Production planning methodology in hybrid systems

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Abstract: The aim of this study is to present a methodology of resource planning under deterministic constraints. Most small and medium-sized enterprises are representatives of the MTO group. This results from a shorter product life time due to the changing expectations of customers. This, in turn, contributes to the separation of R & D departments in organizational structures of enterprises and close cooperation between industry and research units specializing in the field of operation of a given producer. More and more products are designed to be unique so as to suit client’s requirements. Similarly, the process of manufacturing such a product will be unique. From the point of view of management, the preparation of production and the production itself in this case has more features of a project-type task than typical production.

Many enterprises, in particular small and medium-sized ones, the activity of which is flexible in terms of the offered products create a hybrid system encompassing series production, single-batch production and projects.

The article presents a new approach to the topic of scheduling in such hybrid systems combining MTS, Projects and MTO. The presented method of scheduling is based on the assumptions of the Theory of Constraints. In small and medium-sized enterprises, which fight for every order, it is necessary to use production scheduling methods that are characterized by flexibility, transparency and reasonably low labour intensity, taking into account numerous resource constraints involved in production in a hybrid system. In this system we face a decision-making process which forces us to answer the question: can a new order be accepted to be fulfilled in a strictly defined deadline.

1. Introduction

Challenges and changes in industry require a new strategy for new product development (NPD) under conditions of other orders processing, involving different kinds of activities and planning methods as well as various levels of complexity and flexibility.

In this context, numerous enterprises create hybrid systems, which offer products at various stages of product lifecycle, products characterized by various changeability and reproducibility, make-to-stock (MTS) and make-to-order (MTO) products, including implementation of project tasks. This means that typical products, the market demand for which is predictable and determined on the basis of marketing research, are manufactured in one system, and the current production is MTS. At the same time, MTO production is launched, based on the customer’s order, the products of which are characterized by a certain degree of individualization to meet particular clients’ requirements. Additionally, the company extends its offer with the manufacture of products requiring a multi-stage processing, frequently related to NPD production. This is a project-orientated production. For this purpose, the R&D department is
separated in the organizational structure, the task of which is to implement product innovations so as to ensure the offer competitiveness. Despite difficulties entailed by managing such a complex system, enterprises decide to employ this solution so as to use its resources in particular working stations, machines and equipment in the best possible way.

The activity of each enterprise is subject to constraints, some of which are deterministic (are known and constant), e.g. the number of resources and their accessibility; other constraints are accidental, related to incidental situations, such as failure of a machine or an employee’s absence, which can be influenced by the company only through predictive actions, decreasing the probability of their occurrence or reducing their effects. In this article deterministic resource constraints are discussed. In this context the condition for task implementation is planning an activity that ensures access to limited resources (i.e. stations and/or machines) in time. Each decision regarding order execution involves an analysis of resources accessibility within a time in which a given order (a set of orders) is to be performed. In the context of the project, it is necessary to verify constraints resulting from the project scope, time planned for its performance (defined beginning and end) and costs. These three values are dependent on one another. The scope of order defined by the client determines the time of its execution and costs. The influence of a change in the scope is directly proportional to the remaining two values. The project performance conditions are a compromise between the client’s expectations (term and costs) and the producer’s capabilities (resources accessibility).

2. Problem formulation

The system in which MTS, MTO and project-type tasks are accepted for fulfilment is considered in the paper. A procedure that will enable taking decisions in conflict situations, when two different tasks requiring access to the same limited production resources are reported to the system at the same time is searched.

Creating a schedule in a limited planning horizon takes into consideration the earlier resource utilization by other tasks. An assumptions of the Theory of Constraints (TOC), considering it a flexible and practical method, which takes into account the changeability of many factors functioning in hybrid systems has been adopted. TOC assumes that all processes in an organization are mutually dependent chain links.

