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ARTICLE

# Sectoral Advanced Planning Systems (APS) Based on Utility Functions

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## ABSTRACT

This paper contains the example of sectoral APS systems, for which the problem algorithmic space coincides with the relevant operational environment with great accuracy. The method of scheduling for technological processes with looping is described, based on the simultaneous application of two criteria: the value of relative direct costs and the average utility of order fulfillment. The influence of buffers on the work of shops is considered. The proposed method provides an automatic grouping of the same type of jobs on all machines involved while taking into account the required duration of jobs. A package of application programs has been developed that allows planning for an average number of orders. The result of the program is a set of non-dominant (not improved) options that are offered to the user for making a final decision.

***Keywords:*** Scheduling; Production intensity; Buffer; Job shop

## 1. Introduction

In the author's view, the APS definition that best corresponds with its destination is done by Chen, W.L., etc. [1]: "APS systems are considered as an effective approach for generating an optimized production plan considering a wide range of constraints, including raw materials availability, machines, and operators' capability, service level, secure stock level, costs, sales, and demand".

Effective planning has to chime mid-term planning with short-term (daily) scheduling. For this purpose, the schedule of operations on the shop work centers during a fixed planning horizon must be the basis of shop manufacturing. Here, shop work centers include not only the process equipment of

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the shop, but also buffers for various operations, the transport devices inside the shop, and even (though not always) the means of transport for delivering raw materials or picking up finished products.

Recommendations for the application of specific APS systems are usually limited to one or more industries. Some authors, Wiers, V. and de Kok, T. [2] or Kilger, C. [3] list such possible branches, the number of which varies from 8 to 12 accordingly. In spite of the publication of these recommendations, some more modern APS systems, (e.g. Preactor) are used in various fields but with varying degrees of success.

In the author's opinion, there are 2 key requirements for the APS system application for planning in a production system. The first one certainly is to comply as much as possible with all functional restrictions for a specific processing stage. The second requirement consists of the right choice for the criteria for planning optimization.

Almost all of the papers dedicated to production planning include a criterion (or several criteria) to evaluate the quality of such planning. The selection of either criterion is very often determined by reasons of convenience of mathematical methods rather than real features of the considered production system [4].

Many authors, such as Setia, P. etc. [5] or Günter, H.P. [6] point out the need for careful compliance of functional limitations associated with the operating environment and algorithmic capabilities. To identify such connections, Jonsson, P. and Mattsson, S.A. [7] consider 4 possible variants of operating environments: complex products specially manufactured by order (type 1); configuration of products by order (type 2); production of batches of standard products (type 3); mass production (type 4). As a result of a survey of enterprises on the applications of existing APS systems, in the study of Ivert, L., K. [8], the conclusion is that the functionality of these systems often does not match the numerous operational features of these enterprises.

According to Lupeikiene, A. etc. [9], each individual APS system, according to the general theory of algorithms, has its own problem space and, obviously, this space should generally coincide with the space of the operational production environment.

It should be noted that the actual purposes of real production cannot always be formalized to the degree sufficient for mathematical optimization. The reason for this situation usually is that there are several purposes, rather than one, which often contradict each other. As stated in Fleischmann, B. etc. [10]: "There are often several criteria which imply conflicting objectives and ambiguous preferences between alternatives. In this case, no 'optimal' solution (accomplishing both objectives to the highest possible degree) exists."

APS system for a real operational situation must use a multi-criteria approach to simultaneously consider the timely completion of orders (i.e. customer service level) and other criteria that reduce expenses. However, these criteria contradict each other, and the need for their simultaneous implementation is named as "Dilemma of Operation Planning" [11]. The solution to this problem lies in finding the expedient point of "logistic positioning", i.e. a reasonable tradeoff for conflicting objectives. In some works [12,13], positioning and grouping are also used for production lines.

Here the criteria of scheduling quality are two time-current functions: the utility function of total orders set on the planning horizon and the function of relative costs for the same horizon [14].

As an example of a sectoral APS, this paper considers a case that is quite common in machine-building production when the sequence of the technological process includes the transfer of batches of parts from one workshop to another and back. An example is the processing of a batch in a machine shop, the transfer of a batch to a heat treatment or electroplating workshop and the return of this batch to the original workshop to complete the manufacture.

For such a technology, the concept of "loop" shop-to-shop routing is often used, denoting the possibility of circulation between workshops. It is obvious that the APS system for the case under consideration should cover both interacting workshops. Moreover, expanding on the above example, it can be assumed that the heat treatment workshop can serve several mechanical workshops and the schedule of work for each workshop may depend to some extent on the situation in other workshops.

Usually, the job performed in the theory of schedules is understood as a specific position (part) with the corresponding designation in the design specification, which must be manufactured to fulfill the current order for finished products. At the same time, the number of objects in one job should ensure the completion of this order, and the job completion period should be set in accordance with the duration of assembly operations with different levels of input into the finished product.

Obviously, with several levels of input for objects of the same job, the total number of these objects can be produced in several batches. In addition, with a significant complexity of the operation performed, the job can be divided into batches that can be performed in parallel at different work centers in order to speed up the job. During thermal or galvanic processing, the number of simultaneously processed parts is limited by the physical volume of the furnace or bath, which also leads to the need to divide the job into batches.

In some cases (equipment breakdown, urgent job, lack of material, etc.), the job has to be interrupted and then resumed in the next batch. Thus, each job mentioned in the scheduling assignment often passes through a network of work centers and buffers not as a whole, but as a collection of several batches, moreover, at each technological operation, the number of such batches, in principle, may be different.

The rest of the article is organized as follows: Section 2 describes the model of the production system. Section 3 establishes the interaction of work centers. Section 4 describes the algorithm for solving the problem. A numerical example is given in Section 5. Section 6 contains the short result. Section 7 describes the main conclusions.

## 2. Calculation model of the production system

**Figure 1** shows a diagram of a network of work centers and buffers, simplistically describing one of the variants of machine-building production. Let's assume that the processing time of delivering blanks of parts or raw materials entering the system in **Figure 1** is small, although this is not always the case—for example, when delivering sheet materials [15]. Batches of parts and assembly units are moving along the production system in accordance with the technological route with a given flow rate. In some cases, the packaging involves the transfer of batches of parts from the machine shop for heat treatment to the thermal shop, and then return to the machine shop for refinement and subsequent assembly with other parts. We will call this variant of shop-to-shop routing as a "loop".

