The Multi-Agent method for real time production resource-scheduling problem

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Abstract An operational scheduling method of production resources for enterprises has been analyzed and is being proposed. In order to assemble a client's order, it is necessary to produce each detail by making the number of technological operations via an appropriate production resource. For scheduling and managing the production process, it is necessary to define the whole structure of the final assembly with a technology map. This representation is proposed by using a special ontological definition, and give the example for an enterprise producing electrical products. The process of scheduling has a high level of complexity due to the variety of types of resources used, and the dependence of production processes on many factors and conditions. Also considered real time events and each time getting information about a new fact of processing of each detail on each resource, the current production plan has to be rescheduled. Traditional methods for solving the problem are not possible using in real time scheduling, which is why it is proposed the multi-agent approach for that task. The developed system based on the proposed method is used by the real enterprise produces electrical products in Samara city, where, as a result, the number of delays in the execution of production orders was reduced by 10%.

Keywords multi-agent methods, production resource management, ontology of the production enterprise, real-time scheduling

1 Introduction

The problem optimization of organization and production scheduling was first described in 1939 by Leonid Kantorovich in his work *Mathematical methods of organization and production planning* [1]. Since then, it has become one of the most significant tasks of the optimization theory. At the current moment, there are many practical cases of such problems, which do not have exact solution methods because in each specific case, different criteria of optimality, restrictions and preferences are used: the mutual dependencies of different plans, interchangeability of various machines during a particular technological operation, the order of transferring parts to production, dependence on the terms of delivery final product to customers, the current loading of one's own resources and the possibility to cooperate with other production enterprises, the terms of payment and receipt of materials and components, etc. Additionally, the task becomes more complicated by the need to solve it in real time, when by using the flow of external factual data requiring it to change the incoming conditions and reconstruct the solution in an acceptable time.

In the early 2000s V. Gorodetsky, M. Wooldridge and N. Jannings demonstrated the possibility of using multi-agent technology for solving such problems [2, 4, 6]. In 2006, S. Chapman gives an overview of the main approaches applied in production scheduling [3]. With regard to the development of the theory in 2010, D. Easley and D. Kleinberg, based on the ideas of A. Sandholm, proved the theorem establishing the equivalence of the assignment problem and iterative auctions in the agents' virtual market. As a result, the important advantages of this approach were confirmed: intuitive understandability for users, ease of including new business requirements, the possibility of parallel processing, etc. [5]. In the works of V. Wittich, G. Rzhevsky and P. Skobelev, a method of adaptive scheduling was proposed, and the first prototypes and industrial control systems for production resources were created [7-9]. In 2014 O. Granichin in his work about NP-hard planning problems of computing on grid-networks, proved the possibility to have a quasi-optimal solution in polynomial time [10]. In 2010-2017, P. Skobelev and I. Mayorov proposed a situational approach to resource management and developed a multi-agent platform for the creation of intelligent systems, preserving scenes in the context of the situation to improve the quality and effectiveness of planning in the course of changing the situation by events [11-14].

At the same time, the definition of the problem based on ontology and development of methods for obtaining and processing actual data from production resources for solving the problem in real time, in the described theory, was not considered. Therefore, it becomes urgent to develop new methods and tools for solving the problem in real time for creating new management systems that would allow solving a wider range of tasks using an ontological description, build an initial schedule, and adaptively schedule resources based on actual events coming from participants in the production process.

2 Setting the task of initial planning of production resources

Consider a set of production orders, O_n, $n = \overline{1,s}$ and a set of resources (machines and other equipment) R_j, $j = \overline{1,m}$. Each order is characterized by a technological map, with a description of all the details D^i_k, $k = \overline{1,p}$, which can also consist of other details (there is a multilevel nesting). Every detail D^i_k, described by materials M^{ik}_z, $z = \overline{1,q}$, of which it is manufactured, and an ordered set of technological operations TO^{ik}_j, $j = \overline{1,m}$, which are required to be made with the material or another part by the resource R_j for a known part time TD^{ik}_j. The technological map describes by the following ontological structure:

$[O_n]$
$\{[D^n_1]$
$[M^{n,1}_1]$
$[M^{n,1}_q]$
$\{[D^{n,1}_1]$
$[M^{n,1,1}_1]$
$[M^{n,1,1}_q]$
$\{[D^{n,1,1,\ldots}_p]\}$
$[TO^{n,1,1}_1]$ $[R_1]$ $[TD^{n,1,1}_1]$
$[TO^{n,1,1}_m]$ $[R_m]$ $[TD^{n,1,1}_m]\}$
$\{[D^{n,1}_p]\}$
$[TO^{n,1}_1]$ $[R_1]$ $[TD^{n,1}_1]$
$[TO^{n,1}_m]$ $[R_m]$ $[TD^{n,1}_m]\}$
$\{[D^n_p]\}$

For each resource R_j is known a daily time window $[TRs_j;\ TRf_j]$. It defines availability of this resource for work (working shift of the machine), taking into account the workers' work and rest time. The same detail cannot be processed on several resources simultaneously; while one resource processes one detail, the second resource can be used to process another detail. It is required to make a shift-daily work schedule for each resource R_j for the production of all O_i orders, according to their technological maps, with a minimum downtime of resources R_j.