The organisation’s functioning based on TOC involves management through the prism of the awareness of constraints and implementation of 5 steps described below (figure 1):

| Step 1 | Step 2 | Step 3 |
|--------|--------|--------|
| Identification of system constraints, prioritizing them depending on their influence on maximization of the goal’s function. |
| 1a) determination of resource production capabilities |
| 1b) determination of the resource utilization in relation to production capabilities |
| 1c) determination of critical constraint resource (CCR) |
| Decision on the manner of CCR maximum use. |
| Adjusting the work schedule of non-critical resources for the maximum utilization of CCR |
| Subordination of all the other activities to the maximum exploitation of a constraint. The undertaken actions are global. The technique employed is DBR (Drum-Buffer-Rope); drum is the system constraint determining the rhythm of work of the remaining resources. Rope is the schedule and buffers are additional resources, aimed at ensuring the maximum utilization of CCR. |
Enhancing (strengthening) the bottleneck capacity.

If the bottleneck is no longer a constraint, identification of the next bottleneck and return to step 1.

**Figure 1.** Management in the context of TOC – 5 steps of the procedure.

In the context of this article the key step is step number 2, which consists in creating a schedule that minimizes shutdowns on critical resources. To determine the flow for MTS and MTO production, Optimized Production Technology (OPT) – a production type of TOC, can be used. On the other hand, for project-type orders, one can employ tools typical of project management, i.e. Critical Chain Multi Project Management (CCMPM), which is an extension of the Critical Path Method (CPM) with the solving of resource conflicts. [13]

The proposed approach to the scheduling of the described class of systems involves 3-stage planning of resource utilization. First (stage 1) MTS orders are processed. Production orders are started on the basis of marketing analyses. They are cyclical during a long planning period and evenly utilize resources in subsequent time periods. The sale of MTS products secures the fulfillment of sale plans, and the schedule can be created over a long time interval. Next (stage 2) the utilization of resources for project-type tasks is taken into account. Projects have many stages and are characterized by a long period of one-off demand for resources.

Fulfilment of MTS and Project orders largely relies on production capabilities of resources so as to increase their usage and minimize idle periods. The enterprise undertakes orders to meet urgent needs of the client (stage 3). These are one-off orders (MTO), which use the resources for a short time, hence there is a possibility of utilizing short idle periods between orders fulfilled.

**3. Model**

There is a production system $S$ characterized by two values $S=\{Z_i, P\}$, where: $Z_i$ – set of resources (machines, stations), $i=1, 2, \ldots, I$; $P$ – set of processes (order portfolio) waiting for execution, $P=\{PS_s, PR_r, PJ_j\}$; $PS_s, s=1, 2, \ldots, S$; $PR_r, r=1, 2, \ldots, R$; $PJ_j, j=1, 2, \ldots, J$

a) $PS$ - make to stock production (MTS), which occur at quite regular previously planned periods of time

b) $PR$- orders are characterized by a big one-time demand for resources

c) $PJ$ – make to order production (MTO) launched upon client’s request and respond to urgent needs.

Process is defined as a technological process which involves performing subsequent technological operations characteristic of a given product, (figure 2).

**Figure 2.** Diagram of a 4-resource production system which implements $PR_r=1, PS_s=1, PJ_j=1$. 
The duration of the operation of transport, control and storage has been accounted to operational times.

The planning period adopted for this model is equal T. At a time of MTS orders inflow the resources are available throughout the planning period.

A production order represents the client’s expectations, the measure of which is the size of order and its completion time. The order includes performance of a defined number of products within a limited time. Each production order corresponds to a process.

Each of processes has a specific route i.e. the sequence of operations is described in matrices respectively MPS, MPR, MPJ, size of order B, pre-set dat of process completion tz.

\[ PS_s = (MPS_s, B_s, tz_s, T_s) \]
\[ PR_r = (MPR_r, B_r, tz_r, T_r) \]
\[ PJ_j = (MPJ_j, B_j, tz_j, T_j) \]

Matrix of process MPS is described:

\[ MPS_s = \begin{bmatrix} M_1^s & M_2^s & \ldots & M_i^s \end{bmatrix} \begin{bmatrix} t_1^s & t_2^s & \ldots & t_q^s \end{bmatrix} \]

where the first line indicates the resource on which subsequent process operations are carried out. The second line indicates the duration of particular operations executed on these resources.

