM-B consists in combining its components (item 2.1) into an interconnected system of their aggregates:

— ***a**ggregated* ***TO*** (*ATO*) — a certain set of *TOs* belonging to the same *G&S*;

— ***a**ggregated* ***TP*** (*ATP*) — *TP* of production of a *G&S*, which consists of *ATO*, which do not intersect and together make up a *DTS* of this *G&S*;

— ***u**nit of* ***e**nterprises* (*UE*) — the set of *PFs* that are at the disposal of the unit's staff (the *PF* cannot be part of different *UE*s). It is accepted that only one *UE* can be the executor of the *ATO*: the *ATO* cannot be partially executed by different *UE*s and, unlike the *TO*, has no option for execution by different *UE*s. This simplifies the structure of the PPM and at the same time does not impose significant restrictions on the determination of the performer of the *TOs* that are part of the *ATO* — all *PFs* that can perform them we will try to concentrate in the corresponding *UE*. The integration of *PF* in the *UE* are designed in dialogue mode, based on the following criteria: *a*) similarities in the professions of *PF* operators (it is convenient to transfer experience and quickly find a replacement for the operator); *b*) similarities of equipment concentrated nearby (easy to maintain and replace); *c*) possibilities of sequential processing of *PA* in one *UE* (to reduce transfers of processing items between *UE*s); *d*) if *TO* can be performed using several different *PFs*, it is desirable to concentrate all of them in one *UE*;

— ***a**ggregated* ***TS*** (*ATS*) — built by consolidating time measurement units, which is used in PPM-B;

— ***a**ggregates of* ***PF*** (*APF*) — each *UE* has its own list and composition of *APF* groups that do not overlap with each other and, to a certain extent, interchangeable. For *APF*, the time fund tied to *ATS* is determined based on the expectations of: acquisition, write-off and repair of equipment; admission, dismissal and absence of employees. For each *ATO*, the *APF* consumption rate is determined as a result of the aggregation of the corresponding *PF* types that use the *TO*s included in the *ATO*.

— ***a**ggregates* ***NR*** (*ANR*) — do not overlap and to some extent are interchangeable so that it is possible to specify them with the necessary *NR*s during detailed planning for the near future. Stocks and receipts of *ANR* are linked to *ATS*. For each *ATO*, the rate of *ANR* consumption is determined as a result of the aggregation of the corresponding types of *NR*s that use the *TOs* included in the *ATO*;

— ***a**ggregated* ***G&S*** (*AG&S*) — group of *G&S*, which we plan with the help of the same *ATP*. As a result of the generalizations, different *G&S* (even those whose detailed technology is still unknown) can be planned with the help of the same *ATP* — their correct specification will be carried out at the stage of decomposition of the plan built on their basis. The adjustment of *ATO* parameters, depending on the time of their execution (and therefore the version of the *DTS* used) is carried out expertly by *G&S* designers.

The list and composition of *UE*s and their *APF*s, *ANR*s and *ATSs* for each aggregation level are fairly stable. For their initial creation and subsequent correction, the planner of the corresponding level receives information about similar *PF*s / *NR*s and in the dialogue mode makes appropriate decisions.

The following decisions about the PPM structure determine the logical complexity of algorithms for solving planning problems. Models with a simpler structure and a greater degree of aggregation can be used for planning for more distant periods and for larger *UE*s. Their purpose: to coordinate rough long-term plans with related enterprises; weed out unpromising variants of detailed plans; divide the task of detailed planning into weakly dependent subtasks.

Next, we will consider variants of PPM structures, which differ in established restrictions on the mutual position of *ATOs* belonging to the same *ATP* in time; other PPM components: *UE*/*APF, ANR, ATS* have a similar structure and can only have a different degree of aggregation, which corresponds to the aggregation of resources used by the *ATO*):

— PPM for volume-calendar planning (PPM-VC) uses *ATP-VC*;

— PPM for volume planning (PPM-V) uses *ATP-V*.

To simplify the designations, we will omit the "-VC" suffix for PPM-VC components (for example, A*G&S* instead of *AG&S-VC*); all PPM components for volume planning will be marked with the addition "*-V*" suffix (e.g. *AG&S-V*).

3.1. ***Aggregated Technological Process for Volume-Calendar Planning.*** The structure of the *ATP* model is similar to the simplified *DTS* model (item 2.2): for A*G&S*, we create a separate *ATP* consisting of *ATOs*, which are connected by the relationship "previous-next" (we will mark it with an oriented arc in the *ATO* graph) so that the previous one must be fully executed (all its *TO* components are completed) before the execution of the next one begins (starts at least one *TO* from the composition of the next one). At the same time, we do not impose other restrictions on the mutual position of *ATO* in time — we will determine the terms of execution of *ATO* when building a ***v**olume-**c**alendar* ***p**lan* (VCP) using an algorithm similar to A1. For an *ATO*, the *UE* that performs it and the corresponding *APF* and *ANR* vectors, which are used by the *ATO* during its execution, are defined. The *ATO* execution time cannot be less than the set minimum, but can be more. With the structure of the *ATP* model, it is possible to set various restrictions on the use of *APF* and *ANR* during the *ATO* execution period, for example:

— certain components of the *ANR* must be submitted in a certain minimum time before the end of the *ATO*;

— for certain components of the *APF*, a limit is set on the amount of the time fund consumed by them, depending on the time until the end of the *ATO*.

The *ATP* construction algorithm aggregates *TOs* running in the same *UE* and with a close advance in relation to the readiness of *AG&S*. The presence of such *TOs* in one *ATO* contributes to their execution without undue delay, which means the reduction of WIP. The relationship "previous-next" for a pair of *ATOs* is determined by their composition — the presence of *TOs* in the composition of different *ATOs*, which are in this relationship in the *DTS* model. When building an *ATP*, it is necessary to ensure that there are no closed paths between *ATOs*, laid on the "previous-next" routed connections — such *ATOs* block each other when determining the possibility of launching them for execution. We calculate the need for resources for *ATO* as the sum of the needs of *TO* components and aggregate (roughen) both by time (using *ATS*) and by *APF* and *ANR* groups. The parameters of the duration of *ATO* and restrictions on the periods of consumption of *APF* and *ANR* are determined based on the composition of *ATO*.

When describing the algorithm, we will use the notation:

— P(*X*) — parameter P of object *X*;

— M{*X*}, or {*X*}: set M of objects *X*, or set of objects *X*.

***Algorithm* A2** (building *ATP*):

1. Preparation of input data and supporting structures:

• {*UE* →{*APF* →{*PF*}}} — the list of *UE*s, its composition of *APF* and the composition of each component of the *APF* vector;

• {*ANR* →{*NR*}} — the list of *ANR*s and the composition of each component of the *ANR* vector;

• *DTS* of the *AG&S* for which the *ATP* is intended to be built. *AG&S* may indicate a *PA*s kit. Parameters must be defined for each *TO*, included in the *DTS*:

— UE(*TO*) — the unit performing the *TO*;

— PF(*TO*) — PF ∈ UE(*TO*), which usually performs *TO* of this type;

— D(*TO*) — duration of *TO* execution (on average);

— NR(*TO*) — non-renewable resources used in the execution of *TO*;

— R(*TO*→{*TO*}) — links to subsequent *TOs* for this *TO*; in the general case, there may be several of them with different occurrences;

• In the process of calculations will be determined:

— A(*TO*) — minimum advance of readiness in relation to *G&S* readiness, taking into account the execution of the following *TO*s as part of already formed *ATOs*;

— L(*TO*→{*ATO*}) — references to *ATOs* that include *TOs* following this one; in the general case, there may be several of them with different occurrences;

