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Prioritizing and Scheduling of Production Orders in Non-homogenous Production Systems

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Abstract
The aim of the work was to develop a prioritizing and scheduling method to be followed in small and medium-sized companies operating under conditions of non-rhythmic and non-repeatable production. A system in which make to stock, make to order and engineer to order (MTS, MTO and ETO) tasks are carried out concurrently, referred to as a non-homogenous system, has been considered. Particular types of tasks have different priority indicators. Processes involved in the implementation of these tasks are dependent processes, which compete for access to resources. The work is based on the assumption that the developed procedure should be a universal tool that can be easily used by planners. It should also eliminate the intuitive manner of prioritizing tasks while providing a fast and easy to calculate way of obtaining an answer, i.e. a ready plan or schedule. As orders enter the system on an ongoing basis, the created plan and schedule should enable fast analysis of the result and make it possible to implement subsequent orders appearing in the system. The investigations were based on data from the non-homogenous production system functioning at the Experimental Plant of the Łukasiewicz Research Network – Institute of Ceramics and Building Materials, Refractory Materials Division – ICIMB. The developed procedure includes the following steps: 1 – Initial estimation of resource availability, 2 – MTS tasks planning, 3 – Production system capacity analysis, 4 – ETO tasks planning, 5 – MTO orders planning, 6 – Evaluation of the obtained schedule. The scheduling procedure is supported by KbRS (Knowledge-based Rescheduling System), which has been modified in functional terms for the needs of this work assumption.

Keywords
Procedures for process planning, Production planning and control, Job and activity scheduling, Production planning, Scheduling, Non-homogenous systems.

Non-homogenous production systems

Big enterprises are usually oriented towards high-volume or mass production, characterized by little or no variability in the range of products. Medium-sized companies are more frequently engaged in small-series manufacturing of a wide variety of products. Large-series production is usually based on the Make-To-Stock system (MTS) of a homogenous assortment. In the 1980s, production could be characterized as "product-oriented". The process of design was focused on product development, while the course and possibilities of the production process were taken into account only to a small extent. However, the life of products on the market was much longer than now, while their number and variety were considerably lower (Mula et al., 2006).

In the subsequent decade production changed into the process- and market-oriented one in order to meet the rising expectations of customers. The Make-To-Order (MTO) system in which production was based on customer's orders was a response to this change. According to Rajagapalan (Rajagopalan, 2002) and Kingsman (Kingsman et al., 1996), in the case of MTO, the demand for products should be met in a specific time frame. Most standard components are available in the process of design, but the final shape of a product is not always defined. MTO also limits the level of finished products in stock compared to MTS. In MTO production planning the follow-

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ing criteria are taken into consideration: actual time needed to manufacture a particular product and the due date of delivery specified by the customer. MTO is managed on the basis of a customer's actual order whereas MTS is based on a forecast of future orders. Forecasts can also play a big role in MTO. They are taken into account in a medium-term horizon while balancing the production capacities and establishing a demand for production capacities. This part of hierarchical planning is defined as aggregate production planning (Rafiei et al., 2013). Rajagopalan in (Rajagopalan, 2002) notes that the division of production into MTO and MTS is determined by the customer's demand but also by the producer, as production flexibility entails increased costs of retooling, whereas its lack results in increased storage costs. In a similar way, Adan and Wal in (Adan & van der Wal, 1998) have drawn attention to stocks control and production planning in MTO and MTS. They have also noted that Production-To-Stock (MTS) allows for obtaining huge supplies, while in MTO the process of order fulfillment may take too long when the system is being intensively used. It therefore seems that a combination of MTS and MTO is a favorable solution. The authors have considered a method for allocating products to MTS and MTO and separation of production capacities. Additionally, they have analyzed the influence of the level of stocks in standard (MTS) and non-standard production (MTO) warehouses on production lead time. If a product is designed and made to order in so-called Engineering-To-Order (ETO) system, the lead time is much longer. ETO is a unique, one-off production aimed at meeting an individual order. The final product is designed and manufactured according to the customer's requirements (Knosala, 2017). An increase in the number of enterprises working in MTO and ETO systems is on the one hand caused by customer's increasing expectations with regard to variability, and, on the other hand, by the development of technology, manufacturing methods as well as the application of flexible production systems and modern IT, cooperation and managerial solutions that enable meeting their expectations.