Any transfer of processing objects between workshops is carried out through the appropriate buffers. In **Figure 1**, the arrows show the possible directions of transferring batches from Workshops 1 and 2 to Workshop 3 and vice versa. The finished products arrive at a special warehouse, from which they are shipped to customers. In this example, it is assumed that the shipping process is not directly related to the production schedule, although in some cases, due to the great complexity of packaging and transportation, the shipment should be taken into account [15].

**Table 1** shows the task for scheduling production on some selected horizons. Each of the 32 jobs of this task is described by a code, which in the first position contains the number of the workshop that produces batches for this job. The subsequent positions contain the serial number of a job; three possible types of objects are considered: parts, assembly units for sub-assembly and assembly units as finished products. The job in a line is intended to complete a job in another line or is a finished product. In the latter case, zero is written as the entry object.

In other columns in **Table 1**, the code of the part or assembly unit, the order code for the finished product, and the required quantity for the order completion are recorded. If at the time of planning, there are no necessary blanks or materials, you must specify the expected time of receipt in calendar hours after the start of planning. The required moment of

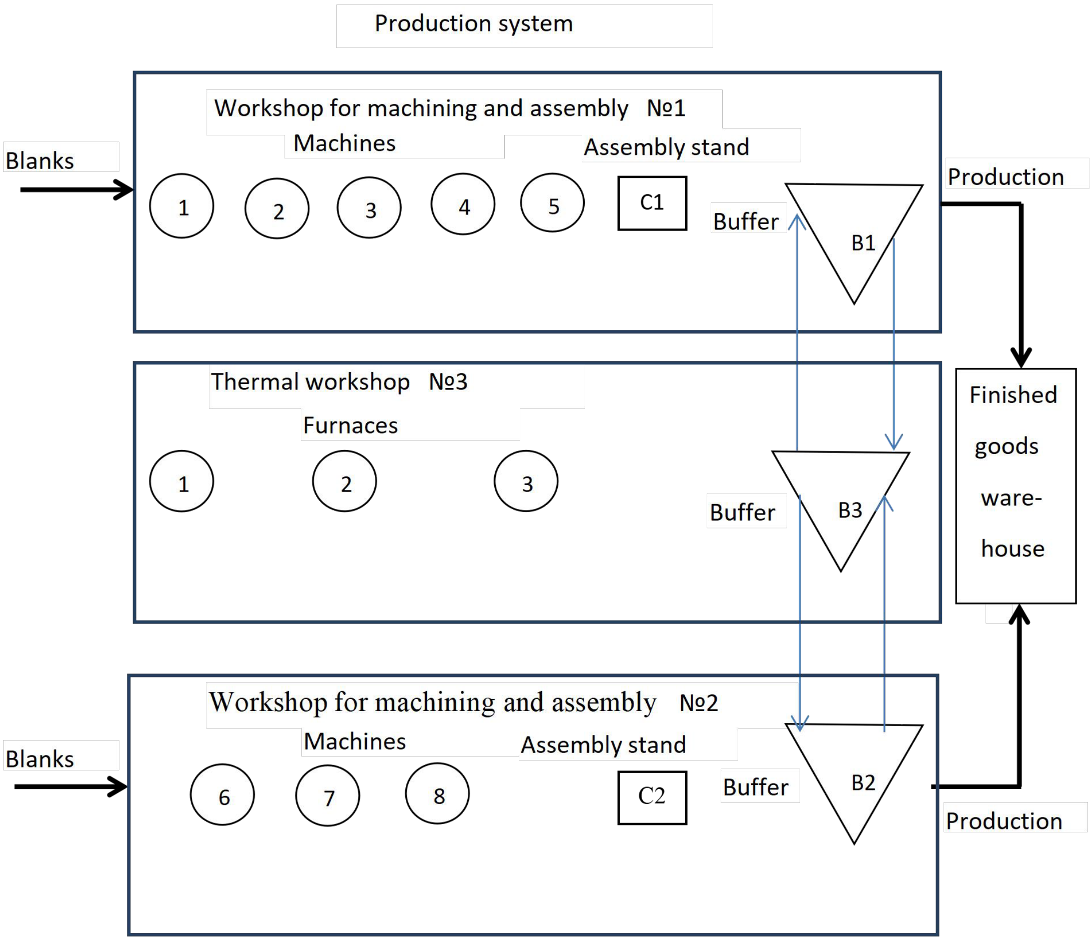

**Figure 1**. Scheme of processing and assembly in machine-building manufacturing.

job completion is set according to the first moment of need for objects of the corresponding type for the current order, which is determined by the process of explosion.

A certain percentage of the total number of objects for a particular job may have been previously shipped to the customer and some items may be in stock awaiting shipment. In particular, for job 108 representing finished products, 20% were sent earlier. Accordingly, for all jobs sequentially included in job 108, the number should be reduced by 20%.

**Table 2** lists the types of possible parts and specifies the minimum production lot size. Since the parts can be processed in an oven or in a bath, it is necessary to set the estimated volume of one part, determined by its dimensions. At the time of planning, both in the buffers of the respective workshops and in the warehouse of finished products, there may be free remains of parts of these types. A similar table is compiled for assembly units.

A fragment of the list of detailed operations for parts of each type is shown in **Table 3**. For each operation with the current serial number, the type of machine or oven used, the type of fixture used, the possible heat treatment code, and the processing time of the operation in minutes are indicated.

