*Make to Order production, TOC, moving bottleneck,
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IDENTIFICATION OF BOTTLENECKS IN THE UNIT MAKE TO ORDER PRODUCTION

Abstract

Since the production is aimed at fulfilling specific needs of demanding customers and not at filling warehouses, the production volume should reflect the volume of orders. In times of fight for the client every order has to be performed on time. What is more, in times of fight for shortening the delivery cycle, meeting safe deadlines, that is distant in time, is not enough. Companies are forced to meet short deadlines with keeping the product price competitiveness condition. It is hardly possible without a advanced planning support system. Currently, advanced planning systems are coming into use, however their cost exceeds the possibilities of small and medium enterprises and algorithms used often require great customization to industries' needs and conditions of unit and small-batch production. Such conditions lead to a need for simplified methods. The methods used so far are not capable of finding the global optimum of such big data ranges. For this reason computer tools for applying to the industrial scale are needed. The above method basis on the data so far collected in ERP system.

1. INTRODUCTION

The guarantee of success on contemporary, more and more competence-driven and changeable market is fast and flexible implementation of production processes, which also assures immediate adjustment of production to changes both of the environment and more and more demanding customers. If the 70's

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were the times of costs reduction, the characteristic of the 80's was quality improvement, the 90's were focused on flexible production, the beginning of the 21st century is characterized by focus on customer's satisfaction [7, 1, 12, 10, 11], This trend translates into production of articles adapted to customer's needs and to shortening the availability of products – very often below the production cycle. To implement the tasks connected with production control in such conditions it is necessary to develop operational plans determining the order of production tasks performance by individual production sections. For the plans no to be a chance set of tasks it is necessary to order them properly and to optimize the course of processes. Production control in the moving bottleneck is particularly important. For the solution to this problem authors suggested simplified method based on "back" or "forward" scheduling strategy.

2. STRATEGIES OF ORDERS SCHEDULING

There are many algorithms used to solve scheduling problems, which can be divided into two main groups: optimization (exact) and approximation (approximate). The first group are algorithms, which ensure finding an optimal solution. From a practical point of view, when we solve the problems for a larger scale we apply only approximation techniques that do not guarantee finding the optimum, but require fewer resources and they are faster. The main problem in approximation algorithms is "getting stuck" in one of the local extremes. The main strength of this type of algorithms is finding a feasible "good enough" solution. The group of approximation methods may also includes algorithm presented in the following subsections. A key element of this method is scheduling - a function used to determine the time and the allocation of tasks to the resources of the manufacturing system. One of the tasks of scheduling function is to determine the length of the manufacturing cycle [10, 11].

In determining the order of realization of the tasks two strategies for scheduling are basically used – "backward" and "forward" strategies. In some practical solutions mixed method, which is a combination of these two strategies, is also used.

Depending on the purpose, i.e. the type of asked question, one of the (following scheduling strategy) "backward" or "forward" scheduling strategy is used [12] .

Backward scheduling answers the question: When at the latest we should start manufacturing operations, to make the tasks on time?

In practice, safety time buffer is usually accurate. This technique is used among others to capture the „bottlenecks" in production flow, being on the basis of management in OPT/TOC strategy. Backward scheduling is based on the assumption of keeping the date of availability of the product for the customer, according to his order.

Back scheduling is based on the following algorithm:

- end date of manufacturing of the finished product is set,
- using Gantt charts (regression of planned production cycle of individual components is made), the desired date of availability of a number of components and the structure of the product is calculated,
- with multilevel structure of products the operation is repeated, until reaching the lowest level, i.e. the level of raw materials subsystems,
- the number of necessary components for a variety products and semi-products is aggregated ,
- calculated demand includes stock of semi-products and resources and progress of the running manufacturing orders.

This means that manufacturing should begin no later than the earliest date of commencement of semi-products production. Using the data of the operations of the manufacturing process, i.e. the time of the task staying on the manufacturing resource, for every operation, the time needed to execute the batch of products, parts or subassemblies is calculated. The need for occupation time of machine (or employees) calculated individually for every product, is summarized in the considered planning horizon for all products intended for production.

