Model of production schedule modification assessment for digital production management systems

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Abstract. The article presents mathematical models of production schedule assessment enabling the user to verify possibility and expediency of new order implementation by calculating the new schedule which will take into account this new order, enterprise resources and production risks associated therewith. Importance of these models consists in their feasibility as “Available-to-Promise” business-function for scheduling process automation and production schedule assessment. Presented models are expandable, scalable and flexibly adaptable to application environment and to organizational structure of various enterprises. Practical implementation of mathematical models and their integrating into digital production environment assume their implementation and monitoring by information system. This article is addressed to specialists involved in production automation and control.

1. Introduction

Practical market environment of single-item and small-series production is subjected to continuous and fluctuating changes which fact is verified by both factors – academic research [1, 2] and during discussions in professional associations [3, 4]. Enterprises which are targeting the customer interests under conditions of competitive performance and active promotion of digital economy are bound to promptly respond to ongoing changes, evaluate production schedules implementation for the new orders, continuously improve production technology [5], improve production scheduling quality and take into account production risks [6, 7]. Particular difficulties occur during heavy industry digitization, namely, for the spheres of missile and aircraft engineering [8, 9].

There are many approaches and methodologies in the sphere of scheduling and enterprise management which while plotting the plans at various life-cycle stages of the product [10] and correlating the scheduling levels [11] are using the following criteria sets: “just-in-time” [12] (accounting for national specificity inclusive [13, 14]), “risk management” [6, 7], “target cost” [5]. Criteria set may vary in condition of ongoing enterprise development and environment change. This is why, model expected be the basis of automation process shall have flexible configuration [15] enabling expert or decision-maker to adjust and/or select criteria system. Among basic indicators to be taken into account are the following ones: production cost, product lead time, production risks (product defects, equipment faults, materials supply delays, sickness etc.)

Therefore it is essential to formalize the multicriterion problem in the form of mathematical model of production schedule assessment with further modification thereof. Within the framework of development of automated production-technological process control system intended for aircraft-
building enterprise and aiming to plot aforesaid mathematic model we undertook preliminary survey to identify specific aspects of scheduling process adopted by “Aviastar-SP” corporation. Based on investigation results, we assigned a task to plot mathematical models of schedule modification which should be integrated into digital production control system.

2. Methods of investigation
Currently, any competitive enterprise is utilizing advanced systems, for instance:
- BI – class: QlikView, Prognoz Platform, Deductor, IBM Cognos, SAP BI etc.;
- ERP – class: 1C, Galaktika ERP, SAP ERP, MS Dynamics AX etc.;
- MES – class: InfoPro: modes planning, Galaktika AMM (Advanced Manufacturing Management), MCIS (Motion Control Information System), I-DS dispatch control system, 1С:MES Operations management etc.;
- APS -class: Ortems APS, ITRP: Process-based production, Galaktika _АММ_ (Advanced_Manufacturing_Management) etc.
or own automated enterprise management systems developed with account to enterprise specific aspects enabling better production management, scheduling and material resources control [16, 17]. At that, all those systems consider only one of below criteria: just-in-time [18], cost estimation-based [19], risk accounting [9] and incomplete production management [5].

Modern production management systems include special business-function allowing to identify the possibility of order implementation which is called “available-to-promise” function (ATP). This function helps to define required quantity of items to fulfill the order and date of actual order execution [15]. Depending on new order fulfillment deadline, it is possible to identify four probable situations:
- by the required execution date there is no sales and production schedule;
- sales and production schedule has been compiled, however there is no production master schedule;
- production master schedule has been compiled, however, if is still not in progress;
- master schedule is in process of implementation [15].

The paper is addressing case No.4 when together with ongoing production master schedule a new order is furnished and it is required to evaluate this order implementation and to re-estimate the production schedule without affecting ongoing orders in terms of handover deadlines and product quality. At that, it is required to consider risks of delays associated with particular stages of items (parts) processing.

3. Results obtained
There are two possible ways of assessment: with or without schedule modification. Let us describe each individual model.

Model 1 – assessment of new requisition inclusion without ongoing schedule modification.
In order to assess the possibility of new requisition inclusion into ongoing production schedule we propose to introduce the following reference designations:
- \( S \) – set of groups of production resources defined by equipment, accessories, tackle, tools, material resources, labor resources etc. involved in production process;
- \( M \) – set of items incorporated in ongoing production schedule.