In some work centers (buffers, furnaces, baths), it is possible to have several jobs together, as well as their simultaneous execution. The free balances physically located in buffers and warehouses are not indicated in **Table 4**, and their values are shown above in **Table 2**. In addition to **Tables 1-4**, a table of the complexity of setting heat treatment modes, a table of the applicability of devices and a working calendar are used as initial data. In this article, it is proposed to use the method of branches and boundaries for scheduling. To do this, you need to build a multi-level tree of operations, consistently consider-

**Table 1**. Jobs on the selected horizon.

| **Job code** | **The shop number** | **Object type code (1—parts, 2—assemblies, 3—products)** | **Part code or assembly code** | **Where does it enter (job number, warehouse-0)** | **Order code for finished product** | **Expected receipt of the workpiece at the beginning** | **Required calendar day of readiness after start** | **Quantity based on order for finished products** | **Weight coefficient** | **Sent as a percentage of the order** | **It is a part of assemblies in warehouses as a percentage of the order** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 101 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 200 | 2 | 0 | 0 |
| 102 | 1 | 1 | 2 | 105 | 2 | 0 | 1 | 30 | 1 | 20 | 0 |
| 103 | 1 | 1 | 4 | 105 | 2 | 0 | 1 | 60 | 2 | 20 | 0 |
| 104 | 1 | 1 | 3 | 105 | 2 | 0 | 2 | 30 | 3 | 20 | 0 |
| 105 | 1 | 2 | 1 | 108 | 2 | 0 | 2 | 30 | 1 | 20 | 0 |
| 106 | 1 | 1 | 5 | 108 | 2 | 0 | 3 | 40 | 1 | 20 | 0 |
| 107 | 1 | 1 | 3 | 108 | 2 | 0 | 3 | 20 | 1 | 20 | 0 |
| 108 | 1 | 3 | 5 | 0 | 2 | 0 | 4 | 20 | 1 | 20 | 0 |
| 109 | 1 | 1 | 2 | 114 | 3 | 1 | 3 | 40 | 1 | 0 | 50 |
| 110 | 1 | 1 | 6 | 114 | 3 | 1 | 2 | 40 | 1 | 0 | 50 |
| … | .. | .. | .. | .. | .. | … | … | … | … | … | … |
| 205 | 2 | 1 | 9 | 208 | 4 | 0 | 2 | 20 | 1 | 0 | 0 |
| 206 | 2 | 1 | 5 | 208 | 4 | 0 | 2 | 40 | 1 | 0 | 0 |
| 207 | 2 | 1 | 7 | 212 | 4 | 0 | 4 | 20 | 1 | 0 | 0 |
| 208 | 2 | 2 | 9 | 212 | 4 | 0 | 4 | 20 | 1 | 0 | 0 |
| 209 | 2 | 1 | 8 | 212 | 4 | 1 | 4 | 20 | 1 | 0 | 0 |
| 210 | 2 | 1 | 6 | 212 | 4 | 1 | 5 | 20 | 1 | 0 | 0 |
| 211 | 2 | 1 | 7 | 212 | 4 | 1 | 5 | 20 | 1 | 0 | 0 |
| 212 | 2 | 3 | 9 | 0 | 4 | 1 | 7 | 10 | 1 | 0 | 0 |

**Table 2**. Types of manufactured parts.

| Part code | Minimum lot | Estimated volume of the part (by dimensions) in liter | Free remains of parts in the buffers of workshops, pcs. | Free remains of parts in the warehouse of finished products, pcs. |
|---|---|---|---|---|
| 1 | 50 | 2.0 | 0 | 0 |
| 2 | 20 | 1.5 | 0 | 0 |
| 3 | 20 | 1.0 | 10 | 0 |
| 4 | 50 | 2.2 | 0 | 0 |
| 5 | 30 | 0.7 | 40 | 10 |
| 6 | 20 | 2.4 | 0 | 0 |
| 7 | 40 | 1.4 | 0 | 0 |
| 8 | 30 | 3.5 | 0 | 0 |
| 9 | 30 | 2.5 | 0 | 0 |

**Table 3**. Fragment of the operation details.

| Part code | The operation number | Number of the type of machines or furnace | Device type number or heat treatment code | Processing time, min. |
|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 8 |
| 1 | 2 | 1 | 3 | 12 |
| 1 | 3 | 102 | 1 | 120 |
| 1 | 4 | 4 | 7 | 4 |
| 2 | 1 | 1 | 1 | 8 |
| 2 | 2 | 102 | 1 | 120 |
| 2 | 3 | 4 | 7 | 10 |
| 3 | 1 | 1 | 3 | 12 |
| 3 | 2 | 2 | 3 | 6 |
| 3 | 3 | 101 | 3 | 130 |
| 3 | 4 | 3 | 4 | 12 |
| 3 | 5 | 4 | 7 | 12 |
| 4 | 1 | 1 | 1 | 8 |
| 4 | 2 | 3 | 0 | 12 |
| 4 | 3 | 101 | 3 | 60 |
| 4 | 4 | 2 | 6 | 6 |

**Table 4**. Initial state of work centers.

| Name of the work center | Work center code | The number of the type of machine or oven or buffer | Workshop number | Mark of inclusion | Working volume in liters | Fixture code or heat treatment code | Job code in the current planning | The number of the operation being performed (or performed in the buffer) | Batch number for the current operation | The percentage of job performed on the operation by the batch | Expected release time in hours or the last downloads in the buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Machine | 1 | 1 | 1 | 1 | 0 | 0 | 0; | 0; | 0; | 0; | 0; |
| Machine | 2 | 1 | 1 | 1 | 0 | 1 | 101; | 2; | 1; | 33; | 10; |
| Machine | 3 | 2 | 1 | 1 | 0 | 8 | 104; | 2; | 1; | 17; | 9; |
| Machine | 4 | 3 | 1 | 1 | 0 | 0 | 103; | 4; | 1; | 30; | 12; |
| Processing center | 5 | 4 | 1 | 1 | 0 | 10 | 102; | 3; | 1; | 30; | 10; |
| Machine | 6 | 5 | 2 | 1 | 0 | 6 | 206; | 5; | 1; | 50; | 0; |
| Machine | 7 | 1 | 2 | 1 | 0 | 7 | 201; | 1; | 1; | 100; | 8; |
| Processing center | 8 | 4 | 2 | 2 | 0 | 9 | 203; | 4; | 1; | 100; | 9; |
| Furnace | 9 | 102 | 3 | 1 | 100 | 2 | 103; | 3; | 1; | 50; | 8; |
| Furnace | 10 | 102 | 3 | 1 | 100 | 1 | 102; | 2; | 1; | 50; | 8; |
| Furnace | 11 | 101 | 3 | 1 | 120 | 1 | 0; | 1; | 0; | 0; | 12; |
| Assembly stand | 12 | 201 | 1 | 1 | 0 | 0 | 0; | 1; | 0; | 0; | 0; |
| Assembly stand | 13 | 202 | 2 | 1 | 0 | 0 | 0; | 1; | 0; | 0; | 10; |
| Buffer | 21 | 301 | 1 | 1 | 1000 | 0 | 101;104;110;114; | 1;5;1;1; | 1;1;1;1; | 20;20;50;20; | 8;8;10;8; |
| Buffer | 22 | 302 | 2 | 1 | 1000 | 0 | 205;206; | 2;4; | 1;1; | 100;50; | 0;8; |
| Buffer | 23 | 303 | 3 | 1 | 1000 | 0 | 202;107; | 2;2; | 1;1; | 50;100; | 0;8; |
| Finished goods warehouse | 24 | 304 | 0 | 1 | 2000 | 0 | 101;120; | 4;1; | 1;1; | 20;30; | 8;8; |