— F{*TO*} — "front" *TO*s, which are previous to incomplete *ATO*∈ N{*ATO*} (see below);

— K{*TO*} — the set of *TOs* selected from the F{*TO*} that are prior to the *ATO* selected from the set of incomplete and included to the set of completed *ATO*s in step 5;

• Parameters are defined for each *ATO* that will be created:

— Id(*ATO*) — identifier *ATO*;

— UE(*ATO*) — executive *UE* of the *ATO*;

— A(*ATO*) — advance of *ATO* readiness in relation to *G&S* readiness;

— D(*ATO*) — the minimum duration of *ATO*, defined as the maximum duration of sequentially executed TOs (chains) in the composition *ATO*;

— St(*ATO*) = A(*ATO*)+ D(*ATO*);

— R(*ATO*→{*ATO*}) — links to the following *ATOs* (arcs in the *ATO* graph);

• sets of *ATO*, initially empty:

— N{*ATO*} — incomplete *ATOs*, their composition is expected to be supplemented and parameters to be determined;

— Z{*ATO*} — filled *ATO* with defined composition and parameters.

2. Creating an initial K{*TO*}:

The final *TO* of *PA*, representing the selected *AG&S* (multiple *TO* if *AG&S* is a *PAs* set) is included to K{*TO*}. The value of parameter A(for all *TO* belonging to the set K{*TO*}) set to zero: A(*TO: TO*∈ K{*TO*}) = 0. We leave the list of subsequent *ATOs* for each *TO*∈ K{*TO*} empty: L(*TO* →{*ATO*}: *TO*∈ K{*TO*}) = ∅.

3. Replenishment of N{*ATO*}:

For each TO*∈ K{*TO*} we find *ATO** from the N{*ATO*}, to which it can be attached by signs: is performed in the same *UE* and has close values A(*TO**) ≈ A(*ATO**). Then we adjust the value A(*ATO**) for the found *ATO**: A(*ATO**) = (the minimum value of A(*TO*) for all *TOs* that were included in *ATO** at the step 3). To the list of the following for *ATO**, we include the following *ATOs* for *TO**: R(*ATO** →{*ATO*}) = R(*ATO** →{*ATO*}) ∪ R(*TO** → {*ATO*}).

If no such *ATO* was found for the selected *TO**, then we create a new *ATO** in the set N{*ATO*}. We set its parameters in accordance with *TO**, on the basis of which it is created: Id(*ATO**) = sequence number; UE(*ATO**) = UE(*TO**); A(*ATO**) = *A*(*TO**).

4. Adjustment of *ATOs* characteristics from the set N{*ATO*}:

For each *ATO** from N{*ATO*}, we review *TO*∈ K{*TO*}, which were included in its on the previous step. For each *TO*∈ K{*TO*} we go through all the previous *TO* (chain of *TO* in reverse order of their production, possibly with ramifications), which are made in the same unit, until we come across *TO*, which are produced in another unit. The set F{*TO*} is supplemented by these last *TOs*; and for these, the *ATO** is specified as follows — R(*TO*→{*ATO*}) is supplemented by a reference to the *ATO** with the corresponding occurrence.

For all *TOs* that have been reviewed for a given *ATO** together with their predecessors (excluding those included in F{*TO*}), we include them in the given *ATO** and adjust the *ATO** characteristics accordingly: we add the need *NR* to the corresponding *ANR* component of the given *ATO**: *ANR* = *ANR*+ NR(of new *TOs*); add the need *PF* fund to the corresponding *APF* component: *APF* = *APF* + PF(of new *TOs*). The duration of *ATO** (D(*ATO**)) is adjusted to the maximum duration of *TO*s chains that are part of *ATO**. For each *TO*, with which the set F{*TO*} was supplemented, the readiness advance is determined as the advance of the start of the corresponding *ATO**: St(*ATO**)=A(*ATO**)+ D(*ATO**).

5. Selection of priority *ATO* from the set N{*ATO*}:

One of the N{*ATO*} — *ATO** is chosen as filled, removed from the set N{*ATO*} and assigned to the set Z{*ATO*}. The criteria used to evaluate the priority of the selection are: the minimum advance of the launch: St(*ATO**) = Min (St(*ATO*): *ATO*∈ N{*ATO*}).

TO∈ F{*TO*}, which refer to the selected *ATO** are assigned to the set K{*TO*} and removed from the set F{*TO*};

— If K{*TO*} ≠ ∅, then proceed to step **3**;

— If K{*TO*} = ∅, then proceed to step **6.**

6. Assessment of completion of the algorithm:

— If N{*ATO*} ≠ ∅, then proceed to step **5**;

— If N{*ATO*} = ∅, then complete the algorithm.

***End of* A2.**

A diagram, explaining the sequence of steps 3÷5 of algorithm A2 is shown in Fig. 3

Chains *TO* within N{*ATO*} marked with the same color enter the same *ATO* only when the advance of their final *TOs* is close — within the given parameter. The colors of connected *ATO* and *TO*, which are in different sets, cannot be the same.

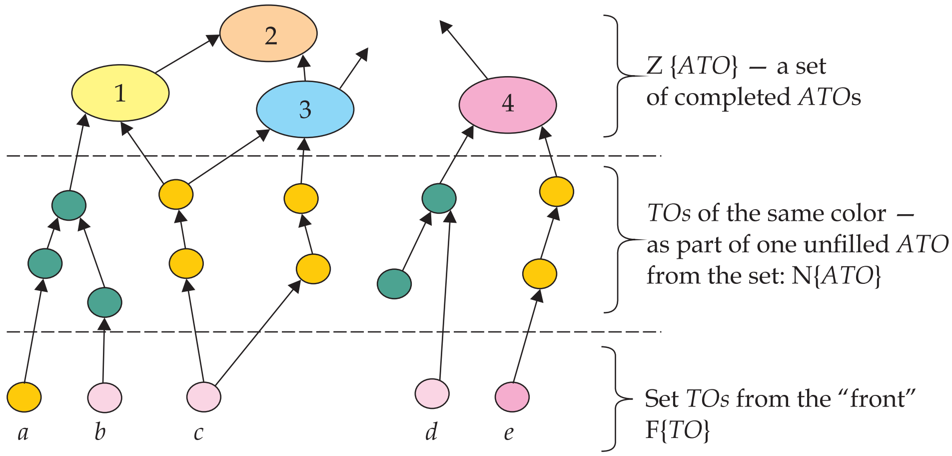

Fig. 3. Scheme for algorithm A2. The color indicates the UE performing the ATO and TO

Let's admit, that in step 5 an *ATO** will be selected, which includes the *TOs* marked in green. In the set Z{*ATO*} *ATO** will appear in green, the following for which: *ATO* 1 and *ATO* 4. *TO a, b, d* will be assigned to the set K{*TO*} in step 5 and transferred in step 3 from the set K{*TO*} to the set N{*ATO*}; while *TO*: {*a*} will join an already existing *ATO* with the same color constituents of *TO*, and {*b, d*} will form a new *ATO*, since there are no corresponding colors among N{*ATO*} for these *TOs*. In step 4, the new *TOs a, b, d* will be continued by the previous ones according to *DTS*:

— those of the previous ones performed by the same *UE* (will have the same colors as the corresponding new one) will be part of the formed/replenished *ATOs* and will be used to adjust their characteristics;

— those of the previous ones, which are performed by another unit, will complete the process of searching for previous ones and will enter the set F{*TO*}.