2.1 Initial scheduling method

To solve the problem of initial scheduling, it is proposed to use the "greedy" iterative method, where the details of all orders are distributed according to the production resources by the following algorithm: orders O_i are processed sequentially from 1 to s. Of all the details of the D^i_k i-th order, first select those that lie at the lowest level of the technology map, then the level above and so on, to the highest level. Details lying on the same level are processed sequentially, according to their ordinal number in the level, taking into account the successive execution of technological operations TO^{ik}_j on the resources R_j. When planning the operations of each detail the method checks the availability of the necessary M^{ik}_z

materials required for the production of the detail, if there is not enough material, the part is skipped. Gaps in the schedule of the required resource are analyzed taking into account the window of availability of its current shift time window $[TRs_j; TRf_j]$ and first of all the empty spaces, created by the previous scheduling operations, are filled in starting with the earliest gap. If the size of the gap is not sufficient to perform the operation, then the next gap is analyzed. In the worst case scenario, if it is not possible to use any available gap, the operation sets it at the very end of the schedule. If, in view of its setting, the finish time of processing larger than the right time of the current resource shift window $[TRs_j; TRf_j]$, it goes to the next available shift. All the details of subsequent orders process in a similar way. The algorithm repeats until all operations of the details of all orders are scheduled to available resources.

2.2 An example of using initial scheduling method

Let's consider an example of planning two orders O_1 and O_2 of the production a transformer-locking unit and switching lever for the transformer substation. The technological map for these orders has the form:

[O_1] Transformer locking unit
{[$D^1{}_1$] Channel
[$M^{1,1}{}_1$] Metal sheet 4 mm 1.5 kg
{[$D^{1,1}{}_1$] Channel-01
[$M^{1,1,1}{}_1$] Metal sheet 4 mm 1 kg
[$TO^{1,1,1}{}_1$] Sawing of metal [R_1] Laser complex [$TD^{1,1,1}{}_1$] 60 sec
[$TO^{1,1,1}{}_2$] Bending [R_2] Hydraulic press [$TD^{1,1,1}{}_2$] 60 sec
[$TO^{1,1}{}_1$] Sawing of metal [R_1] Laser complex [$TD^{1,1}{}_1$] 80 sec
[$TO^{1,1}{}_2$] Bending [R_2] Hydraulic press [$TD^{1,1}{}_2$] 60 sec}}
{[$D^1{}_2$] Channel-02
[$M^{1,2}{}_1$] Metal sheet 3 mm 2.5 kg
[$TO^{1,2}{}_3$] Cutting [R_3] Band saw machine [$TD^{1,2}{}_3$] 120 sec}
[O_2] Lever for turning on transformer
{[$D^2{}_1$] Flange
[$M^{2,1}{}_1$] Metal sheet 6 mm 0.2 kg
[$TO^{2,1}{}_1$] Sawing of metal [R_1] Laser complex [$TD^{2,1}{}_1$] 50 sec
[$TO^{2,1}{}_2$] Bending [R_2] Hydraulic press [$TD^{2,1}{}_2$] 70 sec}
{[$D^2{}_2$] Sleeve
[$M^{2,2}{}_1$] Pipe 30x6 mm 0.2 kg
[$TO^{2,2}{}_3$] Cutting [R_3] Band saw machine [$TD^{2,2}{}_3$] 160 sec}

For simplicity, let's assume that all production resources (in our example there are 3 of them) are available for work all the time (time windows $[TRs_j; TRf_j]$ are not limited), and all the production materials required in the technological maps are available.

The distribution of details by resources begins with the deepest level of the technological map, in our example it is the detail of ***Channel-01***, it cuts on the laser complex in 60 seconds, then it goes to the hydraulic press, where it bents for 60 seconds. Next, it goes to the level above and plans the parent detail ***Channel***, which also cuts and bends, but only after the previous child detail. After that, the last detail of ***Channel-02*** is planned. It is processed on another separate resource and does not depend on the previous two details, let's put it first. The resulting schedule is represented by the diagram (Fig. 1).