Forward scheduling answers the question: When manufacturing of the product will be completed, if you know the date of commencement of the associated manufacturing process?

"Forward" scheduling involves making the following algorithm:

- start of production of the product components, as the earliest possible,
- "forward" calculation of the deadlines for the various operations for every planned to manufacture products using Gantt charts and the structure of products,
- calculation of availability time and quantity of planned to buy materials. With multi-level structure of products this operation is repeated until reaching the level of finished products.

This procedure enables determination of the earliest date of products availability. Using the available data of the operation of the manufacturing process, the time of the task staying on the manufacturing resource, for every operation on a specific machine or line the time needed to manufacture the batch of products, parts or subassemblies is calculated.

Scheduling techniques are also used for resource burdens equalization, which aim is as large as possible and evenly production capacity utilization. This aim must be achieved assuming proper distribution, in time, dates of manufacturing orders realization, but distribution, which respects specified time of orders realization. Due to the occurrence of overloads of critical resources, in practice, this balance will never occur. These overloads result in lengthening the production cycle. Calculation of material resources along with balancing the planned workstations load allows to assess the feasibility of the assumed plan. The calculation takes into account the available production capacities and calendars of machinery and equipment availability. In small and medium enterprises, where the dominant rule of management by projects is usually reduced to the simultaneous handling two or more orders [2] using of these scheduling techniques is particularly desired functionality. The result of the scheduling function is the main manufacturing schedule defined in information management ERP systems, as Master Production Schedule (MPS). In terms of the cost of the process realization, the best solution is the back scheduling method.

3. IMPLEMENTATION OF SCHEDULING ALGORITHM FOR BOTTLENECK LOCATION

Let us assume, that the order involves making a class of homogeneous products in a limited time in the system, in which at the same time other manufacturing orders can be carried out. Order model takes into account the processes in the system and reflects the needs of the customer. Manufacturing order is determined by: the size of the order, completion date, size of the batch, the route of the flow manufacturing process and operation times for particular system resources [6, 12].

3.1. Elements of the algorithm

Step 1. Scheduling of orders by priority rule.

An input data is a unordered set of orders $Zl = \{Zl_1, Zl_2, \dots, Zl_l, \dots., Zl_L\};$), $L -$ is the number of orders, l – means the order identifier.

For every Zl_l order the order of realization of scheduling function is determined. It is $\forall_{i,j \in Z}$ defined as sequence constraint, means such constraint $i \prec j$ where $\prec$ operator means sequence constraint. Sequence constraint is not technological constraint but organizational one. Every order is assessed in accordance with the rule $R = \{R_1 \prec R_2 \prec R_3 \dots, R_r\}$, which is an ordered set of organizational rules determining placement of the next order priority in the set being the subject of the scheduling function, r- number of organizational rules. As the priority rule we can assume, for example: delivery date (it is also constraint), client code, for which a package of orders is realized, deterministically defined priority tasks realization time (first large tasks and then small), etc. After scheduling of orders an ordered $Zl' = \{Zl'_1 \prec Zl'_2 \prec Zl'_3, \dots, Zl'_L\}$ set was received, which is a reflection of the Zl set, where $\forall_{Zl_i \in Zl}$ there exists such $Zl'_j \in Zl'$,that $Zl_i \equiv Zl_j{}'$.

Step 2. Searching for planned completion of the order date.

Starting from the Zl'_1 order planned completion date $Zl'_1 d_1 = \max_i\{Zl'_1 d_i\}$ is searched.

Step 3. A search of tasks according to the rule of linkages of the manufacturing process constraint, starting from the highest level.

For $Zl'_1 = \{J_{1,1}, J_{1,2}, \dots, J_{1,n}\}$ order rank order of job tasks according to the order resulting from the technological constraint is made. Every $J_{1,i}$ task, which realization means realization of order is searched. It is usually the task from the highest level of product structure, usually a task assembly job. For $J_{1,i}$ task $J_{1,i}\ d_i = Zl'_1 d_1 - Zl'_1 T_{buf}$ completion date, where $Zl'_1 T_{buf}$ is time buffor of Zl'_1order. To calculate the size of the buffor we can use Drum-Buffor-Rope (DBR) techniques taken from Theory of Constraints (TOC).

