On the requirements for operational planning systems for industrial production

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Abstract. The article analyzes and systematizes the requirements of potential and real users to computer systems for operational planning and production management. There is a particular attention to production systems of the “Advanced Planning and Scheduling” (APS) class, which have a high degree of integration with the systems of the “Manufacturing Executable Systems” (MES) class. There is also a brief overview of the reasons for the creation of APS systems, as well as their general ideology and conceptual problems in the development. A number of key requirements for APS systems are considered, as far as possible, in the order in which they arise both during the development and the operation of these systems. The article was based on the long-term interaction of its authors with representatives of manufacturing enterprises of various sizes, belonging to different industries located in Russia and the countries of the Commonwealth of Independent States. This interaction was carried out as a part of the implementation of the “Zenith SPPS” information system in the pilot and industrial operation.

1. Introduction
In the course of the development of information systems for managing the activities of enterprises and organizations, the functions that make it possible to optimally and quickly distribute the use of certain resources in time are becoming increasingly important. In this article, there are the requirements for planning information systems intended for use in single or small-scale production. The planning problem arises regularly in these industries, since the production process is difficult to reduce to monotonous overlapping flows of materials. There are the following important conditions for the need for operational planning:

- large range of manufactured products with a variety of technological processes;
- technological complexity of manufactured products;
- large number of production orders.

Our experience of interaction with industrial enterprises [1] shows that when creating information management systems, the resources of an automated object can be conveniently divided into the following groups: human, material, financial, information, and time resource. At the same time the information one may be any resource not belonging to another group. Usually, the information resource
is the documentation of the enterprise, as well as technology and controls. With this approach, each group of resources has pronounced features that distinguish it from any other group.

Another important object of planning is a task, that is, an action that requires a certain set of resources to complete. When planning, the task (and only the task) can spend some resources and generate others. A task in industrial production is often equivalent to a technological operation. In production planning, a technological operation is considered as an element of route technology, that is, as processing a certain amount of semi-finished products at a certain workplace.

Existing operational planning systems can be divided into “single-orders” and “multi-orders”. “Single-orders” are designed to work with orders, the resources for which are fairly isolated. These are mainly various systems of enterprise project management (EPM). “Multi-orders” are used when orders seriously “compete” in the matter of access to limited resources. These are systems of advanced planning and scheduling (APS). In fact, EPM systems can be considered as a special case of APS systems.

Providing conditions for the simultaneous execution of several orders using common resources makes production planning a difficult problem: there is an approximately factorial dependence of the number of solutions on the number of manufactured objects (semi-finished products, parts, assemblies, products, etc.) [2]. Therefore, as a rule, we do not find an optimal solution, but a “good” acceptable one, for which various empirical methods are used. The resource constraints existing at the enterprises, as well as the natural deviations between the “plan” and the “fact,” decrease the difference between the optimal and acceptable production schedule. However, with a large number of restrictions, the possibility of a situation increases when an acceptable solution will not be found at all. In this regard, APS systems are recommended to be used where simpler planning methods cannot adequately resolve complex trade-offs between competing priorities.

Operational production planning systems can be divided into technology-based dependencies based on resource constraints by the method of structuring and processing data. In the first case, after entering the tasks, their sequence is established, and the complete or partial completion of the previous one is considered the determining condition for the beginning of the subsequent technological operation. In the second case, the condition for the start of any operation is only the presence of a certain set of resources. “Resource-centric” systems is more universal, although much more technically difficult. To ensure productive work with various volumes of data, including minimizing the input amount of information, mixed-type systems are used, where both technological and resource limitations are supported.

The presence of a universal planning system that operates taking into account the above resource groups leads to a lot of private tasks. The authors of this article and their colleagues interacting with end users and system integrators about the Zenith SPPS mixed-type APS system [3], on average once a week, receive a new proposal for serious improvement of the system. Now we are going to consider the basic generalized requirements of enterprises to such systems.