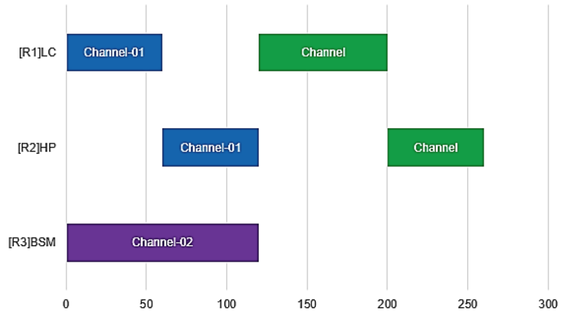

Fig. 1. The diagram of the initial operations on resources allocation

Proceeding to O_2 order planning, which received simultaneously with the first, the empty spaces is used as much as possible in the already existing schedule. Order O_2 consists of two details, which need to be processed on the same level, so the order of their processing is not important. Let's start with the detail ***Flange***, it cuts on the laser complex in 50 seconds, the method look for the first R_1 empty space, there is one after processing the detail ***Channel-01*** with the duration of 60 seconds; since there is enough time, it put the detail there. Next, ***Flange*** needs to be processed on R_2 within 70 seconds, looking for the first available space on R_2, after the end of processing on R_1. An empty space at the beginning of 60 seconds in length does not fit the needed time, the method go further to find a place after the detail ***Channel-01*** with a length of 80 seconds, put the ***Flange*** there. Let's consider the last detail ***Sleeve***, it is processed only on R_3 for 160 seconds, the method finds the nearest free space of the required length after ***Channel-02*** and put it there. A new schedule is shown in Fig. 2

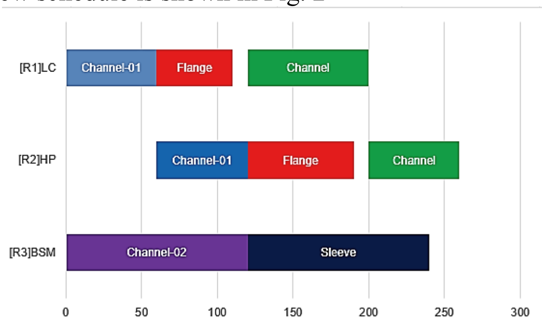

Fig. 2. The diagram of scheduling order O_2.

3 The dynamic rescheduling by actual events

The task of constructing a dynamic schedule based on actual events in real time is more complex than the initial scheduling problem. In the case where the schedule changes dynamically over time, new orders can be added, already known orders can be canceled or partially changed, resources will become unavailable, but most often there can be delays in progress during the schedule execution.

Our approach is based on association orders and resources by software agents which interact with each other; and based on agents interests, is capable of responding to changes in the composition of orders and resources, identifying conflicts in the schedule, making decisions and interacting with each other to resolve conflicts and seeking compromise through negotiations (mutual concessions) [12-14]. This allows us to find coordinated solutions and maintain a balance of interests of agents and the entire system, which in general is a multicriteria objective function. Each resource R_j is associated with a resource agent, each detail D^i_k is associated with a detail agent. Agents can send and receive messages and make decisions according to their logic and the current situation, which is determined by the state of each agent. Current agent states change when orders arrive and external events are committed.

When a new order comes into the system, the detail agents appear according to the technological map of this order. They send out a request for their placement on resource agents, which in turn analyze their current status, the availability of empty spaces, thus evaluating their schedule and offering options to place details. The detail agent seeks the option to place itself as early as possible. The resource agent R_j, in turn, tends to be constantly busy and minimizes the idle time within its work shift window [TRs_j; TRf_j], which is calculated by the formula:

$$Dtime^j = TRf^j - TRs^j - \sum_{k=1}^{p} TD^j_k \qquad (1)$$

where k is index of the placed details of orders on the resource R_j, TD^j_k is the processing time of these details. The global target function F is defined as the total idle time of all resources:

$$F = \{P \rightarrow max, \sum_{j=1}^{m} Dtime^j \rightarrow min\} \qquad (2)$$

where P is the total number of scheduled details on all resources. With the improvement of the global function F, the current version of resource allocation represents the current version of the schedule, after which agents of unplaced and poorly placed details try to improve their position via negotiations with other details. If, as a result of these negotiations, the global function has improved, the new version of resource allocation is accepted as the current version of the schedule and the process is repeated until new actual events arrive, or new agents' negotiation lead to global improvement.

3.1 The example of dynamic rescheduling by actual events

Let's consider the initial schedule described in Fig. 2, it is supposed that now it's is somehow possible to record actual events about the completion of processing of each detail on each resource (for example, by using the workers' terminal), after which the schedule will need to be adaptively reconstructed. For simplicity sake, let's count the time from point 0.