Additions and comments to the A2 algorithm are given below:

1. Let us prove that the *ATP* constructed by the A2 algorithm does not contain closed paths. At each step 5, some *ATO** is selected from N{*ATO*}, which refers to already filled *ATOs*, since the N{*ATO*} includes *TOs* only previous to the already completed *ATO*. On the other hand, the *ATO** selected in step 5 can be referenced only by *ATO*∈ N{*ATO*} that are not filled yet; *TOs* preceding *ATO** can be included only to still unfilled *ATO*∈ N{*ATO*}. Thus, the set of *ATOs* referred to by any *ATO** (directly or indirectly) does not intersect with the set of *ATOs* referred to *ATO** (directly or indirectly), so closed paths in the constructed *ATP* graph are impossible.

In the given proof and in algorithm 2, as well as in Figure 3, the case when intermediate *TOs* from the chain are connected by the "previous-next" relationship with *TOs* that are not part of the *ATO*, to which the chain belongs is not taken into account. In this case, there are no guarantees that the connections between *ATOs* will not form a closed path. To reduce this probability, it is possible to use a reduction in the *TO* combination tolerance with different advances. In the unlikely event that a closed path is formed, it can be removed in dialog mode. A certain complication of the A2 algorithm is also possible, which we will leave outside the scope of this article.

2. Step 4 of the algorithm can be adapted to determine the restrictions on the consumption of *APF* and *ANR* components, in particular those specified at the beginning of section 3. When joining the *TO* to the *ATO*, not only the total need for *APF* and *ANR* is determined, but also its distribution by time periods into which the *ATO* performance period is divided; such a division can be established by the structure of the *ATP* model and used in determining the composition of *ATO*.

3. *DTS* usually presents variants of *AG&S* production, which differ in *PA* composition and/or the method of their production — depending on the *G&S* copy number. When building *ATP*, we use the option specified as a parameter. All other *DTS* variants must not violate the *ATP* structure, i.e., must not have *TOs* that cannot be classified as *ATOs* according to the rules of the *A2* algorithm. If such design/technological modifications are necessary, then it will be necessary to introduce a new *G&S*, create an A*G&S* group for it and build a separate ATP for it. This condition is related to volume-calendar planning decomposition algorithms, which are simplified if it fulfilled.

4. In a situation where the sequence of *TOs* performed in one *UE* includes a short-lived *TO* performed in another *UE* returning for further processing to the same *UE*, it is possible to ignore such a step to the other unit to simplify the *ATP*. Such situations can be resolved through mutual services between *UE* at the level of building detailed plans. Algorithm A2 can be easily adapted, if at step 4, when passing through the *TO* links, we come across a *TO* that is performed in another *UE*, evaluate the possibility of skipping the latter due to the short duration of the *TO* or by a certain *UE* performing it.

5. Models with the *ATP* structure can be built for different levels of enterprise management: departments, workshops, etc.; at the same time, they must be nested within each other. This is possible because the structures of the input data repeat the structures of the output. As an initial model for building *ATP* of a certain level, you need to use either a detailed *DTS* or an aggregated one of an immediately lower (more detailed) level, so that the formed aggregates can be easily decomposed into constituent components. The same applies to the construction of *ATP-V* (item 3.2), for the construction of which it is possible to use the pre-aggregated immediately lower level.

3.2. ***Aggregate Technological Process for Volume Planning.*** PPM-V are used for ***v****olume* ***p****lanning* (VP) at the highest level of enterprise management and for the most remote period of time and therefore allow the highest degree of aggregation and simplification of the model structure. In particular, the structure of the *ATP-V* model is a simplified version of *ATP* — it fixes: the duration of *ATO-V*; their mutual location in time; use of *APF* and *ANR* during *ATO-V* performance discretes. Thus, the term of readiness of the product position of the enterprise (*AG&S-V*) completely determines the terms of production of *ATO-V*, which are part of it, as well as the volume of consumption of *APF-V* and *ANR-V* within the limits of execution of *AG&S-V*. PPM-V focuses more on determining *what and in what quantities to sell and buy* than *when to produce and consume*. Taking into account the possibility of equalizing the consumption of resources in time at lower levels of management, we will allow unevenness of their consumption in time when planning using *ATP-V*.

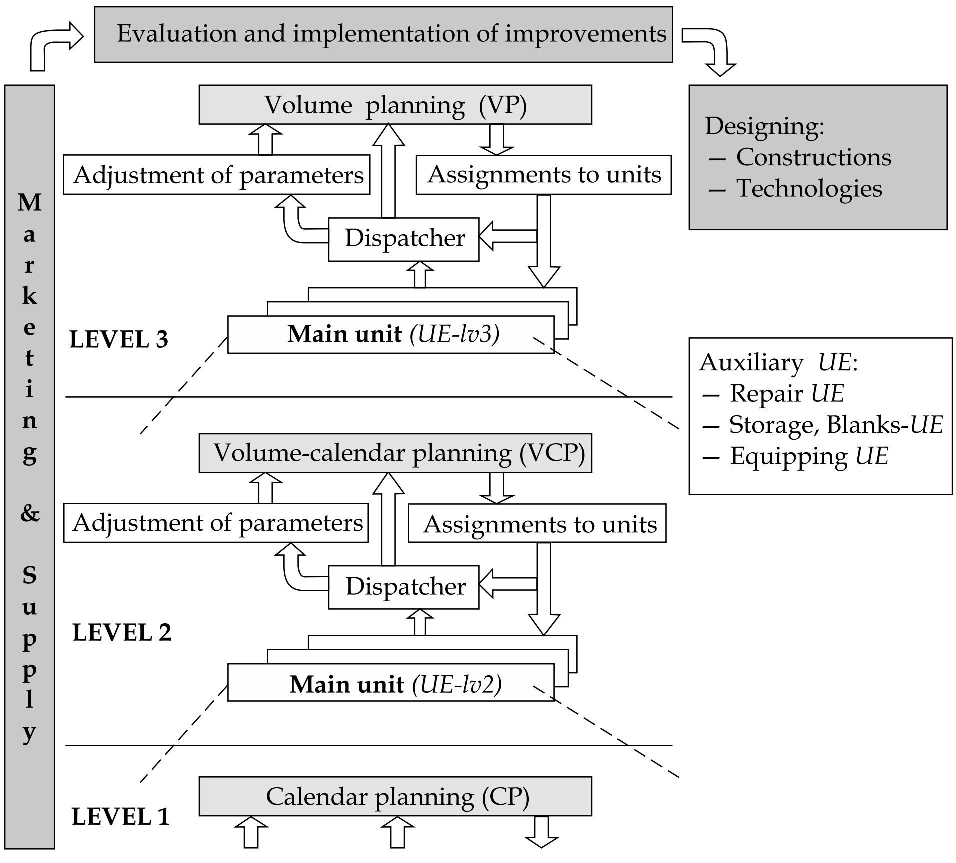

Fig. 4. The structure of the 3-level enterprise management system (simplified). Management of UE-lv1 (PF) is carried out in the same way as for other levels

ATP-V is usually built on base of *ATP*. The composition of the *G&S* group (*AG&S-V*), which are planned by one ATP-V, includes those with similar *ATP*; one of them is chosen as a typical representative, for whom *ATP-V* is being built. The same as for *ATP* of any degree of aggregation:

— the required specification of *ATP-V* will be carried out at the stage of decomposition of the plan, built on its basis (in the form of *ATOs* that were used during the construction of *ATP-V*);

— adjustment of *ATP-V* parameters, depending on the time of their execution (and therefore the variant of *ATP* used) is carried out expertly by *G&S* designers.