2. Entering the nomenclature of resources and their “availability maps”

Before entering information on orders, products, parts, and operations into the system, it is necessary to build an information model of a specific production. First, we need to describe the resources available at the enterprise. Usually, information about those resources that are used during the execution of tasks is entered at the beginning, and after their completion they are released in the same amount. Such resources can be permanent. There are, first of all, work centers and work performers. Production sites and workshops can also be described as separate permanent resources. Then the names and properties of the consumed resources are introduced: those or other materials, blanks, parts, and semi-finished products necessary for the manufacture.

For each resource, we must enter an “availability map” that will determine when and to what extent this resource can be used. For a permanent resource, it will be close in meaning to the work schedule, and for an expendable resource, it will be close to the delivery schedule. It makes sense to automatically receive information on the nomenclature and supplies of expendable resources from the warehouse system. The supply of a consumable resource can be a separate task. In addition to the supply of
3. Creating a list of planned tasks with resource requirements

When the production capacities of the enterprise are described in the system, we can describe what, how, and when we want to produce. Information about this should go to the APS system:

- from customer relationship system (CRM): name of the production order, how many and which products produce, start and end dates, and special requirements;
- from automated control system of technological process (ACS TP): product composition, technological operations for their manufacture, standard duration of operations, required expendable, and constant resources;
- from warehouse management system (WMS): availability of source material (especially in case of alternative manufacturing methods), as well as unclaimed semi-finished products and finished products.

In the system of technological preparation, the type of machine and equipment is usually indicated, the indication of specific units (inventory numbers) is not necessary. If there is only one machine of this type in the workshop, then the operation will be performed on it. If there are several machines, then the APS system should independently determine which one is preferable, if possible, adjusting the operation time. The generated order must be able to directly edit the technologist (figure 1).

Figure 1. Correction of the generated order in the Zenith TECH application.
In fact, for the correct and effective entry of the task list, a separate subsystem of automatic order formation is required, which has custom access to various enterprise information systems [4]. When the basic parameters of the order are known, this subsystem makes it concretized. From the list of products available in the technological preparation system, items included in the order are selected. Information about the manufacturing processes of these products are copied and attached to the order. If the order contains a new product that is not in the technical training system, only general information about such a product is attached to the order. Then the product is added to the list of products of the enterprise and a manufacturing process is developed for it. Then, this information is also copied to the order.

4. Fulfillment of general target requirements for the production schedule

The production schedule is the process of distributing tasks over time, taking into account resource, technological, and organizational limitations. Since such restrictions are often contradictory, there is a question of what exactly is a sign of an optimal schedule, or at least which sign is most in demand.

There can be many signs of schedule optimality: minimum time to complete the most recent operation, minimum average time to complete all operations, minimum number of readjustments, minimum transport costs, minimum amount of resources consumed, etc. According to the authors of this article, in practice, the main criterion for optimality should be considered to minimize the time of interoparational lay-out of semi-finished products, subject to the maximum number of orders being completed on time. If these conditions are met, then we can introduce additional restrictions from the above-mentioned ones.

The need to fulfill orders on time is obvious from an economic point of view. As for minimizing the time of interoparational treatment, it not only saves significant money by reducing the volume of work in progress, but also solves the problem of damage to the semi-finished product due to the long waiting time for further processing. This is especially critical in a number of industries, such as chemical or food, but it also occurs in those industries where treatment as a whole is not critical, for example, in metal processing.

As it is known [5], there is a way to calculate the schedule, in which we try to give each operation the closest possible start time. This method of calculating the schedule is called leading or direct. There is another way to build a schedule, when for each calculated position of the operational plan, an attempt is made to establish the latest possible start of operations, at which it is still possible to complete the work on time. This method of calculating the schedule is called the inverse one. Fulfillment of orders on time while minimizing the time of interoparational treatment requires a balanced combination of both calculation methods.

Algorithms for the combined calculation of the schedule are difficult: it is necessary to recalculate individual fragments of the schedule, while maintaining the correctness of the remaining part. Despite this, the technology of combined calculation is very promising and requiring further study.