ing the feasibility of building new tree nodes. To determine the boundaries at each level of construction, we will apply the criteria for the order utility function and the cost of operations described in Mauergauz Y. [14]. The calculation algorithm is given below.

## 3. Interaction of work centers in the production system

**Figure 2** shows possible options for the interaction of work centers. In any case, the main component of such interaction is some (active) work center in which the current operation is carried out.

In this example, there are three types of active work centers: a) machines in workshops 1 and 2 for machining, b) assembly stands in the same workshops, and c) furnaces in shop 3. **Figures 2a and 2b** show possible operations for shop 1, and **Figure 2c**—for shop 3. To carry out an operation, sources of materials, parts from previous operations or assembly units are always needed to continue the assembly. As follows from **Figure 2**, such sources for the operation in the shop can be a warehouse of materials from outside the shop, other machines in the same shop, as well as the buffer of the shop.

The recipients of the results of the operation can be both in the same workshop and outside it. For example, **Figure 2a** shows that the recipients can be machines for performing a subsequent operation located in the same workshop, which stands for assembly, as well as a buffer of this workshop. In addition, if it is necessary to perform heat treatment as the next operation, the finished batch should be transferred to the buffer of the thermal shop 3.

If the operation is the last one, and the manufactured parts are finished products, then batches of these parts are transported to the finished product warehouse. If it is absolutely necessary to use the equipment of another machine shop for further processing, then the recipient is its buffer. During the assembly operation (**Figure 2b**), the recipients are either the buffer of the current workshop or the finished product warehouse. After the heat treatment (**Figure 2c**), the batches of parts are transferred to the buffers of the machine shops.

It follows from **Figure 2** that during any processing or assembly operation, it is necessary to consider possible changes in the contents in the buffers of workshops and in the finished product warehouse.

Changes are possible both at the beginning of the current operation and at the end of it. Moreover, if the processing time of the batch is long enough, it is possible to transfer part of it to the buffer. Below are the variants of these changes.

a) At the beginning of the operation on the machine or the assembly stand of the machine shop, the system must ensure the availability of the vacated work center. If the previous operation on this center is completed, but the processed objects are still in the center itself or in a storage location near the center, these objects must be moved to the buffer of the corresponding workshop.

b) A batch of workpieces or parts awaiting the continuation of machining must be transported to the vacated machine for a new operation. If the source is the work center – the machine (**Figure 2a**), then it is also completely released. If the source is a workshop buffer, then the contents of the buffer are reduced by the amount of the batch being moved.

c) The operation of assembling a batch of some job begins only if there is a certain amount for all parts and assembly units included in this assembly. The specified quantity for different positions may be different, and the timing of the batches may also vary. Obviously, the size of the assembly batch is determined by the minimum available batch for the item included in the package, and the start time of the assembly batch is set at the moment when the last of the required positions appear.

At the start of the assembly batch (**Figure 2b**), the parts and assembly units involved in the assembly from the machines and from the buffer of the workshop must be moved to the assembly stand. At the same time, the remaining number of parts and assembly units for all participating positions should be in the buffer of the workshop.

d) For heat treatment (**Figure 2b**), batches of parts must be transferred to the buffer of the thermal workshop. During the operation, joint heat treatment