The *ATP-V* construction algorithm is practically no different from the A2 algorithm, but:

— *G&S* use *ATO* parameters that belong to *ATP* instead of the corresponding *TO* parameters;

— *ATP* construction results are interpreted according to *ATP-V* structure.

3.3. *The Structure of a Multi-level Production Management System.* Next we consider a 3-level enterprise management system. In Figure 4 shows its simplified version to explain the interaction of the PPMs system in the management process.

Block: "Sales & Supply" predicts and coordinates mutual relations of *UE* with consumers and suppliers of the enterprise at all 3 levels of management. This ensures a single representative from the enterprise for interaction with related enterprises.

Powers of "Auxiliary *UE*s" are determined based on the service needs of the main ones; operational management is carried out through the ordering of their services by consumers in accordance with the established service regulations specific to each of the auxiliary *UE*s. The planning of the processes of auxiliary units is done separately, using models similar to those for the main units.

The "Dispatcher" block takes part in the coordination of *UE* plans of the corresponding level: among themselves; with related enterprises (through "Sales & Supply"); interprets the state of a higher-level plan based on the plans of lower-level *UE*s. In the case of significant deviations of the interpreted state from the state provided for by the higher-level plan, the higher-level planning block makes a decision to restructure its plan.

The block "Adjustment of parameters" analyzes the deviations of the planned tasks of the *UE* from the detailed plans, by which they are implemented, investigates the reasons for the deviations and adjusts the parameters of the corresponding planning models.

The "Design" block studies the needs of consumers, the capabilities of suppliers and designs the production of *G&S* (see section 4).

The "Evaluation and implementation of improvements" block collects proposals from the company's personnel and external stakeholders, regarding the functioning of all the company's systems, evaluates the feasibility and possibility of their implementation, in particular, plans tasks for the design of "*G&S* for own needs" and orders projects to external organizations.

Next, we will consider in more detail the functions and implementation of some of the blocks presented in the diagram.

3.4. ***Volumetric Planning*** (VP). The enterprise plan is built based on forecasts of external market conditions, which are created by many manufacturers and consumers. We believe that our company practically does not affect these conditions. The task of an individual enterprise is to use these conditions to achieve maximum financial success. VP is built with such a goal and with minimal restrictions on the use of the available potential and wide possibilities of adaptation to the conditions prevailing on the market.

The task of VP is to guide the current activity of the enterprise, the results of which will affect the activity in distant periods. Such activities include:

— the work of designers and sales departments of the enterprise, who study the needs of the modification of the enterprise's products and forecast the demand and prices for *AG&S-V*, which can be achieved due to certain design improvements;

— the work of technologists of the enterprise and supply departments, who improve existing technologies and evaluate proposals of designers, regarding the cost of manufacturing future *AG&S-V* options;

— conversion of production capacities to adapt them to future production needs;

— selection and training of employees for their work in conditions of future technologies.

The planning algorithm based on the *ATP-V* model should allocate *AG&S-V* to *ATS-V* discretes in such a way as to ensure the best trajectory of the company's movement in monetary terms: by obtaining the maximum income from the sales of *AG&S-V* and minimal costs for the purchase of additional resources and services, as well as for labor costs. In addition, it is important for the enterprise as a whole to load the available resources proportionately: selling equipment or lying off employees is not desirable from many points of view. A change in the company's capacity is possible, but it must have the prospect of use beyond the planned period. At the enterprise level, it is advisable to cooperate with banking institutions: if there is a lack of funds for the production of profitable A*G&S*-V, or if there are reserve funds, the use of which can be postponed until the need for them appears. It is also necessary to take into account tax payments to state bodies. A long period of time may be used to carry out planned calculations (item 3.6). This circumstance makes it possible to involve experts in forecasting the parameters of the VP calculation.

Next, the volume planning algorithm is presented, which involves the participation of experts in forecasting external circumstances, as well as in determining the possibilities of improving the consumer qualities of *AG&S* due to design improvements and reducing their cost price due to the improvement of technology.

Algorithm **A3** (VP)

1. In the dialog mode for the VP extension period, we define:

• available *APF-V* time funds and ANR-V supply plans, wich are coordinated with suppliers;

• to estimate the possibilities of changing *APF-V* power and *ANR* supply:

— price forecasts for *ANR-V* and *APF-V*, which can be used in the manufacture of *AG&S-V*;

— forecasts of personnel recruitment and training opportunities, in particular, what can be used in production and provided with equipment;

• financial resources of the enterprise at the beginning of the extension period;

• forecasts of conditions that will be provided by banking institutions, in particular, profit on loans and deposits;

• forecasts of demand for *AG&S-V*, which will be expedient to produce and their prices, taking into account possible improvements;

• forecasts of a possible reduction in the cost of *AG&S-V* due to technological improvements of *ATP-V* and taking into account design improvements.

Forecasts of the specified parameters are tied to ATS-V discretes and allow errors in estimates.

2. The initial production state for VP construction is determined based on the VCPs, constructed for *UE level 3* (*UE-lv3*). The initial state construction algorithm interprets the VCP of the specified *UE* in terms of PPM-V. It is quite universal for related management levels and is described in item 3.7.

3. Completion of the status of VP by the next *AG&S-V*; this intermediate state of the VP is schematically depicted in Figure 5.

ATS-V discretes are filled with *AG&S-V* needs in *APF-V* vector components during the planning period. One color shows the use of several vector components by the same *AG&S-V* during several *ATS-V* discrete.

At step 3, one of the *AG&S-V*s is selected (from those defined for planning in step 1) and the term (*ATS-V* discrete) and the number of its instances for completing the VP are determined. The choice is made by reviewing several options, which are evaluated according to the criterion of changing the total score of the next VP state. Among the components that affect such an estimate:

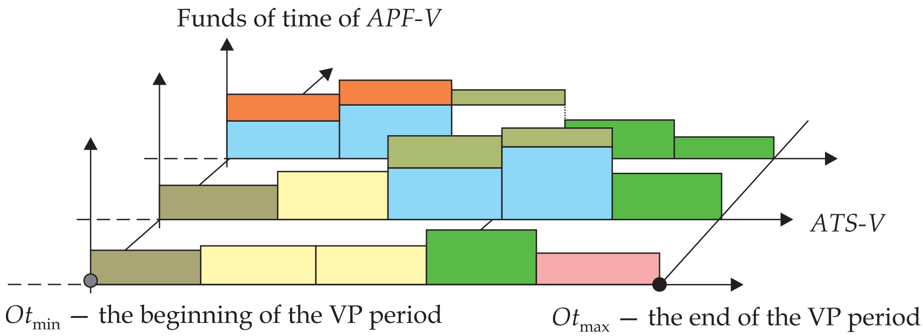

Fig. 5. State of VP construction

a) receipt of funds from the sale of *AG&S-V* (the earlier the receipt, the higher the score) — increases the overall score;

b) financial expenses for the production of *AG&S-V* (expenses for both *ANR-V* and labor costs are taken into account; the earlier the payment of expenses, the higher the score) — reduces the value of the total score;

c) reduction of *APF-V* underload (for each component of the *APF-V* vector and discrete time, a coefficient is used that indicates the importance of loading) — increase the values of the overall score;

d) increase in *APF-V* overload (for each component of the *APF-V* vector and discrete time, a coefficient is used that indicates the inadmissibility of overloading) — they reduce the values of the overall score.

The evaluation values of points *a*) and *c*) increase the overall evaluation, others decrease it (taken into account with a negative sign). The variant of linking *AG&S-V* to VP with the highest positive evaluation is accepted as the result of every step 3.