Analogical form will be taken matrices MPR and MPJ.

4. Case study

Hybrid manufacturing systems are commonly seen in enterprises which produce refractory materials. These companies offer products for high-temperature units in metallurgy, power industry, cement branch etc.

A wide range of market demand includes the following products:

a) Standard PS products, the manufacture of which is started on the basis of marketing analyses as demand for these products is not stable. The products are characterized by long life cycle due to their universal application. These are e.g. standardized formed refractory products, such as bricks, wedges as well as chamotte mortars and refractory castables. Clients expect a fast, most frequently immediate delivery term, which is the reason why these materials are manufactured in the MTS system, i.e. to stock.

b) PJ products made to individual clients’ order. These are mainly monolithic materials, which, due to refractory cement they contain, have a short expiry date, i.e. up to 6 months, and prefabricated elements made from these castables. These materials are characterized by better quality and, in consequence, the market demand for them is limited and changeable. Additionally, depending on technological conditions of the recipient, they require an individual approach to e.g. grain size distribution. Therefore, these materials are produced in the MTO system, i.e. they are made to order.

c) Unique PR, the production of which involves designing a refractory lining which is a working layer of high-temperature units exposed to the erosive and corrosive attack of chemical substances in manufacturing processes at the client’s. The project is carried out in many stages, i.e. designing, selection of material and production are followed by an industrial trial, which verifies the design assumptions. Projects of this kind last several months. An example of such a project is manufacture of the fluidized bed boiler lining, which is currently under construction at Power Plant Jaworzno.

Being engaged diverse production, an enterprise faces numerous constraints. They include producer’s own constraints (machines, stations, financial expenditures, warehouse surface area, know-how, procedures), constraints resulting from clients’ requirements (completion terms, quality requirements, price) as well as the constraints on the part of contractors that supply materials and subassemblies necessary for the production (price, completion dates, quality).

In the described enterprise production is non-rhythmic. It is organized in production work cells and is characterized by a low level of technological advancement.
Stage 1.
In the system one order classified as PS₁ is planned to be processed

\[ \text{PS}_1 = (\text{MPS}_1, B_1, t_{z1}, T_1) \]

The order is described by the process matrix MPS₁

\[ \text{MPS}_1 = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 4 & 2 & 7 & 4 \end{bmatrix} \]

\[ B_1 = 1, \ t_{z1} = 35 \text{ unit of time} \]

\[ T_1 = 17 \]

The allocation of activities to resources versus time has been presented in figure 3a.

Stage 2.
Additionally, one project-type order was reported. It has been described below:

\[ \text{PR}_1 = (\text{MPR}_1, B_1, t_{z1}) \]

\[ \text{MPR}_1 = \begin{bmatrix} 1 & 3 & 4 & 9 \\ 7 & 5 \end{bmatrix} \]

\[ B_1 = 1, \ t_{z1} = 35 \text{ unit of time} \]

Based on the course of the project, the earliest and latest possible terms of particular tasks’ completion are determined. Meeting the deadlines is secured by the final project completion date. The available time intervals for performing particular activities have been marked with a dotted line in figure 3b. Figure 3c presents a schedule taking into account the tasks completed in the MTS mode and project-type tasks.

![Figure 3. Gantt graph.](image)

3a – resource usage resulting from the completion of cyclical orders PS₁ (stage 1), 3b – resource usage resulting from orders PR₁ (stage 2), 3c – resource usage resulting from the completion of orders PS₁ and PR₁.
Stage 3.
At this stage we analyse the possibility of performing order PJ$_1$, which was not taken into account in production plans.