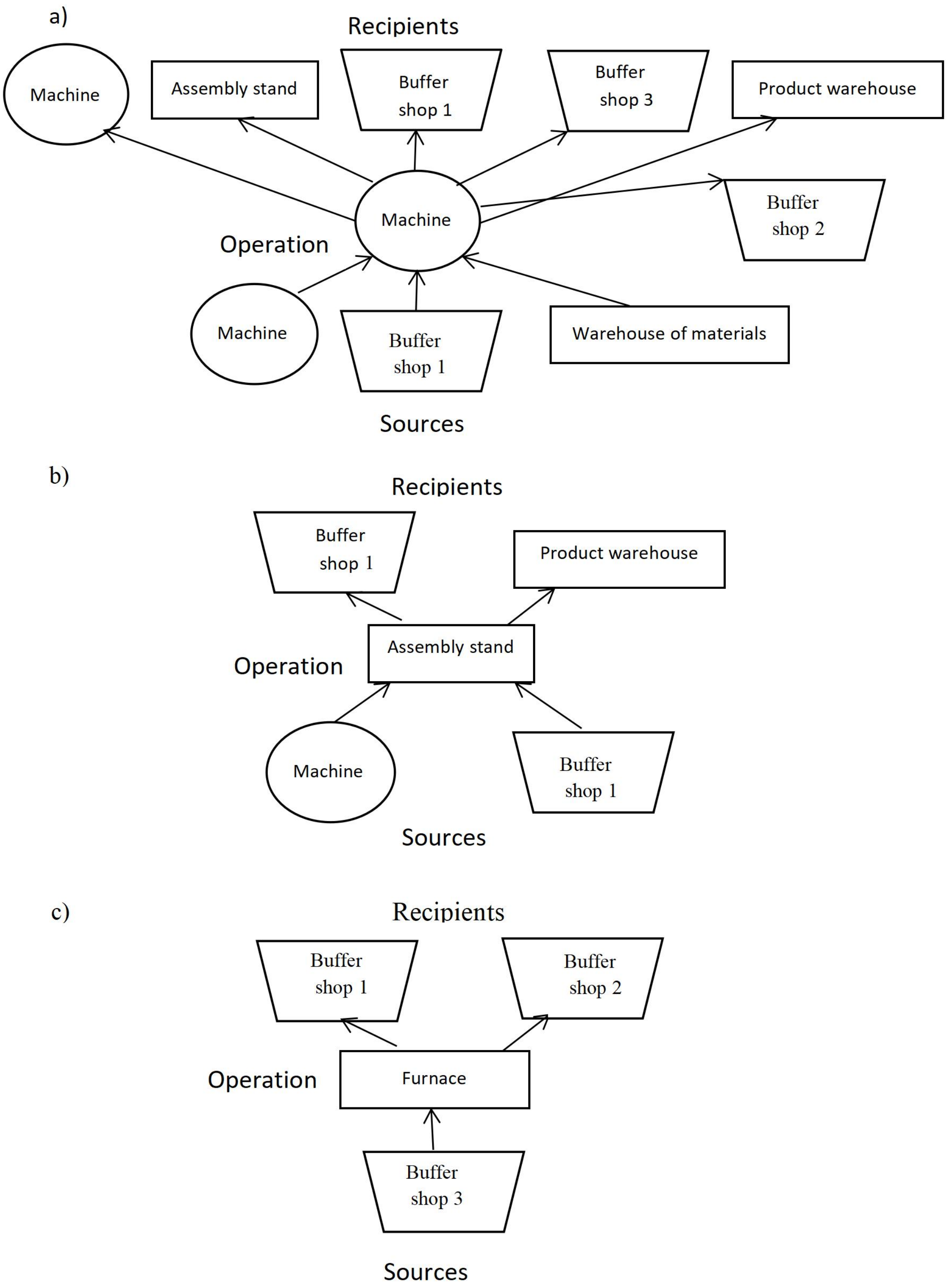

**Figure 2**. Options for interaction of work centers. a) machines in workshops 1 and 2 for machining, b) assembly stands in the same workshops, c) furnaces in shop 3.

is possible for different batches coming from different workshops. The number of parts in one batch of heat treatment may be less than the quantity received due to the limited working space of the furnace. Therefore, at the beginning of the operation, the contents of the thermal buffer are reduced in accordance with the loading of the furnace. After processing, batches of parts must be immediately transferred to the buffers of the corresponding workshops.

e) The batch of the job that are finished products must be transferred to the appropriate warehouse after assembly on the stand (**Figure 2b**) or the last operation on the machine (**Figure 2a**). The rules of changes in buffers described above are taken into account in the algorithm below and the corresponding computer program.

## 4. Solution algorithm

The structural formula of the present problem in accordance with the known three-element method of classification of schedules has the form:

$$FJ\left|pmtn,\ prec, d_i, s_{mx}, b_x\right| U, \bar{V}. \tag{1}$$

The parameter of the first field FJ describes flexible job shop. In the second field, the parameter *pmtn* shows that processing at work centers is carried out in batches, in general, not equal to the size of orders; the parameter *prec* defines multi-stage processing; $d_i$ is the specified moment of completion of the job; $s_{mx}$ is labor intensity for the preparation of the operation at the work center $m$ for the operation $x$; $b_x$ is available capacity of the work center (or the required buffer) for the operation $x$. The third field contains the target functions $U$, $\bar{V}$.

Recall that the production intensity [14], in the case of multi-stage production, has the form:

$$H_i = \frac{w_i p_i}{G}\frac{1}{(d_i - t)/(\alpha G)+1} \text{ if } d_i - t \geq 0$$

$$\text{and} \tag{2}$$

$$H_i = \frac{w_i p_i}{G}((t - d_i)/(\alpha G)+1) \text{ if } d_i - t \leq 0,$$

where $w_i$ is weight coefficient; $p_i$ is remaining processing time in hours until the end of the job; $G$ is duration of the planned period in calendar hours; $t$ is current time; $d_i$ is the specified time of task completion in calendar hours; $\alpha$ is psychological coefficient.

If job execution is multistage, the process time of job $i$ that remains until completion consists of process time on $N_i$ of certain $j$ operations.

$$p_i = \sum_{x=1}^{N_i} p_{ix}. \tag{3}$$

Necessary release date of operation $g_i$ in hours is as:

$$g_i = d_i - p_i + 1. \tag{4}$$

The current utility for an order $i$ is:

$$V_i = w_i p_i / G - H_i. \tag{5}$$

The nature of dependencies (2) and (5) is described in detail in Mauergauz Y. [15]. If the number of orders on the planning horizon is $n$, their total current utility is equal to the sum of the utilities of each, because orders are usually independent.

Then the total value of the function of the current utility of orders:

$$V = \sum_{i=1}^{n} V_i = \frac{1}{G}\sum_{i=1}^{n} w_i p_i - \sum_{i=1}^{n} H_i. \tag{6}$$

The average utility $\overline{V_l}$ of the entire volume of planned jobs at level $l$ is calculated for the time from the initial moment t = 0 to the end of the last already planned operation [15] at each step of the algorithm.

The calculation of the value of direct costs at the $l$ level for job $k$ should be carried out according to the recurrent formula [15].

$$U_{l+1,k} = \frac{c_s}{c}\left(\sum_{j=1}^{l} s_j + s_{km}\right) \tag{7}$$

where $c$ is the cost of a work shift; $c_s$ is the cost of an hour of changeover; $s_j$ is the complexity of setting up for each job $j$ in the chain for a tree node that includes a level $l$; $s_{km}$ is the complexity of job $k$ transportation to machine $m$.

For solving the problem (1) it makes sense to apply the method, based on the MO-Greedy approach [16]. In this case, the algorithm for calculating production schedules can represent a tree of sequential decisions about conducting a new operation. At each level of tree construction, from all possible such solutions, those are selected for which the criteria for the average utility of orders $\bar{V}$ and costs $U$ on the planning horizon are "non-dominant". This means that possible solutions with the worst values for both criteria are discarded. In a greedy algorithm, at each step, a choice is made that seems to be the best.

Let's describe the algorithm step by step.

Step 1. *(Distribution of free balances between the jobs of the new task)*

Step 2. *(Determination of percentages of operations at the initial moment)*

Step 3. *(Determination of the remaining process-*

*ing time for all jobs)*

Step 4. *(Calculation of utility functions at the initial moment of planning)*

Let's put the level number $l = 0$; initial cost function $U_0 = 0$; initial orders function $V_0$ is determined by the formula (5); number of nodes $Z_0 = 1$.