4. If in step 3 a variant of VP addition with a positive evaluation is found, then it is accepted and step 3 is repeated with a new state of VP. Otherwise, the algorithm terminates and its results (the resulting VP state) are available for user analysis.

***End of* A3.**

The results of the algorithm A3 are drawn up in the form of the trajectory of the enterprise in monetary terms and deviations of resource consumption from those predicted or agreed with related enterprises. The imbalance can be eliminated by:

— changes in projected prices for *AG&S-V* due to improvements in their consumer qualities;

— changes in consumed resources for the production of *AG&S-V* due to technological improvements;

— clarification of the forecasted and coordinated supplies of *APF-V*, *ANR-V* resources.

If it is impossible to reconcile the imbalance, the A3 algorithm can be run with other forecast values of the parameters, as well as the coefficients of penalties for exceeding the need for *APF-V* or their underloading. An imbalance of resources is permissible in principle, but it will require compensation for the internal costs of *UE-lv3*. Penalties for imbalance are those additional internal costs for which a compromise must be found with external profits associated with the production of profitable *AG&S-V* and not the production of unprofitable ones that could load unused resources.

In parallel with the VP calculations for the main production, calculations are carried out regarding the capacity of auxiliary units using the service standards, established on the basis of the analysis of the operation of the enterprise.

3.5. *Volume-calendar Planning* (VCP). For *UE-lv3* as *G&S* will be *ATO-V* — a set of *ATO* results, that are transmitted outside the *UE*; each of them has its own *ATP*. Each such *AG&S* may be one of next:

— is transferred as processing items to another *UE-lv3* or;

— is transferred outside the enterprise) or;

— used as a subject of processing for *ATO-V*, which release date is outside the planning period for *UE-lv3*.

VCP is carried out for each *UE-lv3* independently with the following agreement: between *UE-lv3*; with related enterprises (through sales and supply departments); with a higher-level Dispatcher who is interested in following the higher-level plan.

External constraints for *UE-lv3* are obtained as a result of decomposition of the planned task from a higher level. When building the VCP, we refine the obtained rough restrictions in such a way as to obtain the best conditions for our unit, followed by their coordination as described in item 2.3:

— we allow inconsistencies with *AG&S* readiness plans established by VP — with subsequent coordination with consumers;

— we allow inconsistencies with *ANR* supply plans established by VP — with subsequent coordination with *ANR* suppliers;

— we allow inconsistencies with the plans for the supply and installation of new equipment established by the VP — with subsequent coordination with equipment suppliers;

— we allow inconsistencies with the recruitment and training plans of personnel established by the VP — with subsequent coordination with the personnel management service.

Internal losses are those that lead to an increase in the tension of *UE-lv2* plans and for which they will demand compensation at the stage of their acceptance of planned tasks. When building the VCP, the planner estimates the amount of compensation that will have to be paid to the executing units:

— we allow compatible (overlapping) execution of *ATOs* that are in the "previous-next" relationship — *UE*s will have fewer opportunities to choose the order of launching *PA*s, in particular, combining them in a party;

— we overload/underload the use of *APF* — the intensity of planned tasks increases not only in the executor's unit, but also in the one that performs equipment repair due to the increase in the intensity of its use.

In the same way as it was previously described regarding the CP (item 2.3.), the VCP is restructured according to the results of agreements with the new coefficients of penalty functions for violation of restrictions in order to achieve benefits from the compromise of internal losses (compensations to its units) and mutual fines with neighbors.

3.6. *Prolongation of Plans of Different Levels of Aggregation.* In Figure 6 time intervals are plotted along the time axis T (marked by rectangles; the arrow on the time axis indicates the end of the interval; the scale is conditional),

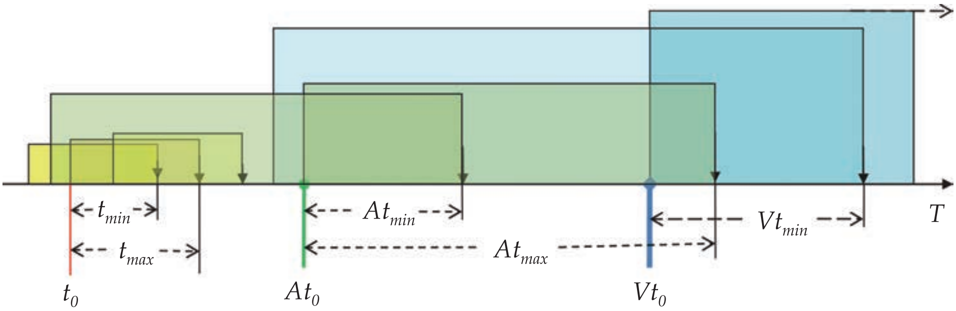

Fig. 6. Scheme of extension of plans of different levels of aggregation

which represent the periods of existence of the plans: CP ($t_0 \div t_{\min}$, $t_0 \div t_{\max}$); VCP ($At_0 \div At_{\min}$, $At_0 \div At_{\max}$); *VP* ($Vt_0 \div Vt_{\min}$, ($Vt_0 \div Vt_{\max}$ — outside the picture)). For each level, the moments of prolongation are at the beginning of the corresponding interval; one of them is marked: t_0 — for CP; At_0 — for VCP; Vt_0 for VP.

The VP of the enterprise is built periodically so that the minimum interval of its existence is not less than $Vt_{\min}$; in particular, at the moment Vt_0, the VP is extended to $Vt_{\max}$. The period between successive prolongations is $V\tau = Vt_{max} - Vt_{\min}$. $V\tau$ is also the interval for which the VP is extended.

Each *UE-lv3*, which is a unit of the enterprise, builds an VCP periodically so that the minimum interval of its existence is not less than $At_{\min}$, in particular, at the moment At_0, each *UE-lv3* receives a scheduled task (its part of the VP) for the period up to $At_{\max}$, decomposes it and prolongs its VCP. The period between successive prolongations is $A\tau = At_{\max} - At_{\min}$. $A\tau$ is also the interval for which the VCP is prolonged.

Each *UE-lv2*, which is a subdivision of one of the *UE-lv3*, builds a CP periodically so that the minimum interval of its existence is not less than $t_{\min}$, in particular, at the moment t_0, each *UE-lv2* receives a scheduled task (its part of the VCP) for the period up to $t_{\max}$, decomposes it and prolongs its CP. The period between successive prolongations is $\tau = t_{\max} - t_{\min}$. τ is also the interval for which the CP is extended.

3.7. *Interpreting a Lower-level Plan as Initial State of a Higher-level Plan.* The initial state for plan prolongation at each level is defined as the final state of the existing plan of the corresponding level. In case of violation of the current plan, it may be necessary to adjust it out of the ordinary, similarly to what was indicated in relation to the CP (item 2.2). In the event that the planned task issued to a lower level of management cannot be fulfilled — it is interpreted at a higher level with significant deviations from the expected state, it is necessary to rebuild the plan of the higher level. A lower-level plan is used as an initial state, which is interpreted in the concepts of a higher-level model. This initial state does not change until an extension (or rebuild) of the lower-level plan is required. That is, higher-level plan calculations can continue for the lifetime of an unchanged detailed plan without the risk of becoming obsolete due to a change in the initial state. This property of the higher level of control relying on the lower level UEs planning their activities gives those advantages over technical automatic control systems — the planning receives a non-changing initial state for calculation.

To explain the algorithm of interpretation of the lower-level plan in terms of the higher-level model, we will take PPM-B as a lower-level model and PPM as a higher-level model. The initial state creation algorithm for *VCP* construction interprets the *UE-lv1* plan in the form of *ATO* completion times according to the CP, as well as *APF*s occupied by them and *ANR*s used.