$J_{1,i} \equiv J'_1$task, where $J' = \{J'_1 \prec J'_2 \prec J'_3, \dots, J'_n\}$ which is an ordered set of J tasks, according to technological ordering where $\forall J_i \in Zl$ exists such $J'_j \in J'$, that $J_i \equiv J'_j$.

Step 4. A job task sequencing of operations according to order of realization (according to order of manufacturing process).

For J'_1 task, consisting of a set of O_1^i operations carried out on groups of workstations (M^a) $J'_1 = \{O_1^1, O_1^2, \dots O_1^i, \dots, O_1^n\}$ order of operations realization is analyzed.

Operations in the area of tasks must be carried out in given technological order ie. every i operation should be done after i-1 operation, and before i+1 operation. To simplify the notation set of operations of j-th task is similarly determined by O_j. For $\forall i \in O \overset{\text{def}}{=} \bigcup_{i=1}^{N} O_j$, O_1^ioperation, which should be carried out as the first one is searched. For simplicity, it is determined as O_1^N. Date of completion the operation $O_1^N\ d_N = J_{1,1}\ d_1$ completion, where N is the last operation in the process for $J_{1,1}$ task.

Step 5. Obtaining the duration of the operation with considering the advancement.

For O_1^N operation, from J'_1task, of Z'_1 order, duration of $p_{v_k N}$ operation is searched, where:

p_{ik} – processing time of i operation by k variant $(1 \le k \le m_l)$,

v_k – way of the operation (decision variable), $v_k \in \{1, \dots m_l\}$.

The following variables have an impact on the $p_{v_k j}$ value:

t_{j_i}– unit processing time of i-th technological operation,

T_{pz_i} – setup time of i-th technological operation,

t_{tr_i} – time of successive transport operations,

$n_{obr\ Zlec}$ – number of pieces in the batch in order,

$n_{obr\ Com}$ – number of made pieces in the batch,

R_{ComO_i} – advancement rate in % of realized $O_i$operation. If the task is made completely $R_{ComO_i} = 1$ (100%).

Generalizing for every O_i operation its duration is calculated according to formula:

$$(\forall i, v_k \in \{1, \dots m_l\}) : p_{v_k i} = \begin{cases} T_{pz_i} + n_{obr_i\ Zlec} * t_{j_i} + t_{r_i}\text{; for } R_{ComO_i} = 0 \\ (1 - R_{ComO_i}) * t_{j_i} + t_{r_i}\text{; for } R_{ComO_i} \neq 0 \text{ i } R_{ComO_i} \neq 1 \\ t_{r_i}\text{; for } R_{ComO_i} = 1 \text{ and } R_{ComO_{i+1}} = 0 \\ 0\text{; for } R_{ComO_i} = 1 \text{ and } R_{ComO_{i+1}} \neq 0 \end{cases} \tag{1}$$

$$R_{ComO_i} = \frac{n_{obr_i\ Com}}{n_{obr_i\ Zlec}} \tag{2}$$

Step 6. The calculation of the date of operation commencement

Cycle the manufacturing process of a single batch of the product or element can be organized according to the methods: serial, parallel, serial-parallel. For every of these methods calculating the date of commencement of operations will be different. In the method of backward scheduling: for O_1^N operation, from J'_1 task, of Zl'_1 order it is assumed that $O_1^N C_N$ - means date of completion of N operation (last in process) is equal $O_1^N C_N = O_1^N d_N$, desired date of completion of operation.

Starting from the relation:

$$C_i = S_i + p_{v_k i} \tag{3}$$

transforming it into:

$$S_i = C_i - p_{v_k i} \tag{4}$$

we are looking for S_i, where:

S_i – date of operations commencement (decision variable),

C_i – date of operation completion.