PR$_1$ = (MPR$_1$, B$_1$, t$_{z1}$)

Where the process is described by matrix MPJ$_1$

\[
\begin{bmatrix}
3 & 4 \\
4 & 5
\end{bmatrix}
\]

B$_1$ = 1
T$_{z1}$ = 9

An order is created on the basis of client’s urgent needs – MTO. The order is one-off; therefore, it utilizes the resources over a short period of time. As a result, it increases the effectiveness of resources and utilizes them at idle periods between operations involved in the performance of orders PS$_1$ and PR$_1$.

Symbols used:

- $s_i^{PS_1}$ – beginning of operations involved in the performance of order PS$_1$ on resource $Z_i$
- $e_i^{PS_1}$ - end of operations involved in the performance of order PS$_1$ on resource $Z_i$
- $s_i^{PR_1}$ - beginning of activities involved in the performance of order PR$_1$ on resource $Z_i$
- $e_i^{PR_1}$ - end of activities involved in the performance of order PR$_1$ on resource $Z_i$
- $S_i$ – the earliest term of commencing the operations involved in the performance of PR$_1$ on resource $Z_i$
- $e_i$ – the latest term of completing the activities involved in the performance of PR$_1$ on resource $Z_i$

Symbols:

$S_i^{PS_1}$ – beginning of operations involved in the performance of order PS$_1$ on resource $Z_i$
$e_i^{PS_1}$ - end of operations involved in the performance of order PS$_1$ on resource $Z_i$
$s_i^{PR_1}$ - beginning of activities involved in the performance of order PR$_1$ on resource $Z_i$
$e_i^{PR_1}$ - end of activities involved in the performance of order PR$_1$ on resource $Z_i$
$S_i$ – the earliest term of commencing the operations involved in the performance of PR$_1$ on resource $Z_i$
$e_i$ – the latest term of completing the activities involved in the performance of PR$_1$ on resource $Z_i$

Figure 4. Gantt graph.

4a – the usage of resources resulting from the performance of orders PS$_1$ and PR$_1$ (state from figure 3c) 4b – the usage of resources resulting from the performance of order PJ$_1$ (stage 3), 3c – the usage of resources resulting from the concurrent performance of orders PS$_1$, 2, PR$_1$ and PJ$_1$

Symbols used:

$s_i^{PJ_1}$ - commencement of activities involved in the performance of order PJ$_1$ on resource $Z_i$
\begin{align*}
\epsilon_i^{\text{PJ}} & \quad \text{end of activities involved in the performance of order PJ on resource Z}_i \\
\text{MS} & = \{\text{MPS}_i, \text{MPR}_j, \text{MPJ}_i\} = \begin{bmatrix}
1 & 2 & 3 & 4 \\
4 & 2 & 7 & 4 \\
1 & 3 & 7 & 5 \\
3 & 4 & 5 & \\
\end{bmatrix}
\end{align*}

In the created schedule of a hybrid system we have a clearly defined beginning and end of activities planned to be carried out, which will not change in a given planning period. The duration of activities is the difference between the end and commencement of an activity.

\( \Delta_i^{j} \) duration of activity on resource \( i \)

\[
\Delta_i^{j} = \sum_{i=1}^{j} (e_i^{PSj} - s_i^{PSj}) + (e_i^{PRj} - s_i^{PRj}) + (e_i^{PJ} - s_i^{PJ})
\]

in the example:

- planning period \( T=35 \) units of time
- \( \Delta_1^{1} = (e_1^{PS1} - s_1^{PS1}) + (e_1^{PS2} - s_1^{PS2}) + (e_1^{PR1} - s_1^{PR1}) + (e_1^{PJ} - s_1^{PJ}) = 4+4+9=17 \) units of time
- \( \Delta_2^{1} = (e_2^{PS1} - s_2^{PS1}) + (e_2^{PS2} - s_2^{PS2}) + (e_2^{PR1} - s_2^{PR1}) + (e_2^{PJ} - s_2^{PJ}) = 2+2=4 \) units of time
- \( \Delta_3^{1} = (e_3^{PS1} - s_3^{PS1}) + (e_3^{PS2} - s_3^{PS2}) + (e_3^{PR1} - s_3^{PR1}) + (e_3^{PJ} - s_3^{PJ}) = 7+7+4=25 \) units of time
- \( \Delta_4^{1} = (e_4^{PS1} - s_4^{PS1}) + (e_4^{PS2} - s_4^{PS2}) + (e_4^{PR1} - s_4^{PR1}) + (e_4^{PJ} - s_4^{PJ}) = 4+4+5+5=18 \) units of time

The time between the performance of tasks is the state of idleness of resource \( \Delta_{ij} \).