***Algorithm* A4** (interpretation of the initial state of the VCP)

1. We select *AG&S*, which are expected to be planned, the given release dates of which are within $At_{\max}$. We are starting to review *AG&S* with shorter terms of readiness. For each selected *AG&S*, a *DTS* option must be defined, in advance agreed with the customer.

2. We choose the next *AG&S*. Similar to algorithm A2, we go through the *DTS* of the selected *AG&S* from its final *TO*.

3. We form the initial *TO* "front" for the selected *AG&S* — the set F{*TO*} similar to step 2 of algorithm A2.

4. We choose the next *TO* from the "front" F{*TO*}.

We check the presence of the selected *TO* in the detailed CP of the corresponding unit:

a) if such a *TO* is present, then it and all previous ones are either present in a detailed plan or completed:

— they do not need to be included in the *ATO*; it is enough for the *ATO* that contains the selected *TO* to set/adjust the readiness period, which should be the maximum (according to the detailed plan) among all *TOs* found for the given *ATO*;

— they are marked as having found their application in the detailed manufacturing plan of the selected *AG&S* and are not checked in subsequent steps;

— the resources that are planned in the CP for this and previous planned (but not executed) *TOs* are removed from those available for their use to build the VCP; *PF* and *NR* residues will be represented as *APF* and *ANR* and used in VCP construction;

b) if there is no *TO*, it is included in the *ATO* along with all previous ones performed in the same unit: the *APF* and *ANR* they need are added to the needs of the given *ATO*. Intermediate *TOs* for included ones performed in other units (as part of other *ATOs*) complement F{*TO*}.

5. We check the presence of *TO* in the "front" F{*TO*}:

— if present — proceed to the next step **4**; — otherwise, the *ATP* of the next *AG&S* is adjusted by those available in the detailed *TO* plan; proceed to step **6**.

6. We check for *TOs* in the detailed plan, that were not used in the revised *AG&S*:

a) if present, the *TO*, checks for unrevised *AG&S* that are expected to be performed within the limits $At_{\mathbf{max}}$:

— if they are present, then proceed to step **2** (choose the next *AG&S*);

— otherwise, in the detailed plan there will be *TO*s that are not included in any *ATO*, that belong to those, selected for the construction of VCP *AG&S*; such *TOs* are passed on to the user for analysis;

b) if in the detailed plan all *TOs* have been used, then the algorithm is complete. VCP of all *AG&S*s earmarked for planning are adjusted by detailed plans. For some *AG&S*s with set dates within $At_{\max}$, VCP adjustments may not be necessary.

***End of* A4**

Partially planned *ATOs* for which readiness dates are determined based on the detailed plans (step **4*a***) but remain unplanned by the detailed *TO* plan (step **4*b***) require an adjustment of the duration of execution (for example, in proportion to the volume of resource requirements).

A new initial state for the construction of the VCP may be needed both when transitioning to the VCP planning, and in the event of the need to adjust the VCP in connection with the violation of the planned tasks at the level of the CP, offered by the units. The level of violations that require the restructuring of the control center is determined by the Dispatcher of the appropriate level, who evaluates deviations from planned tasks.

3.8. *Assignment to Units: Decomposition of Aggregated Plans.* The process of decomposition (detailing) is the reverse of aggregation and consists in determining the composition of already planned aggregated operations (*ATO* for VCP, *ATO-V* for VP). It is carried out with the aim of issuing planned tasks to units — executors of aggregated operations, when the time has come to extend their plans. Consider the decomposition algorithm using the example of the decomposition of *ATO* into *TO* for *UE-lv2.*

Only those *ATO*s, whose terms are defined by the constructed VCP within the period for which the detailed plan is expected to be extended (up to the moment t_{max}, item 3.6), are detailed. We believe that the planned tasks have already been issued to the units by the time t_{min}. For each copy of *AG&S*, the *ATO* of which is supposed to be detailed, the *DTS* variant, according to which it is produced, must be defined; prior to that, the *AG&S* manufacturing plan exists in a form that allows for various specification. If the *DTS* option affects the consumer properties of A*G&S*, the choice must be agreed with the consumer. If the *DTS* option affects specific *NR* and *PF* needs, the selection must be coordinated with the executing unit's capabilities and those units that affect those capabilities: the supplier and the Store. To simplify such agreements, *DTS* options for one A*G&S* should be selected that are close in terms of consumer properties and execution technology.

***Algorithm* A5** (decomposition of VCP)

1. Determine the list of *AG&S* whose *ATOs* are scheduled within the period $t_{\mathbf{min}} \div t_{\mathbf{max}}$ — P{*AG&S*}.

2. We choose the next *AG&S* from P{*AG&S*} and exclude it from P{A*G&S*}. Similar to algorithm A2, we go through the *DTS* of the selected *AG&S* from its final *TO*.

3. We form the initial *TO* "front" (set F{*TO*}) for the selected *AG&S*, similar to step 2 of algorithm A2.

4. We choose the next *TO* from the "front" F{*TO*}; we check certain conditions according to which we perform actions:

a) If the *TO* is part of the *ATO*, which is scheduled beyond t_{max}, then it is skipped together with the previous ones that are performed in the same unit until the *TO* is found in the previous *ATOs* and we fill F{*TO*} with them. We exclude the selected *TO* from F{*TO*} and proceed to step **5**;

b) If the *TO* is part of the *ATO*, which is planned within the period $t_{min} \div t_{max}$, the *TO* is included in the planned task for the unit that performs the *ATO*; the result of the found *TO* is a the item of unit task with a lead time equal to the *ATO* lead time. Prior to the found *TO*, which are performed in the same unit, will be scheduled within their unit; previous ones performed in another subdivision (included in another *ATO*) add F{*TO*}. We exclude the selected *TO* from F{*TO*} and proceed to step **5**;

c) If the *TO* is part of the *ATO*, which was previously detailed — its composition was already brought to the unit as a planned task or the *TO* was included in the *ATO* composition at the stage of determining the initial state by the A4 algorithm and is already present in the detailed plan — such *TO* and all its predecessors are omitted. We exclude the selected *TO* from F{*TO*}.

5. We check the presence of *TO* in the "front" F{*TO*}:

— if present — proceed to the next step **4**;

— otherwise, a planned task regarding the execution of the selected *AG&S* is issued for units within the period $t_{\mathbf{min}} \div t_{\mathbf{max}}$. We exclude the selected *AG&S* and proceed to the next step **6**.

6. We check the presence of *AG&S* in the selected list P{*G&S*}:

— if they are present, then we proceed to the next step **2**;

— otherwise, the algorithm is completed. Planned tasks are issued to units in the form of *TO* readiness terms, the results of which are transferred to other units.

***End* A5**

Algorithm A5 can be slightly improved if, in step **4*a***, we remember the composition of *ATOs* whose manufacturing term is still outside t_{max} and use it when the term of this *ATO* falls within the required limits. The composition of such *ATOs* cannot be changed — the version of the *AG&S* instance intended for the decomposition algorithm remains unchanged because the changes in the *DTS* are interconnected and are made in a complex manner.

The unit's planned task is evaluated by its management, as described in item 2.3. In detailed planning, it will be used as a norm, deviations from which are agreed between units on the basis of mutual fines. Parties, interested in negotiations, will also be:

— block "Sales & Supply"—regarding delivery of *G&S*s from the enterprise and *NR* to the enterprise;

— equipment repair unit — regarding schedules of planned equipment repairs;

— technological department — regarding the equipping supply schedules, agreed at the VCP;

— the Dispatcher who coordinates the product positions of units that are planned to be used as *NR* in the *ATO*, for which a planned task has not yet been issued.