### External cycle

Step 5 *(Identification of possible operations at the following levels)*

For each node $z$ of the constructed tree at level $l$ the loading of each machine is restored, the possible operations are determined and values $g_i$ are calculated using formulas (3) and (4).

### Middle cycle

Step 6. *(Determination of the required machine at the following levels)*

For each operation $k$ that is possible and not previously performed, the necessary family $f$ of machines and devices is determined.

### Internal cycle

Step 7 *(Calculation of utility functions at the following levels)*

For each machine $m$ belonging to the type $f$, taking into account the moment of its possible release, values are calculated $U_{l+1,z,k,m}$ и $\overline{V}_{l+1,z,k,m}$ by formulas (7) and (6).

Step 8 *(Defining content in buffers)*

**End of the internal cycle**

**End of the middle cycle**

Step 9. *(Definition of non-dominant tree nodes)*

If the l + 1 level is not the last, then to dominate the l + 1 level a possible tree node $y$ above a possible node $x$ must be observed inequalities.

$$U_{l+1,y} \le U_{l+1,x}, \ \overline{V}_{l+1,y} \ge \overline{V}_{l+1,x} \text{ and } g_{l+1,y} < g_{l+1,x}.$$

Otherwise: in order to dominate at the last l + 1 level, it is necessary that:

$$U_{l+1,y} \le U_{l+1,x}, \quad \overline{V}_{l+1,y} \ge \overline{V}_{l+1,x}.$$

Step 10. *(Transition to a new level or termination of the program)*

If the level is higher than the last one (all operations are performed), then the end of the program.

Otherwise: Memorizing non-dominant nodes at the $l$ level. Increase the level number $l = l + 1$ and go to step 5.

**End of the external cycle**

A distinctive feature of this algorithm in comparison with the similar algorithm given in Mauergauz Y. [17] is the presence of step 8 to determine the contents of buffers. The corresponding procedure is carried out according to rules a)-e) of the previous paragraph.

## 5. Example of schedule calculation

Let's assume that in accordance with the existing orders, the master plan is formed at the enterprise, on the basis of which tasks are given to workshops for a certain horizon (**Table 1**). Since the previous plan is not always fulfilled, the new plan may consist of both new jobs and jobs that transfer from the previous plan. At the same time, the time reserved for performing such jobs may be negative.

**Figure 3** shows a Gantt diagram for several machines and assembly stands in workshops 1 and 2, as well as for furnaces in workshop 3. Each rectangle of the diagram, as usual, corresponds to the job in the task in **Table 1**. For machines, the code of the device used is written inside the rectangle, for furnaces—the code of heat treatment. Since the job is carried out in batches, the job numbers on the diagram can be repeated.

The system automatically groups the jobs on one machine by the codes of devices, and in furnaces—by the code of heat treatment. For example, machine 5 is used only with fixture 10, on machine 3 the jobs are grouped for fixtures 8, 3 and 4. Furnace 9 is used only for heat treatment with code 1, and in furnace 11 the jobs are grouped by heat treatment codes 3 and 2.

**Figure 4** shows a diagram of batches of jobs on specific processing and assembly operations.

The batch number is recorded above the rectangle of the job, and inside the rectangle is the inventory number of the work center with the operation being

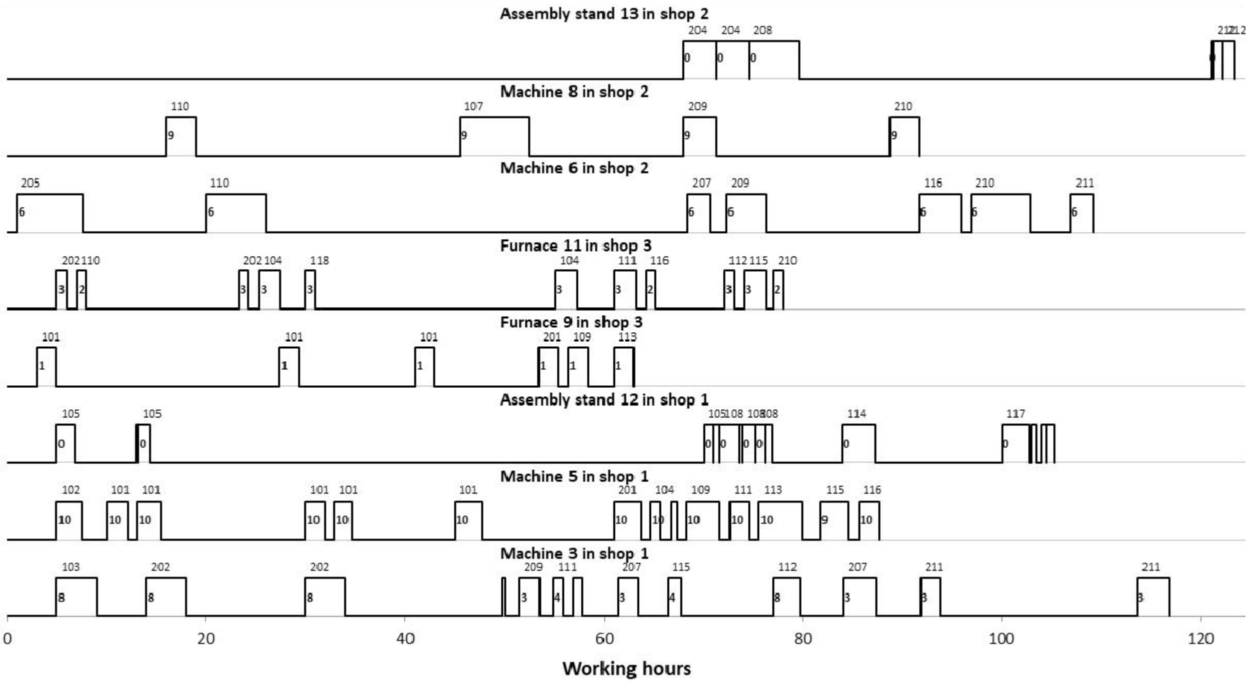

**Figure 3**. Gantt chart.

performed. For example, during the execution of job 101 (**Table 1**), type 1 parts are manufactured, which requires 4 operations.