For each item \( m \in M \) there is a particular sequential processes consisting of \( K_m \) processing stages. At each stage \( j, 1 \leq j \leq K_m \), the following characteristics are known: unique identifier of the group production resources \( s \in S \), involved at this stage; absolute time of item processing at stage \( t_s(s,m,j) \); processing duration \( \tau(s,m,j) \).
Definition. Let us identify the item path \( m \in M \) as population \( z_m = \{ s_j, t_0(s_j, m, j) : s_j \in S, 1 \leq j \leq K_m \} \), satisfying the following conditions:

\[
t_0(s_{j-1}, m, j-1) + \tau(s_{j-1}, m, j-1) \leq t_0(s_j, m, j), \quad 2 \leq j \leq K_m.
\]

Let us introduce the set of paths \( Z, Z = \{ z_m, m \in M \} \).

When item is included in the schedule it is required to define absolute time-related limit value for this item production; let us designate it as \( T_i(m) \). Let us introduce value \( T_i(m) \) – item path termination time \( T_i(m) = t_0(s_j, m, j) + \tau(s_j, m, j) \) with \( j = K_m \). If \( T_i(m) \leq T_i(m) \), it means that item path terminates by the required absolute moment of time; otherwise, the path fails to satisfy time requirements.

At fixed production schedule, the set of paths is generating potential loads for the group of production resources. For each group \( s \in S \) it is possible to plot temporary diagram of load \( D_s(t) \):

\[
D_s(t) = \begin{cases} 
1, & \text{if } \exists m \in M, j \in [1, 2, \ldots, K_m] : 0 \leq t - t_0(s, m, j) \leq \tau(s, m, j); \\
0, & \text{otherwise.}
\end{cases}
\] (1)

Thus, if \( D_s(t) = 1 \), it means that group of production resources is occupied, if \( D_s(t) = 0 \), it means that group of production resources is free.

Let us consider the possibility to include requisition for processing of item \( \tilde{m} \) into ongoing schedule without changing the processing deadlines for schedule-included items and replacement of the group of production resources.

Assume that \( a \) – attribute of production resources related to its respective group, and \( a \in A, A \) – set of attributes dividing set \( S \) into groups.

For item \( \tilde{m} \) there exists a process path indicating (at each stage) the required group of production resources \( a \); similar value of the attribute means possibility of using any group of production resources with this attribute at this particular stage. In such case, adding of new item into ongoing schedule is equivalent to sequential retrieving (at each stage) of free group of production resources having the required attribute.

Assume that \( j \ (1 \leq j \leq K_m) \) – sequential number of processing stage of item \( \tilde{m} \) at which there is a need for the group of production resources comprising attribute \( a_j \). Assume that at stage \( j-1 \) the item was processed with involvement of group of production resources \( s_{j-1} \). Let us introduce \( A_j \) – set of groups of production resources comprising attribute \( a_j, A_j \subseteq A \).

If there is \( t_i \) for some \( s \in A_j \):

\[
T_i(\tilde{m}) \geq t_i \geq t_0(s_{j-1}, \tilde{m}, j-1) + \tau(s_{j-1}, \tilde{m}, j-1),
\]

\[
D_s(t) = 0, \quad t_i \leq t \leq t_i + \tau(s, \tilde{m}, j).
\] (3)

it means that item \( \tilde{m} \) may be processed at stage \( j \) and, therefore, meanings \( s_j = s, t_0(s_j, \tilde{m}, j) = t_i \) apply. If such \( t_i \) does not exist it means that item \( \tilde{m} \) cannot be manufactured in terms of schedule.

Thus, task to assess new requisition inclusion without changing the ongoing schedule is limited to retrieval of path \( z(\tilde{m}) \) (without changing paths \( z(m) \), and \( m \in M \)) which would satisfy the condition \( T_i(\tilde{m}) \leq T_i(\tilde{m}) \).

This model is related to operational management which is not changing the scheduling of ongoing schedule horizons.
Model 2 – assessment of new requisition inclusion with ongoing schedule modification.

Assume that while assessing the possibility of inclusion of new requisition for item \( \tilde{m} \) into ongoing schedule we failed to find the admissible path \( z(\tilde{m}) \) satisfying condition \( T_j(\tilde{m}) \leq T_j(m) \) without modifying \( z(m) \), \( m \in M \).

In such case, it becomes necessary to modify the ongoing schedule. Main problem of modification consists in demand to distribute common resources among the paths.

Definition. Let us identify two paths \( z(x) \) and \( z(m) \), \( x, y \in M \) as intersecting, if \( \exists i \in [1,2,\ldots,K_y], j \in [1,2,\ldots,K_y] : \)
\[
[t_0(s,x,i);t_0(s,x,i) + \tau(s,x,i)][t_0(s,y,j);t_0(s,y,j) + \tau(s,y,j)] \neq \emptyset , s_i = s_j , \text{ otherwise, they will be identified as non-intersecting.}
\]

Definition. Let us identify production schedule as set \( P \) or \( m \in M \).