Numerous enterprises, in particular medium-sized companies, create non-homogenous systems, offering products at various stages of a product lifetime, i.e. products characterized by different variability and repeatability, which are typical of Make-To-Stock Production, Make-To-Order Production, involving project-type tasks (Adan & van der Wal, 1998). One system is based on manufacturing typical products for which the market demand is determined on the basis of marketing research, and the current production is made to stock (MTS). At the same time, the MTO production is started. These products are to a certain extent tailored to customers' particular requirements, and the production starts only when there is a need for a given product. Additionally, the company extends its offer with products requiring multi-stage manufacturing, which is frequently related to new product development (NPD). This is a design-oriented production – ETO. Despite difficulties involved in the management of such a complex system, enterprises decide to choose this solution as business activity on the competitive market forces them to do development research works and to invest in new solutions.

The lifetime of products has drastically shortened, and so has the time of placing new products on the market. Therefore, there is a need for creating a flexible system that can be quickly reconfigured so as to meet the new expectations of the customer. In such a case, management of the production process as a project seems to be justified (Martínez et al., 1997; Martínez & Pérez, 1998; Kovács, 2003). The production process is defined as a unique, complex task which encompasses planning, designing and manufacturing in a single production system or in one location within a specified time frame in order to meet market expectations (Egri et al., 2004).

The problem of planning and scheduling in non-homogenous systems (also called hybrid systems) is widely discussed in the literature. The method of supporting the order promising process according to product homogeneity requirements in hybrid Make-To-Stock (MTS) and Make-To-Order (MTO) contexts is proposed in (Alemany et al., 2018). It has been discussed complex order promising process levels including available-to-promise (ATP) and capable-to-promise (CTP). The authors developed a software tool based on mixed integer linear programming. In (Kalantari et al., 2011), for solving this class of problems the five-level decision support system for order acceptance/rejection is proposed. The separated steps concern: prioritizing customers, a rough calculation of production capacity and inventory, rejecting/accepting orders, setting prices and deadlines, setting of guidelines to negotiate with the customers, scheduling and verification of feasibility. Mixed-integer mathematical programming model is utilized. The mathematical programming model presented in (Ashayeri & Selen, 2001) is also applied for optimization of order selection in MTO/MTS environment. Production orders acceptance and scheduling problems in a hybrid MTS/MTO production environment were also discussed in (Wang et al., 2019). They use a mixed integer programming model to maximize the total profit of the accepted MTO orders in optimization. MTO orders are placed on a fixed schedule in which MTS orders are already included. The benefits of a hybrid planning approach without priority for either MTO or MTS is examined. Markov Decision Process model for a two-product hybrid system was developed to determine when to manufacture MTS and MTO products. Contrary to earlier studies with this approach, this study includes a positive lead time for MTO products. Authors characterized optimal policies and showed how decisions should be based on both inventory level and backlog state of MTO products. A hybrid approach without prioritization for MTO or MTS by developing a Markov decision-making model is explored in (Beemsterboer et al., 2016). The magnitude of savings that is observed for the optimal, hybrid policy compared to MTO (priority) or MTS (priority) approaches, certainly warrants further research and the development of specialized planning procedures for combined MTO/MTS production systems. Four methods of integrating make-to-stock items in the control of a job shop are proposed in (Beemsterboer et al., 2017). Among the methods analyzed: Fixed and Dynamic MTS Due Dates, Dynamic MTS Slack Per Remaining Operation, Rolling MTS Operation Due Dates, the Dynamic MTS Slack Per Remaining Operation turned out to be the most valuable one. It was shown that a popular but simple method of always giving priority to MTO items is strongly outperformed by more advanced methods of integrating MTS into job shop control as it has been able to reduce the MTS lost sales by about 60%. Authors considered that up-to-date status information may improve performance substantially. Loosening the due dates of MTS replenishment orders during periods of low MTS demand enables better capacity utilization to maximize the delivery performance of MTO. The problem of selection make-to-order (MTO) or make-to-stock (MTS) strategy for a given product is discussed in (Zaerpour et al., 2008). The authors propose a decision-making structure including fuzzy AHP and SWOT analysis to solve it. Given optimization criteria are key when choosing the right strategy. several performance measures in the evaluation of the release policy process for MTS and MTO products are presented in (Rezaie et al., 2009). The authors of (Weng et al., 2020) focused on reducing parts inventory and increasing parts utilization in ETO firm. Because parts need to be readied before orders arrive, high parts inventory and low order received rates are always a performance bottleneck. To solve this problem, they proposed a new solution with the two following additional functions: (1) parts requirements planning using future inquiry information, (2) order-receiving planning for efficiently utilizing parts inventory. Parts preparation is conducted by using future inquiry information and the available parts are used through a predetermined order-receiving plan. The order acceptance plan is described as a problem of linear programming with constraints of parts inventory and on short-term inquiries. The total demand and demand ratio of each prescribed value range of each PFS (product functional specification) which were obtained from the future inquiry information were used for parts requirement planning. The concept of the production seat booking system to prepare an order-receiving plan in advance by considering the parts inventory was also applied. Instead of receiving orders using the current FCFS rule, order selection by setting the order-receiving plan can both increase the order-receiving rate and reduce the parts inventory.