At the same time, 20% of the job has already been fully completed and is in the finished product warehouse, and some operations on batches of this job have also been partially completed by the beginning of planning (**Table 4**). The buffer of shop 1 already contains batch 1 of job 101, containing 20% of this job on operation 1. In addition, on machine 2, the batch of the same job ends in the amount of 33% for operation 2. Therefore, the remainder of the job on operation 1 in the amount of 27% should be performed in the form of batch 2.

Because the number of parts for job 101 is 200 (**Table 1**), and the complexity of the second operation of the part type 1 is 12 minutes (**Table 3**), then it is advisable to perform the entire remainder of the job 101 on the second operation, equal to 47%, in several batches. The program automatically splits this volume into 2 batches, shown in **Figure 4**.

Operation 3 (heat treatment) for job 101 is carried out in 5 batches, the sizes are determined by the available volume of furnaces. At the same time, furnaces 9 and 10 are used in parallel, as shown in **Figure 4**. Since the first batch on operation 4 for job 101 is already in stock (**Table 4**), the next 5 batches for operation 4 are executed starting from number 2 (**Figure 4**). Similarly, batches are performed on operations for other jobs.

**Figure 5** shows the schedules of receipt of batches of finished products to the warehouse. As follows from **Figure 5**, the schedule for job 101 (blue) at the beginning of planning (8 hours) contains batch 1 in 20% of the total size of the job. Then, gradually, 5 new batches arrive at the warehouse, eventually amounting to 100%. A similar situation occurs with other jobs describing finished products. The exception is job 108 (brown), 20% of which was shipped earlier (**Table 1**).