Relation, which is determined by formula (4) can only be used for the serial system of process organization in a system where there are no resource constraints. For other conditions, more complex formula should be used:

$$S_i = C_i - \left(p_{v_k i} - p'_{v_k i}\right) - p_{con_m i} \tag{5}$$

where:

$p'_{v_k i}$ – time of shortening of i operation cycle by k way resulting from the overlapping realization of operations ie. using parallel, serial – parallel methods when:

$$p'_{v_k i} < p_{v_k i} \tag{6}$$

$p_{con_m i}$ – time of cycle elongation resulting from resource constraints. The next steps the above dependents will be calculated.

Step 7. Checking the resource constraints

Extension of the time of operation O^i commencement has its source in constraints of availability of reusable and consumable resources. In case of O^N operation, which is last operation the problem mainly concerns resource constraints resulting from the availability of the machine being the main reusable resource. The number of machines of the same type, work schedule and work regulations define availability of reusable resource. If $M^a = \{m_1^a, m_2^a, \dots, m_B^a\}$; then m_i^a workstation is defined by

$$m_i^a = (Ca_i^a, R_i^a, A_i^a) \tag{7}$$

where:

a – means the type of workstation (the group of workstations, which may realize operation of manufacturing system),

Ca_i^a – means resource constraints resulting from the work schedule of workstation (holidays, repairs, renovations of particular machines),

R_i^a – means resource constraints resulting from the work regulations of workstation (shift work, different systems of working on Saturdays, working overtime),

A_i^a – means the number of workstation of type A, i.e.

$$p_{con_m i} = f(Ca_i^a, R_i^a, A_i^a) \tag{8}$$

Due to the clarity of calculation and simplification of algorithm is assumed that:

$$p_{con_m i} = \alpha_i^a * p_{c_m i} + \alpha_i^a * p_{R_m i} \tag{9}$$

where:

a – means the type of workstation (the group of workstations, which may realize operation of manufacturing system)

$p_{c_m i}$ – time of cycle elongation resulting from availability according to work calendar.

$p_{R_m i}$ – time of cycle elongation resulting from availability according to work regulations.

α_i^a – coefficient resulting from the number of machines of the same type.

In the next steps calculation of $p_{c_m i}$, $p_{R_m i}$, α_i^a is done.

Step 8. Updating the time of starting the preceding operation

Assuming that in method of backward scheduling: for O_1^N operation, from J'_1 task, of Z'_1 order it is assumed that $O_1^N C_N$ - means date of completion of N operation (last in process) is equal $O_1^N C_N = O_1^N d_N$, desired date of completion of operation.

Making S_i calculations according to (5) relation we receive $O_1^N S_N$. Moving further back according to the structure of the manufacturing process, it is assumed that the date of completion of the operation (N-1) is equal to the date of commencement of operation (N) with respect to organizational constraints such as the average shift resulting from the documentation availability or from technological waiting such as drying after painting.

$$O_1^{N-1} C_{N-1} = O_1^N S_N - p_{Org_N} \tag{10}$$

where:

p_{Org_N} – time of cycle elongation resulting from organizational constraints.

Step 9. The next operation

If there is next operation for the (given) task, go to step 5, otherwise go to step 10.

Step 10. The next task/job

For J'_n tasks, the pre-job J'_{n+1} is searched. ($J'_n \prec J'_{n+1}$).

If there is a next task, date of completion of the last operation for this task is calculated, otherwise go to step 11.

The date of commencement of first operation of task (J'_n) is equal to the date of completion of the last operation (J'_{n+1}).

$$O_n^N\ C_N = O_{n-1}S_1 \tag{11}$$

Go to step 5.

Step 11. The end of algorithm

4. CHARACTERISTICS OF BOTTLENECKS IN UNIT AND SMALL BATCH PRODUCTION

In conditions of systems, where unit and small batch production is dominant there is often a problem of bottleneck with variable nature. It means that the bottleneck moves. At some workstations it will appear periodically, on the other chronically, and at some it will appear rarely or never. According to the proposed methods, identification of bottlenecks is done by using the scheduling function of the backward direction, method without labor resources constraint. Typically, for manufacturing orders job tasks are initially generated, in a variant defined as main. Such variant is usually optimal variant in static meaning. Imposition of back scheduling function prepared in this way tasks allows for determining the dates of realization in the latest possible date. Due to scheduling without constraints, we can identify overloads of individual resources occurring at specific time periods.