Summarizing this literature review, it is easy to state that non-homogeneous systems are common in production. Systems in which few varieties of products are produced, usually two types of products – one from MTO and MTS, are considered. Various methods and heuristics are combined in planning, but no universal approach to solving these problems can be identified.

Problem formulation

The activity of every enterprise is restricted. This applies to the number of resources and their availability. Other limitations are occasional, related to incidental situations, such as a machine breakdown or employees' absence. The company can influence them only through production activities which decrease the probability of their occurrence or mitigate their effects. The condition for task implementation is therefore the planning of activity which ensures access to limited resources within a time in which particular orders have to be fulfilled (Herroelen et al., 2001; Skolud & Zolghadri, 2004).

An example of a non-homogenous production system is the Łukasiewicz Research Network – Institute of Ceramics and Building Materials, Refractory Materials Branch – ICIMB. Problems involved in planning and scheduling at ICIMB led to searches for efficient methods of production planning and scheduling. In this article, the results of research aimed at developing a procedure of task planning and scheduling in non-homogenous systems have been presented. This procedure should be easy to implement; it ought to be a universal tool in the hands of planners. It should also eliminate the intuitive way of prioritizing tasks while offering an easy manner of calculating the answer, i.e.

a ready plan or schedule. As orders enter the system on an ongoing basis, the created plan and schedule should enable fast analysis of the result and potential implementation of subsequent orders appearing in the system.

Production flow model

A non-homogenous system of multi-assortment production, including discreet, concurrent production processes is considered in this paper. The system is characterized by the following features:

- MTS orders are repetitive, MTO and ETO orders are accidental,
- production orders are defined by the volume of order, completion date, process route, number of batches,
- each process is a sequence of a finite number of operations,
- operations are non-preemptive, i.e. they cannot be stopped before the end,
- processes compete for access of resources in the mutually-exclusive mode, i.e. only one process at a time can be carried out on a resource,
- restrictions in the system are deterministic,
- subsequent operation commences immediately upon completion of the preceding one on the condition that the resources are available (restrictions regarding the sequence),
- times of transport and retooling are included in the time of operation.
- the production flow model has been divided into a system model describing the parameters of the manufacturing system and a model of order describing the customer's need.

System model

We are considering a system of production described by two variables:

$$S = \left(\{Z_n, n{=}1,2,\ldots,N\}, \{P_j, j{=}1,2,\ldots,J\}\right) \quad (1)$$

where: Z_n – n-th resource, P_j – j-th process.