5. Cooperation modeling

The requirements described above provide modeling of the performing process all technological operations within a single production unit. Therefore, one of the questions most frequently asked by potential users of APS systems is: “What do we need to do if a part of the technological operations is performed outside the workshop?”

Technological operations performed outside the production unit are called cooperative work or simply cooperation. Cooperation is used when the performance of certain works “on their own” is impossible or economically unjustified.

In case of stable cooperation with a partner, the technological process and production capabilities of which are well known, we may not use special planning functions. However, in most cases this solution will not be effective. We may not know about the partner’s workplaces, or about the technologies used by it. Moreover, this information may be confidential. But even if this information is publicly available, we will need to enter and periodically update it.
Usually, information is required not about how the cooperation work is carried out, but about the time of completion of the work and their final result. Therefore, in the case of simple or one-time cooperation, it is sufficient to establish a delay in the start of their own operations, which occur after the completion of cooperation activities.

Another popular way to model cooperation activities is to represent a partner within their own system as one virtual workstation. Since the partner can perform several works transferred to him at the same time (for example, for different orders), the operations at such a virtual workplace must be located while maintaining the technological sequence of manufacturing products, but without forming a queue for execution. Therefore, in such workplaces it is advisable to ensure the simultaneous execution of several unrelated operations. In this case, the implementation of cooperation activities is planned to be enlarged, which corresponds to the real vision of the production process. In this case, technologically connected operations sequentially performed by the cooperation partner can be considered as one operation of the route technology.

6. Accounting for the duration of transportation
It is important to ensure optimal costs for the transition of semi-finished products, blanks, and components of products from one workplace (machine) to another with operational production planning. To solve this problem, mechanisms that allow storing the coordinates of each workplace in the system are required. If the system knows these coordinates, it will be able to determine the distance between two jobs. Coordinates can be expressed in any unit of length, and the position of the starting point in this case does not matter, which is convenient from a practical point of view.

The easiest way to solve the problem of minimizing traffic flow is to choose a workstation for the next technological operation that is closest to the place where the previous operation was performed. A more accurate solution requires calculating the time it takes to move a particular part or a batch of parts between two specific workstations. Since the distance between workstations is known in advance, this task can be reduced to calculating the transportation speed. Speed, in turn, depends on many parameters, the main of which are the dimensions of the parts, their weight, and also the way of moving. There are two problems follow from this: the need to enter a large amount of additional data into the system and the need to search and enter an empirical formula for calculating the time or speed of transportation.

7. Determination of the lack of resources
APS systems calculate production schedules consisting of hundreds and thousands of operations, taking into account a large number of resource limitations. Therefore, it is obvious that a situation when any resource is not enough to complete an operation arises quite often. This problem applies to all types of resources, including time. For example, the feedstock may be less than is required to carry out all the planned operations. Or, we can assign a production order so close a shelf-life that it cannot be physically fulfilled for the remaining time, even with an excess of all other required resources.

Several different approaches can be applied to solve the problem of missing resources. The simplest option is the following: if it is impossible to add another operation to the schedule, we need immediately interrupt the calculation and display the corresponding message. In this case, the schedule returns to the state that was before the calculation began. This is a rather rough solution of the problem.

Some APS systems [6] put information about problem operations in a special buffer if it is not possible to calculate the schedule for individual operations (figure 2). Interruption of the reverse calculation does not occur, but such a schedule will require expert analysis and correction for further use, which is not always convenient in real production conditions.

A scheduling, when the system adds problem operations (as if this resource is not enough, and immediately automatically creating a needs table with the name of the resource, required amount, and time of delivery of the resource) is an interesting and promising solution to the problem. As a result, we can calculate the entire schedule while maintaining priorities. If there is a shortage of the “time” resource, the backward calculation of the schedule can be replaced by a leading one with the possibility of the end of the operation going beyond the planning. It is also advisable to enter information on such
an operation in the needs table; resource delivery time in this case will be the actual start time of the operation.