For the described system \( S = ([Z_i, i = 1, 2, 3, 4], \{P_j, j=1, 2, 3\}) \), the matrix representation of processes occurring in the system will be a set of matrices \[1\].

\[ V_i = [V_1, V_2, V_3, V_4] \]

The usage of resources resulting from the state of the \( i^{th} \) resource in a given unit of time can be described as a set of vectors \( V_i \).

The size of this vector equals to the analysed time interval, e.g. the planning period. In this case it is assumed that the vector is equal to \( T=35 \) time units.

\( \text{V}_i = [l_1, l_2, \ldots, l_j] \)

\[
l_i^{j} = \begin{cases} 
0 & \text{if the } i^{th} \text{ resource is not utilized in a given time unit} \\
1 & \text{if the } i^{th} \text{ resource is utilized in a given time unit} 
\end{cases}
\]

where:

\( l_i^{j} \) - element of vector \( V_j \)

\[
V_1 = [1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
\]
\[
V_2 = [0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
\]
\[
V_3 = [1, 1, 1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
\]
\[
V_4 = [0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
\]
An analysis of possibilities of performing a subsequent process consists in checking the accessibility of resources in the area between a point defined as the latest possible term of operation completion and the fastest possible term of commencing the operations involved in a new process (order).

Let us consider the case when another order PJ₂ has been reported to the system. The boundary condition (the latest possible term of completion) is defined by the client – it is the required term of order performance. In the case subjected to analysis $T₂=35$. The new order PJ₂ is described by the matrix

$$MPJ₂ = \begin{bmatrix} 2 & 3 & 4 & 1 \\ 10 & 3 & 4 & 2 \end{bmatrix}$$

Figure 5. The usage of resources of a hybrid manufacturing system.
5a – Gantt graph (state from figure 4c), 5b – alternative way of presenting the usage of resources

Figure 6. Analysis of possibilities to enter a new order in the system.
The figure 6a is the usage of hybrid system resources (state from figure 5b), the figure 6b represents the usage of resources resulting from the performance of new process PJ; and the figure 6c is the analysis of production capabilities in a given planning horizon.

We are searching for a time interval $\geq$ time of the awaiting process operation.

1 - unit of time in which the resource is used
$\emptyset$ - unit of time in which it is possible to perform a new order

In the analysed example the order fulfilment is not possible due to lack of the required accessibility of resource $Z_4$ in a particular planning horizon. Due to the current usage of resources, it is possible to perform one activity after another on resources $Z_1$, $Z_2$, $Z_3$, but in the set planning horizon $T=35$ time units, resource $Z_4$ does not have the required accessibility.

5. Conclusions

In the article the authors have proposed an approach to the scheduling of resources in enterprises which use different systems of production organisation concurrently, creating a hybrid system. This system is a big organizational challenge due to a large number of deterministic constraints it generates. The term “resource” should be understood as machines and equipment, but also employees and warehouse area. The adopted methodology is universal – it can be applied in hybrid systems, but also in manufacturing systems which concurrently process e.g. two types of orders. Even if one of its stages is omitted, the described procedure remains appropriate.

Further investigations will be conducted in order to find sufficient conditions of mathematical co-dependsences describing the decision process involved in the analysis of possibilities to perform a new order in the system with a defined usage of resources in a given planning period.

Due to considerable flexibility and a wide range of applications, the methodology has a huge implementation potential.

6. References

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