Contraventions of the availability of resources are analyzed on a weekly or daily tome period. Adoption of lower density of time intervals e.g. monthly, would be subject to too many errors. There could also be situations, that the sum of the month would lead to no overloads. However, it was decided not to take into consideration shorter periods of time, because this kind of contraventions can be discharged using the another organizational methods. To identify bottlenecks in the tested time periods, a procedure presented in the next subsection was used. Operation of procedure for detecting critical enterprise resources consists in determining the overloads, aggregated into τ weekly intervals and types of M^a resources. The first step of the method is to calculate the availability of types of m^a resources, on the basis of data taken from the ERP system and authorial procedure [9, 8, 12].

5. THE PROPOSED ALGORITHM FOR THE REMOVAL OF BOTTLE-NECKS

Because unit and small batch production is focused on meeting the specific needs of demanding customers, the production size must copy the size of orders. Every order must be realized in deadline for its completion. In conditions of permanent shortening the delivery cycle is not enough to meet the safe deadlines i.e. very distant in time. Enterprises are forced to meet the short deadlines with the condition of maintaining the competitiveness of the price of the product. Without proper support computer system carrying out the planning is practically impossible. Now, advanced planning systems are applied in practice, however, their cost is too high for small and medium enterprises, and used algorithms often require a lot of customization to the needs of industry and conditions of unit and small batch production. Advanced Planning System (APS) are an extension of the base functionality of ERP systems. One of the main problems to solve is optimization of serving and dealing with constraints algorithms with taking into account business objectives of enterprises [12].

This paper contains proposals for optimizing the production plan of actual enterprises and descriptions of the problems confined to the conditions set out above.

5.1. Removing bottlenecks by automatically selecting an alternative process in accordance with the "throughput accounting"

The subject of production management is to make decisions on a regular basis so as to effectively and timely realize short-term tasks in accordance with enterprise strategy. To realize these task, it is necessary to build operational plans, which are responsible for order of manufacturing tasks realization by individual cells (types of resources). In order to plans were not a random set of tasks, scheduling function is used. The task of scheduling is therefore prioritizing tasks in a given workstation in a specific order. Due to the limited production capacity, tasks can not be realized simultaneously, but in a specified sequence. None of the used scheduling methods is not able to arrange the order of the tasks so that there are no interruptions - time buffers which should compensate for disruption. A unique workstation is a bottleneck, for which the schedule is continuous [8, 9, 12]. For such defined conditions the task was formulated as follows:

Development of operational plan of work of machines and workers, so as to meet customer requirements (to meet confirmed deadlines) and in the computational abilities, to make optimization of bottleneck work schedule.

Due to the nature of the task, i.e. difficulty to get a global solution, optimal for scheduling problem with this number of tasks and resources, enterprises have focused on approximate method. In order to obtain a good enough solution that meets constraints of date of orders realization and the local optimization, enterprises have focused on the work of bottleneck and possibility of shortening the date by tasks scheduling on the basis of the additional features of the manufacturing process.

5.2. Choice of manufacturing process in accordance with the planned load of moving bottleneck from an alternative variants

In the practical realization enterprises focuses only on the critical resources. From entire set of tasks and resources analysis was done only for those types of m^a resources for which the following condition is fulfilled [6]:

$$\sum_{k=1}^{K}\sum_{n=1}^{N} \left({}_{k}^{n}tpz^{\,a} + {}_{k}^{n}tj^{\,a} \right) > Fnor^{a} \tag{12}$$

where:

${}_{k}^{n}tpz^{\,a}$ – setup time used on type of m^a resource,
${}_{k}^{n}tj^{\,a}$ - processing time on type of m^a resource,
$Fnor^{a}$- resource availability for type of m^a resource,
n – means operation identifier for J_k job,
k - means job identifier,
N – number of operation,
K – number of jobs.