**Figure 2.** Correction of the generated order in the Zenith SPPS APS system.

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8. Recalculation of part of the schedule

In a production environment, a situation where a full recalculation of a schedule is needed is rare. The constant emergence of new orders and the changing situation in production require not a complete recalculation, but a constant correction of the schedule. This is due to the fact that actually started technological operations, as a rule, should continue to be carried out where they are planned. In addition, actually completed operations are not subject to any rescheduling at all. Representatives of enterprises put forward the requirements for the availability in the APS system of the following methods of schedule correction for not started operations:

- recalculation of all operations from a certain point in time;
- recalculation of operations of certain orders;
- calculation of new orders that have just appeared;
- recalculation of all operations at a specific production site;
• recalculation of operations of only not started orders.

Correction of the production schedule is algorithmically more complicated than a full recalculation, since it requires an analysis of the initial schedule.

9. Duration of the calculation schedule and the performance of the system as a whole
The contradiction between the requirement for speed and the algorithmic complexity of the calculations can be considered the main problem of class APS systems. The developers of such systems always have to find a compromise, simplifying calculation algorithms and increasing the data processing time to the maximum, but still consistent with the real time. The problem is compounded by the calculating of production schedules, which are difficult or impossible to parallelize.

The operating experience of such systems, as well as our observations [7] show that the system functions in real time if the processing of the production schedule corresponds to the values given in table 1.

| Action                                                                 | Duration       |
|------------------------------------------------------------------------|----------------|
| Full recalculation of the production schedule (at least 50 000         | 30-50 minutes  |
| technological operations)                                              |                |
| Partial recalculation of the schedule (at least 10 000 technological  | 10 minutes     |
| operations)                                                            |                |
| Schedule correction when changing the parameters of an individual      | 1 minute       |
| technological operation                                                 |                |
| Reading and drawing the results of calculating the schedule on the     | 250 milliseconds|
| chart when scrolling                                                    |                |

In case of volumetric schedules, the use of technologies that provide additional feedback to the user can increase the maximum time for drawing a chart up to 5 seconds. Such technologies include asynchronous data loading or an indicator that signals the time remaining until the result is displayed.

10. Further processing and presentation of data
No matter how well the information system plans, there is a question about how to track the actual implementation of the plan. In case of operational production planning for further processing of results, manufacturing executable systems (MES) are used. Such systems in real time initiate, monitor, optimize, and document production processes from the beginning of the execution of the order to the release of finished products. Using the data of APS systems, MES systems manage current production activities in accordance with incoming orders, requirements of design and technological documentation, and current state of equipment, while pursuing the goals of maximum efficiency and minimum cost of production processes [8, 9].

To present the planning results, APS and MES systems must have appropriate visual aids, in particular Gantt charts, network diagrams, tables, and completed document forms. In the case of MES systems, it is highly desirable for visual media to provide a high degree of interactivity for the “manual” correction of the available data, as well as the ability to compare the planned results with the actual ones [10, 11].

APS and MES form a single set of process management. Therefore, the operational production planning system should be either initially integrated into MES, or be able to organize effective intersystem interaction.

11. Architecture and user interface
From the point of view of architecture and user interface, operational planning systems generally have the same requirements as other software components of the enterprise’s information environment:
• generally accepted way of storing data;
• availability of standard and easily customizable methods of data exchange with other information systems;
• ability to configure and upgrade the system without the obligatory participation of the developer;
• usability and familiar environment for the end user.

To store information, it is advisable to use the format and tools of any common database management system (DBMS). As a rule, there is a client-server DBMS using a relational data model. It makes sense to apply a three-tier data access architecture when scheduling and other computational activities are implemented on the server inside a special computing core [12]. At the same time, client applications implement a variety of user interfaces and “communication” with the computing core, which is better to organize at the application level of the global information network.

12. Conclusions
End users require versatile, powerful, and easy-to-use operational planning systems for industrial production. A significant amount of various technical requirements is presented to these systems. A constant analysis of these requirements and the identification of common patterns from them allow creating and developing universal planning systems that are applicable not only in industrial production, but also in other systems that manage the resources. The main problem in developing such systems is the need to create complex, but at the same time universal and fast data processing algorithms.

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