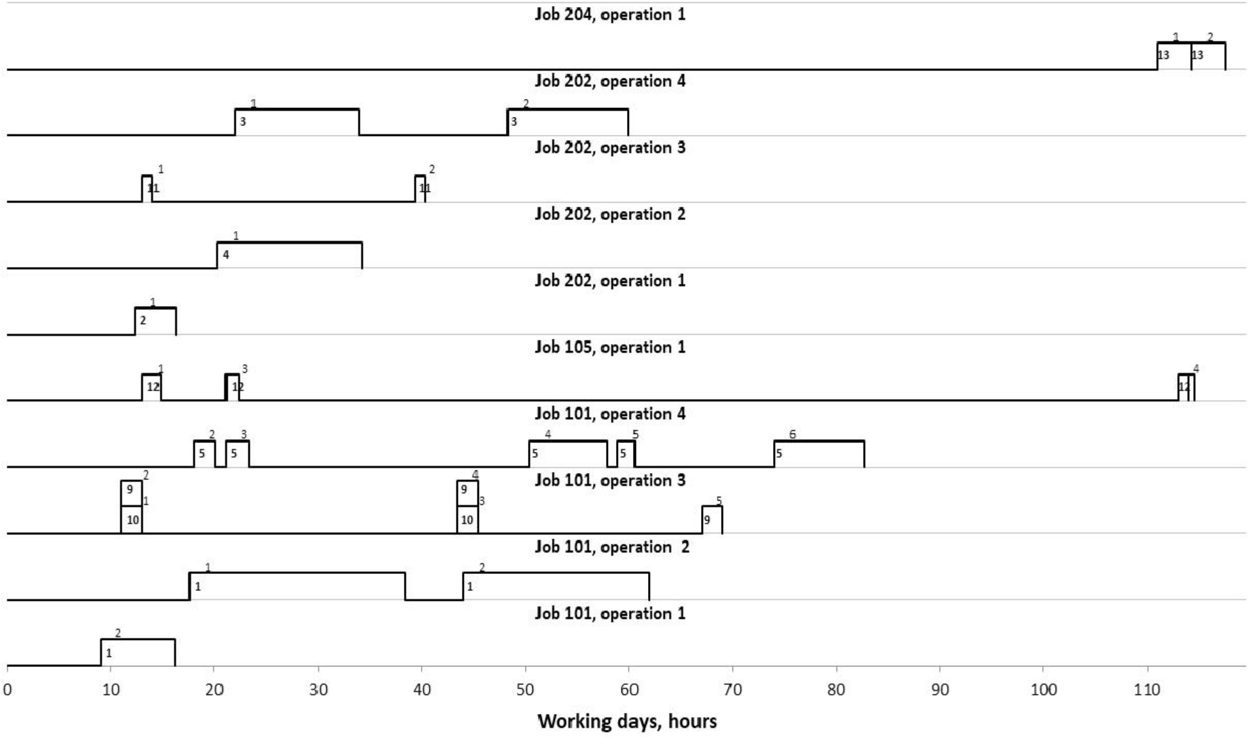

**Figure 4**. Batches of jobs on operations.

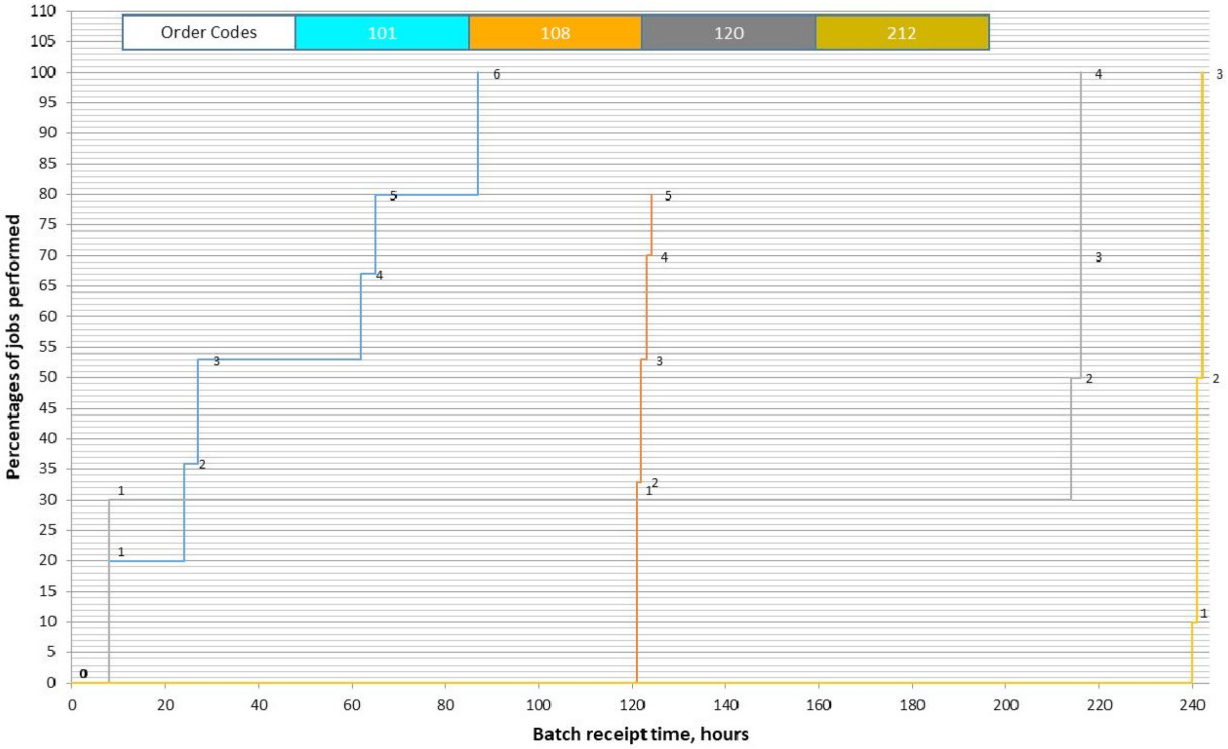

**Figure 5**. Receipt of batches of finished products to the warehouse.

## 6. Results

Using the example of a sectoral APS of a machine-building enterprise, the calculation of the equipment charge plan and the execution of operations for several interacting workshops at once is shown. At the same time, the initial state of the work centers, the possible division of jobs into batches and the movement of material objects in buffers are taken into account. As a result, this solution closely reflects the operating activities of the machine-building enterprise.

## 7. Conclusions

The solutions obtained by the described method are not 100% optimal and, generally speaking, can be improved. The reason is the use of a "greedy" algorithm that does not provide "global" optimization. But the solution turns out to be quite satisfactory, fast and reliable—the duration of the program in the examples given is about 1 min. The main advantage of the utility function method is the possibility of a fairly simple adaptation of the program structure to the specific operating environment of the task under consideration.

Indeed, the differences between various tasks consist in the mechanism for calculating the utility function, as well as in taking into account various restrictions (for example, related to buffers). At the same time, most of the algorithm for building a schedule tree is preserved without significant changes.

The proposed method provides automatic grouping of the same type of jobs on all machines involved, while taking into account the required duration of jobs. To build schedules, a set of decisions is built on the planning horizon, on the basis of which the user makes the final decision. When the horizon increases, the system automatically offers options with increasing grouping of jobs into groups.

The appearance of deviations from the planned course of production should be adjusted in the schedule and taken into account during the next planned cycle. Since the quality criterion of the schedule is a function of the average utility of all jobs within the planned horizon, changes in the value of this criterion with individual schedule adjustments are usually not very large and, accordingly, have little effect on the structure of the schedule as a whole.

## Author Contributions

Conceptualization, methodology, formal analysis, computer programming, resources, writing, visualization, all these are done by the author.

## Conflict of Interest

There is no conflict of interest.

## References

[1] Chen, W.L., Huang, C.Y., Lai, Y.C., 2009. Multi-tier and multi-site collaborative production: Illustrated by a case example of TFT-LCD manufacturing. Computers & Industrial Engineering. 57(1), 61-72.

[2] Wiers, V.C., de Kok, A.T.G., 2017. Designing, selecting, implementing and using aps systems. Springer: Berlin.

[3] Stadtler, H., Kilger, C., Meyr, H., 2015. Supply chain management and advanced planning: Concepts, models, software, and case studies. Springer: Berlin.

[4] Panwalkar, S.S., Dudek, R.A., Smith, M.L., 1973. Sequencing research and the industrial scheduling problem. Symposium on the theory of scheduling problem. Springer: Berlin. pp. 29-38.

[5] Setia, P., Sambamurthy, V., Closs, D.J., 2008. Realizing business value of agile IT applications: Antecedents in the supply chain networks. Information Technology and Management. 9, 5-19.

[6] Günter, H.P., 2005. Supply chain management and advanced planning systems: A tutorial. Physica-Verlag HD: Heidelberg.

[7] Jonsson, P., Mattsson, S.A., 2008. Inventory management practices and their implications on

perceived planning performance. International Journal of Production Research. 46(7), 1787-1812.

[8] Ivert, L.K., 2012. Use of Advanced Planning and Scheduling (APS) systems to support manufacturing planning and control processes [Ph.D. thesis]. Göteborg, Sweden: Chalmers University of Technology.

[9] Lupeikiene, A., Dzemyda, G., Kiss, F., et al., 2014. Advanced planning and scheduling systems: Modeling and implementation challenges. Informatica. 25(4), 581-616.

[10] Fleischmann, B., Meyer, H., Wagner, M., 2007. Advanced planning. Supply chain management and advanced planning: Concepts, models, software and case studies, 4th ed. Springer: Berlin.

[11] Nyhuis, P., Wiendal, H.P., 2009. Fundamentals of production logistics. Springer: Berlin.

[12] Klausnitzer, A., Neufeld, J.S., Buscher, U., 2017. Scheduling dynamic job shop manufacturing cells with family setup times: A simulation study. Logistics Research. 10(4), 1-18.

[13] Logendran, R., Carson, S., Hanson, E., 2005. Group scheduling in flexible flow shops. International Journal of Production Economics. 96(2), 143-155.

[14] Mauergauz, Y. (editor), 2013. Cost-efficiency method for production scheduling. World Congress on Engineering; 2013 Jul 3-5; London. Hong Kong: International Association of Engineers. p. 589-593.

[15] Mauergauz, Y., 2022. Dynamic scheduling for flexible manufacture: 15 computer programs. BP International: India.

[16] Canon, L.C. (editor), 2011. MO-Greedy: An extended beam-search approach for solving a multi-criteria scheduling problem on heterogeneous machines. 2011 IEEE International Symposium on Parallel and Distributed Processing Workshops and Phd Forum; 2011 May 16-20; Anchorage, AK, USA. New York: IEEE. p. 57-69.

[17] Mauergauz, Y., 2015. Dynamic group job shop scheduling. International Journal of Management Science and Engineering Management. 10(1), 41-49.