Suppose at the moment of time T_{70} there was an event of completion processing of the detail ***Channel-01*** on the R_1 resource (it was expected that it would end in T_{60}). As a result of the reaction to this event, all the scheduling on the resource R_1 is shifted by 10 seconds to the right. Since the detail ***Channel-01*** is also processed on the R_2 resource after R_1, the schedule for R_2 also shifts to the right for 10 seconds. With all the changes, the schedule will take the form which is shown in Fig. 3.

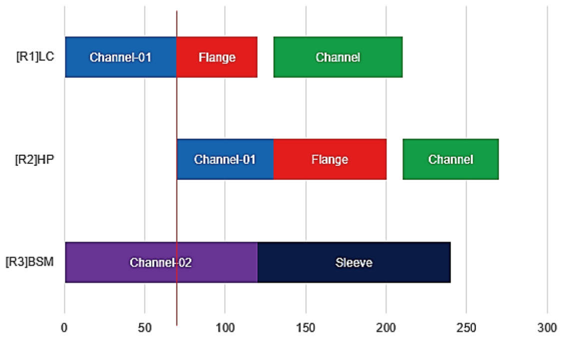

Fig. 3. The diagram of scheduling system reaction for the completion event of T_{70}

Suppose that at the moment of time T_{100}, the completion event of the processing detail ***Flange*** on the R_1 resource and ***Channel-01*** on the R_2 resource has occurred. As a result of the earlier completion of these operations, it is possible to start the following operations earlier. The new version of the plan is shown in Fig.4.

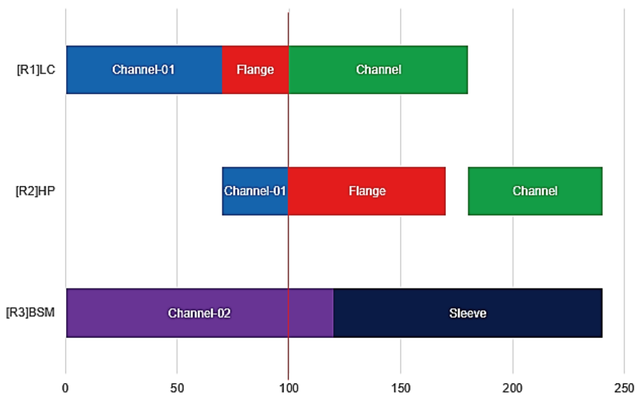

Fig. 4. The diagram of the schedule after the rescheduling event of T_{100}

Suppose at the moment of time T_{180} there is an event of completion processing detail ***Channel*** on the R_1 resource and the detail ***Flange*** on the R_2 resource, but processing detail ***Channel-02*** on the resource R_3 is not yet complete. As a result, the schedule on all three resources will be reconstructed. The new version of the plan is presented in Fig. 5

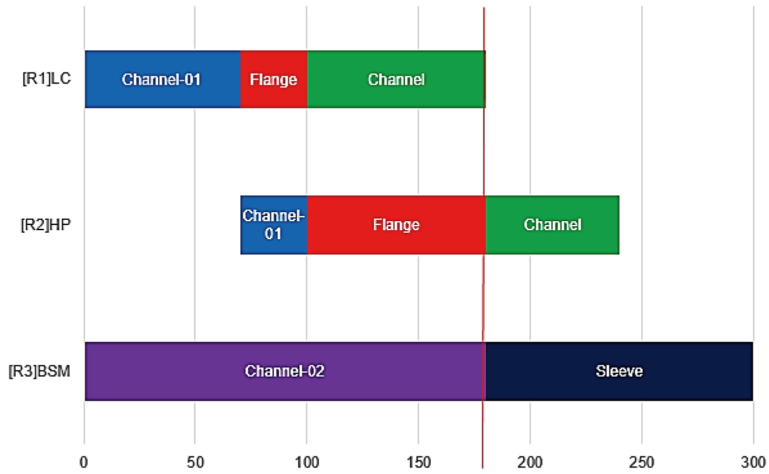

Fig. 5. The diagram of the stabilized schedule after considering all events

When comparing the versions of the schedule after the initial phase (Fig. 2) and after the final actual event (Fig. 5), it can be concluded that the operations are distributed, ensuring minimum downtime of resources according to real-time events.

4 The results

A multi-agent method for real time production scheduling was developed, based on ontological description of the performed operations and the specified optimization criteria – minimization of resources idle time. This method allows building schedules for processing-related operations on specified resources according to real-time events. The system developed based on the proposed method is used in the authentic Samara enterprise, LLC "PC" Electrum", which produces electrical transformers. Because of the system, the number of delays during the production process has been reduced by 10%. The developed method is not limited to the scope of the described subject area (electrical production), it is also applicable to other industries requiring similar production tasks. The scheduling system developed based on the proposed method can work autonomously, or can be integrated with other enterprise systems: warehousing, accounting, etc.

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