Units also prepare data on the balances of *APF*, *ANR* within the limits of t_{max} as an initial state for adjusting the VCP. The Dispatcher can use the data received from the units for comparison with the existing VCP and provide information for making a decision on its reconstruction.

4. Financial Accounts of Units

The basis for introducing a system of coordination between *UE*s of different levels is their separate financial accounts. The receipt of funds to the *UE*'s account is planned when a planned task is issued to it by a higher-level *UE*. These funds should be enough to pay employees (both temporary workers and those on hourly wages). Also, these funds should cover additional costs associated with the intensity of the issued planned tasks (payment of overtime, small batch sizes, regulatory shortages, etc.). The unit can reduce internal costs and receive additional funds due to coordination of plans with adjacent units — units settle among themselves from their own accounts, seeking to minimize internal costs (item 2.3).

Neighbors for *UE*s of any level can also be other enterprises with which interaction takes place through the "Sales & Supply" block. Settlement for mutual services takes place through the enterprise level — the *UE* does not receive funds from another enterprise directly to its account and is not settled from its own account.

The *UE* may pay a fine to the higher-level unit that issued the planned task to it in the event that the state of the higher-level plan, when interpreted by the detailed plan of the given level, has undergone significant deviations and needs to be rebuilt. Calculations should be made through the Dispatcher who interprets the detailed plan. Changing the task of a unit after it is accepted is a rare case, since in the considered algorithms, planning can start no earlier than from the existing plan of units of a lower level. The reverse direction of process modeling has significant disadvantages and was not considered by us.

Unit's accounts can also be used to organize a system, that will interest employees in the general financial results of the enterprise and the units of which they are members. Consider the following scheme. The enterprise and each *UE* will strive to obtain the maximum financial result, as it will affect the amount of bonuses for each employee. Of course, after all mandatory payments, including settlements with services and production units, the enterprise and its *UE* have reserve funds, part of which can be used for incentives — the premium fund. Decisions are made with the participation of representatives of all units of a given level regarding the size of the premium fund and its distribution according to formal indicators, agreed in advance, as well as a result of informal discussions. Each participant in discussions strives to achieve better formal indicators and also to receive a positive assessment from other participants. Similar decisions regarding the distribution of the premium fund take place both at the level of the enterprise, whose premium fund replenishes the premium funds of *UE*s of a lower level, and at all other levels and units, which in turn replenish the premium funds of units of lower levels.

Developers — designers, technologists and rationalizers from any department — are evaluated by the effectiveness of the implemented improvements. The team of developers must determine the degree of participation of each participant and distribute the received premium funds accordingly. Developers should be interested in spreading their inventions at least within the enterprise:

— any improvement should be taken into account when normalizing work for the next planning;

— dissemination of inventions contributes to the overall efficiency of the enterprise.

5. Design Models

The design of new *G&S* or the modification of the design of existing ones involves the study of consumer processes, forecasts of future needs, as well as proposals for the manufacturability of products. Design criteria are consumer value (utility for the consumer) and cost price (manufacturing costs).

The design of the product is a set of components that are connected by interaction in such a way that certain relationships are maintained between the attributes of these components. Components for construction and possible methods of their interaction are introduced in advance from construction experience. On the set of such components and connections between them, relations are provided: abstract — concrete, part — whole and similar with different degrees of similarity.

Design involves presenting the product as a collection of interconnected ***a**ggregated/**a**bstract **c**omponents-converters* (*AAC*) of incoming flows of materials, energy, and signals. The highest level of abstraction is functional converters, which abstract from the material that undergoes changes [11]. The process of designing a complex product consists in detailing the *AAC* and linking them together. Detailing can take place in several stages, depending on the complexity of the product.

***Algorithm* A6** (design-construction)

1. We set the desired function for the *G&S* project, presented in an aggregated/abstract form — its functioning and interface can be clarified in the process of detailing.

2. Among the implemented or described *G&S*, we select similar ones (with a degree of similarity not less than the given one). We will use the *AAC* components and interfaces in the selected *G&S* in the following steps.

3. *G&S* detailing: we select the necessary ones from the received *AAC*s and link them together in such a way as to implement the desired function. Connection involves choosing the type of connection (interface) and setting its parameters. If it is not possible to achieve the goal, we expand the set of *AAC* and interfaces for construction:

— step **2** is performed with reduced *G&S* similarity requirements;

— aggregate and abstract from the functioning and interfaces of the provided *AAC*s;

— we use the components of the provided *AAC* and interfaces and specify them;

— we change the requirements for *G&S* and coordinate them with consumers and adjacent *AAC*s of the project.

After expanding the set of components for the projected *G&S*, we continue the selection of components and setting their parameters to implement the desired function.

4. If the required level of detail is reached, then the project is completed; otherwise, among the *AAC*s, detailing the project, we select the next one for further detailing, consider it a new *G&S* for designing and proceed to step **1**. After detailing the selected *AAC*, we connect it to the project of the initial *G&S*. In the process of detailing the *AAC*, coordination is carried out between the interacting *AAC*s of the same project.

***End of* A6**

The following are comments and additions to the A6 algorithm.

1. When detailing components, it may be necessary to coordinate their interaction and redistribute functions. A change of the general *G&S* interface is not excluded. When evaluating decisions regarding options for the redistribution of functions between *AAC*s and detailing their interaction, they strive to improve the overall project criterion: alternatives are accepted in the case, that the “benefits” in one of the components exceed the “losses” in the adjacent one.

2. For complex projects, it is assumed to highlight several of their interdependent aspects, which are detailed in parallel and in agreement. In particular, UML [11] provides several types of diagrams (classes, states, activities, etc.), that describe the project in different sections. UML can be used at higher levels of design for various subject areas. There are specific methods and software tools for specific subject areas.

3. The design experience is generalized: new *AAC*s are created both by aggregation and abstraction, and by regrouping the structure of existing ones; the similarity ratio is also refined based on which third-party components have proven useful for detailing the *G&S* or *AAC* we need.

4. For the proper functioning of the main *G&S* component, *auxiliary* ones may be needed, the requirements for the functioning of which are determined by the main one; algoritm of their construction is similar to A6. A *control system* may be required to ensure the interaction of the design components. Its design is carried out in a similar way, based on the function it must perform: to measure the

parameters of the main component and its environment and influence the functioning of the main component.

5. After creating a new *G&S* project and launching it into production, the process of its improvement takes place. The organization of such a process requires documentation for the *G&S* project with different degrees of aggregation and justifications for the decisions made to quickly inform the developer: how it is possible to change the functioning and which subsystems are affected by the new option.

6. Since the design processes take place in stages — first the aggregated structure of the project is determined, then the detailing of each of the *AAC*s takes place, then a plan is required for the execution of detailing work, which will identify the executors involved in the detailing of certain *AAC*s of the project and the deadlines for obtaining agreed decisions. To draw up such a plan, it is possible to apply calendar planning models, but with the particularity that: standards of performance of works for them are poorly predictable; the work schedule itself has alternative paths due to the fact that the result of the previous work affects the necessity and performance parameters of the following ones. Design models often include not only mathematical calculations and modeling, but also the creation of prototypes and their testing, the results of which affect the options for subsequent works. Examples of project planning are given in [7].