On the basis of the above formula Λ^a overload for type (group of workstations) of m^a resource is calculated. Calculating of overload in the global system is too vague in terms of operational production plan. It is therefore necessary to take a certain period of time (τ) determining the density of the timeline. Overload is calculated according to relation:

$$\Lambda = \left[{}^{\tau}\lambda^{a}\right]_{\substack{a=1,\dots,A \\ \tau=1,\dots,\mathrm{T}}} \tag{13}$$

where:

$${}^{\tau}\lambda^{a} = \begin{cases} \sum_{k=1}^{K}\sum_{n=1}^{N} \left({}_{k}^{n}tpz^{\,a} + {}_{k}^{n}tj^{\,a} \right) - if\ m^{a}\ in\ \tau\ period\ is > Fnor^{a} \\ 0 - \text{otherwise} \end{cases} \tag{14}$$

and:

A – d number of resource types,
τ – planning period,
T – number of planning periods.

The problem to be solved is the density of division of the timeline. On the basis of analysis it was decided take τ period equal one week.

5.3. Experimental research

The research was done in the unit Make To Order production system. Appropriate samples concerning production system were taken from the SME enterprise. Input data come from accumulated data bases of the REKORD.ERP system.

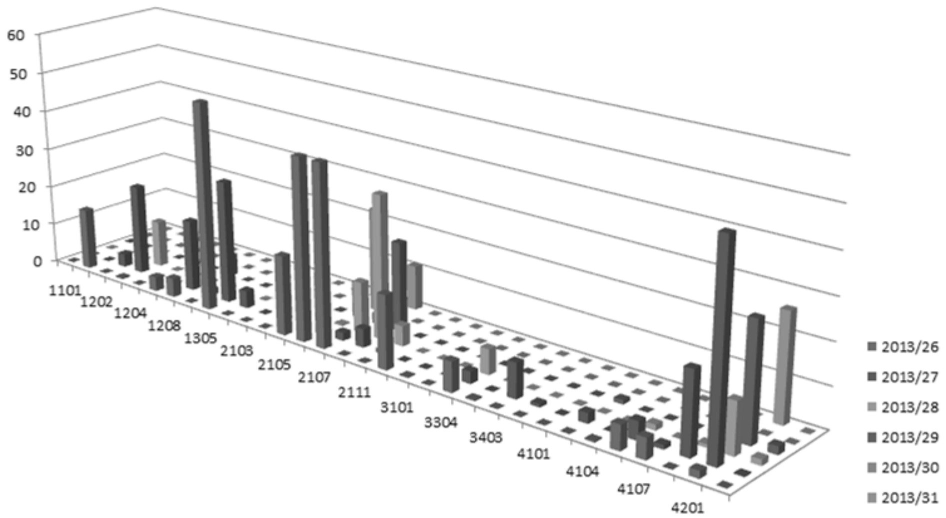

Fig. 1. Graph of tasks' overloading in the week's period [source – own study]

Fig. 1 show graph of tasks’ overloading in the week’s period. Characteristics of moving bottlenecks has been confirmed. The first step of TOC – Identify of constrain was done. The next steps according to TOC are exploit the constraint, sub ordinate everything to the constraint, elevate the constraint, repeat for the new constraint [3, 4, 5].

6. SUMMARY

Backward and forward scheduling control the trade-offs related to producing early in order to obtain maximum resource consumption and increasing inventory, or producing on time but with the less resource utilization. The options available within the supply or production planning methods are very important for the outcome of the plan. In research papers there can be found descriptions of many test problems of tasks ordering. It is difficult to find an example of a problem solved in real conditions of such a number of tasks and job resources. Therefore, the authors have presented the analysis of the problem of tasks ordering on real data in a broad spectrum of many production companies. The authors' aim is not to prove superiority of this method over others. The task was to state usefulness of the method of process alternatives exchange in real conditions. The results below refer to states before optimization and after its application. Providing the above results helped to define the rim conditions of companies in which usefulness of this method is sufficient. Heuristic algorithms cannot be proven using mathematical methods. A number of tests on real data have been carried out to prove this method.

The above method can be called the simulation "on line". This method found application to the industrial scale, as extension of the ERP class system.

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