Model 2 – production schedule: \( \bar{m} = M \bigcup \{\tilde{m}\} \). It this case, the set of paths may be introduced in the form of \( \widetilde{Z} = \{z_m \in \bar{m} \} \). If the set \( \widetilde{Z} \) is not empty, the problem of production schedule selection arises. To select the schedule it is necessary to introduce respective selection criterion. Let us consider some of them.

In order to assess the path \( z_m \) of item \( m \) let us introduce values \( c_j \) – value costs associated with containment of item \( m \) at stage \( j \), \( 1 \leq j \leq K_m \). In general case \( c_j = c_j(m,s_j) \), these costs may include energy costs, equipment depreciation, service personnel salaries etc. In this case, value assessment of the path may be limited to composite function: \( C_m(z_m) = \sum_{j=1}^{K_m} c_j(m,s_j) \). Total value costs for schedule \( p \) may be obtained in the form of :
\[
C(p) = \sum_{m \in M} C_m(z_m).
\]

Also, for schedule assessment, it is essential to make account to random influences negatively affecting the production process. To evaluate path \( z_m \) let us introduce \( \xi_j \) – random values reflecting time delays caused by processing item \( m \) at stage \( j \), \( 1 \leq j \leq K_m \). In general case, values \( \xi_j = \xi_j(m,s_j) \).

Depending on the stage, these may be: untimely materials delivery, defective materials delivery, production personnel sickness, personal days off, non-attendance, maternity leave, industrial injury, production defect etc.

Assume that \( M(\xi_j(m,s_j)) \) – mathematical expectation of time delays at stage \( j \), \( 1 \leq j \leq K_m \). Let us introduce
\[
r_j(m,s_j) = t_0(s_j,m,j) + \tau(s_j,m,j) + M(\xi_j(m,s_j)) - t_0(s_j,m,j+1).\]

If \( r_j(m,s_j) < 0 \) it means that it is possible to state that, on the average, delays are not affecting the path implementation, otherwise there will be systematic delays causing failure to observe stage implementation deadlines.
Path temporal risks assessment may be calculated on the basis of composite function:

\[ R_m(z_m) = \sum_{j=1}^{K_m} r_j(m, s_j)I(r_j(m, s_j) > 0) , \]  

where \( I(x) \) -indicator which returns 1, if \( x \) – is the truth, 0 otherwise.

General assessment of temporal risks in schedule \( p \) may be limited to composite function:

\[ R(p) = \sum_{m \in M} R_m(z_m) \]  

Optimization problem \( C(p) \rightarrow \min \) is linear programming problem and consists in selecting the schedule in which total item production costs are minimized.

Problem \( R(p) \rightarrow \min \) is linear programming problem and consists in selecting the schedule in which total temporal costs are minimized. Composite function \( R(p) \) is limited from underneath by zero, and, if this infimum is achievable it may be reasonable to admit the zero risks.

Analysis of problem data with their visual representation may be implemented with the use of following analytical tools:
- SAS software;
- development environment RStudio, software programming language R;
- software Statistica, integration with language R;
- software package Minitab;
- statistics package Stata,
- statistics package Ewiews,
- software Forecast Pro (forecast calculation) etc.

4. Conclusions

Models presented herein make it possible to assess possibility and expediency of new order implementation by calculating the new schedule which will take into account: this new order, enterprise resources and production risks on the basis of multicriterion assessment of production schedule implementation.

Importance of these mathematical models consists in their feasibility as “Available-to-Promise” business-function for scheduling process automation and production schedule assessment. Approbation of models was carried out within state task implementation for aircraft-building enterprise “Aviastar-SP” corporation; the said approbation was considered as a part of complex (“just in time, target cost, risk accounting”) model of enterprise activity assessment.

Employment of proposed mathematical models in the information environment (BI, ERP, MES, APS class systems) allows improving the quality of scheduling, to assess production schedule implementation, to take prompt decision in respect of new order implementation.

For information system implementation it is possible:
- to use already integrated software products if the latter contain required composite function for mathematical modeling, expert assessment and data presentation;
- to expand available programs with new libraries and modules;
- to develop new information-analytical system with inclusion of obtained mathematical modeling solutions implemented with the use of ready-to-use software products like RStudio, Mathcad, MATLAB etc.

Selection of product depends on particular enterprise conditions.
5. Directions of further investigations
Within the framework of development of automated production-technological process control system intended for aircraft-building enterprise it is proposed to plot the model based on principles “just in time”, “target cost”, “risk accounting” and to perform software-supported implementation of functions of most important business-processes.

In particular, authors are planning to implement function of assessment of production plan modification on the basis of models proposed and to verify models and software referring to data submitted by “Aviastar-SP” corporation. Besides, it is required to further develop the proposed models for “target cost” and risk management cases stipulated by other than temporal factors.

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