7. The *G&S* design is used to design the *TP*. The principle of *TP* design is similar to structural design, but instead of *PA* components, process components are used that transform materials into parts and combine them into assemblies. The *TP* system of various degrees of aggregation and abstraction is prepared and organized in advance. The *TP* design algorithm is similar to A6: for the manufacture of *AAC* (its part or several parts of different *AAC*), *AAC*-processes that were used for processing similar *AAC* are selected and the required *AAC*-process is constructed from them. The system of *AAC*-processes does not correspond to the *AAC* system used for construction and does not fit into the *ATO* system used for planning — it is convenient for each of the developers to think in their own system of structural elements.

8. The design of *TP* can take place in parallel with the design of the structure — technological solutions are somewhat behind the development of the structure because they must implement the designer's ideas. The technologist assesses the possibilities of manufacturing *AAC*: available equipment; the need to purchase a new one; production of equipping; personnel training, and also agrees with the designer on the options of *AAC* that simplify production. At the same time, it uses changes in the design at different levels of aggregation, and adjusts its decisions regarding *AAC*-processes at the corresponding levels of aggregation. On the other hand, the technologist adjusts the *ATO* standards, related to changes in *AAC*-processes, and from production plans receives information about its scope for making decisions regarding the purchase of equipment, allowable costs for the production of equipping and the organization of FPL (backward arrow in Fig. 7).

To accelerate the implementation of design and technological improvements, as well as to ensure their interaction, the stages of construction, *TP* design and planning can be partially combined in time (Fig. 7).

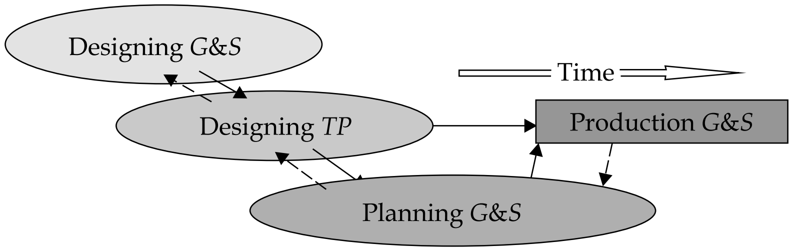

Fig. 7. Combining the designing, planning and production stages of G&S in time

In the design process (until its completion), decisions are made that, on the one hand, can be used in the design of the *TP*, and on the other hand, to evaluate the possibility and effectiveness of the implementation of constructive solutions (back arrow from the "Designing TP" block to "Designing *G&S*").

It is possible to start planning the production of *G&S* at higher levels of management before the design is completed — it is not necessary to know the detailed *TP*, it is enough to assess the impact of the already adopted design decisions on the parameters of the relevant *ATO*.

In addition to the planned task (CP), for the production of the *G&S*, a *DTS* is required, the preparation of which is completed when the *TP* design is completed (arrow from the "Designing *TP*" block to "Production *G&S*").

When creating a *G&S*, it is possible to adjust plans (back arrow from the "Production *G&S*" block to the "Planning *G&S*" block)

Conclusions

The result of the research is a set of algorithms for planning and design, aggregation and decomposition, which can be applied to build a multi-level (integrated) automated management system of a production enterprise. Algorithm for volumetric planning differs from traditional ones and can be adapted for planning goods with a long manufacturing cycle. Dynamic prolongation of plans of different levels and their interconnection is supported by the considered algorithms. The considered algorithms need additions and specification. Some of them have analogues that are used in existing production management systems. Our goal was to show their interrelationships in a multi-level management system.

Models of calendar planning with alternative variants of the technological processes of their production remained beyond our consideration. These include models of processes: equipment repair, design, testing of product prototypes, etc.

Approaches to determining some parameters of the described algorithms and management system (planning periods, number of management levels, degree of aggregation, etc.), as well as means of supporting forecasting and expert assessments, remained beyond our consideration. To solve these problems, the tools of artificial intelligence are promising — evolutionary algorithms, neural networks, machine learning, etc. An overview of publications in the specified direction is given in [12].

DECLARATION

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Contribution of the authors.

Zelinsky V.A. is responsible for the idea of the paper, the structure of the models and their connection in the integrated management system of an industrial enterprise.

Zelinskyi A.O. is responsible for the description and specification of the planning and design algorithms.

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СИСТЕМА МОДЕЛЕЙ ДЛЯ АВТОМАТИЗОВАНОГО ПЛАНУВАННЯ, ПРОЄКТУВАННЯ І КЕРУВАННЯ ДИСКРЕТНИМ ВИРОБНИЦТВОМ

Вступ. Крім процесів виробництва, планування яких відбувається з використанням моделей теорії розкладів та управління запасами, в системі керування підприємством відбуваються процеси проєктування, а також аналіз і коригування моделей, які використовуються і для планування, і для проєктування.

Агреговані моделі виробництва представляють процеси у спрощеному вигляді, що дає змогу планувати на віддалені періоди часу, враховуючи лише суттєві обставини, які можуть впливати на поточні рішення. Результати обчислень агрегованих моделей дають змогу розділити складні детальні моделі на декілька слабозалежних моделей меншої розмірності. Детальні моделі виготовлення товарів та надання послуг використовуються для планування на ближчу перспективу і можуть мати специфічну структуру. Побудовані детальні плани потребують узгоджень між собою і можуть бути використані як початковий стан для пролонгації агрегованих планів. Агреговані моделі конструкцій та технологічних процесів використовуються в задачах проєктування з аналогічною метою — декомпозиції складного проєкту на підсистеми. Крім того, планування виробництва в агрегованому вигляді може починатись ще до завершення детального проєкту — достатньо мати проєкт виготовлення товарів у агрегованому вигляді. Це дає змогу скоротити час від початку розробки проєкту до виготовлення товару.

Метою статті є розгляд системи моделей, які можуть бути використані для автоматизації процесів планування, проєктування і керування виробництвом. Кінцевою метою є створення інтегрованої комп'ютерної системи керування, що може функціонувати без використання паперових носіїв інформації і з максимальним можливим звільненням управлінця, конструктора, технолога і оператора обладнання від рутинних функцій.

Методи. Робота базується на узагальненні процесів виробництва і проєктування, їх поданні в агрегованому та абстрактному вигляді. Моделювання використовується для перегляду і оцінки варіантів планів. Алгоритми планування виробництва і проєктування пов'язуються в багаторівневій системі керування складним виробничим процесом.

Результати. Розроблені алгоритми планування та проєктування, аґреґації та декомпозиції, які можуть бути застосовані для побудови багаторівневої (інтегрованої) автоматизованої системи керування виробничим підприємством. Алгоритм для об'ємного планування відрізняється від традиційних і може бути пристосований для планування товарів з тривалим циклом виготовлення. Динамічне пролонгування планів різних рівнів та їх ув'язування між собою підтримується системою розроблених алгоритмів.

Висновки. За межами статті залишились моделі календарного планування з альтернативними варіантами технологічних процесів їх виготовлення. До них належать моделі процесів: ремонту обладнання, проєктування, випробування дослідних зразків продукції тощо.

Розглянуті алгоритми потребують доповнень і конкретизації. Деякі з них мають аналоги, які використовуються у наявних системах керування виробництвом. Нашою метою було показати їх взаємозв'язки у багаторівневій системі керування.

Підходи до визначення параметрів описаних алгоритмів і системи керування (періоди планування, кількість рівнів керування, ступінь агрегування тощо), а також засоби підтримки прогнозування та експертних оцінок залишились за межами нашого розгляду. Для вирішення цих задач перспективними є засоби штучного інтелекту — еволюційні алгоритми, нейромережі, машинне навчання тощо.

Ключові слова: *модель виробничих процесів, агрегація, декомпозиція, календарний план, керування запасами, проєктування, принцип системної оптимізації.*