The production system structure has been presented in Fig. 1.

It is assumed that:

a) the system consists of N number of resources,
b) parallel resources, (homogenous groups of machines), marked from Zn, Zn′, ..., Zn^k are allowed,
c) system resources, i.e. machines and devices are limited and renewable,
d) at a given time one task can be carried out on a resource,
e) resources are used one after another, like in the permutation flow shop,
f) processes can use a certain number of available resources, i.e. some of them use all resources from 1 to n, other processes can use a part of subsequent resources, e.g. from 1 to k or from k to N, $k < N$,
g) orders are entered into the system on the basis of:
   - forecasts, which means that historical data provides a basis for establishing a production plan in a particular time frame without specifying the completion date (for MTS),
   - customer's orders (for MTO), which appear in the system as a result of sudden demand. For this type of process the end date is the most important.
   - project schedule in which the production stage is distinguished as one of the implementation phases by specifying the date of commencement and end (for ETO),

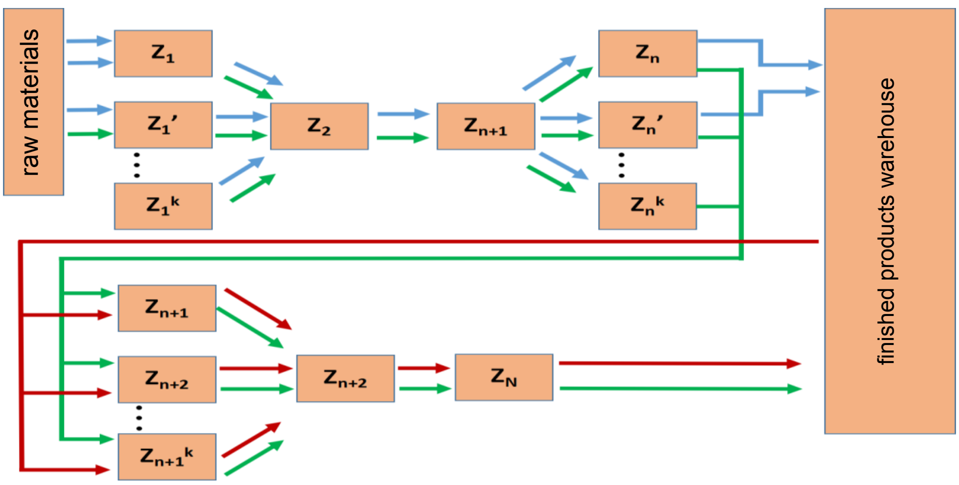

Fig. 1. Production system structure

h) the batch size is limited by the critical resource capacity,
i) the calendar of Ka_n resources is defined.

Production process P_j is an ordered set of actions (operations and activities). In the considered system the process occurs according to a strictly specified process route, which is described by process matrix M_P.

$$M_P = \begin{bmatrix} p_{11}p_{12}, & \ldots, & p_{1r}, & \ldots, & p_{1R} \\ p_{21}p_{22}, & \ldots, & p_{2r}, & \ldots, & p_{2R} \\ p_{31}p_{32}, & \ldots, & p_{3r}, & \ldots, & p_{3R} \end{bmatrix} \tag{2}$$

where: r – operation number, R – number of operations in the process route, p_{1r} – number of resource on which r-th operation is performed, p_{2r} – cycle time on resource r, p_{3r} – preparatory-end time related to operation r.

The process consists of operations:

$$P_j = \{O_{jr},\ r = 1, \ldots, R\} \tag{3}$$

where R is a number of operations in j-th process.

An operation is described by:

$$O_r = \left(Lwz_r, t_r, tpz_r, Ko_r, pre_r, re_r\right) \tag{4}$$

where: Lwz_r – list of resource requirements, specifies the station and additional resources needed to perform the operation, t_r – cycle time, tpz_r – preparatory-end time, Ko_r – operation cost used to estimate the value of an order, pre_r – operation preemptiveness, which defines whether or not a particular operation can be stopped in order to perform another operation, $pre_r = \{0, 1\}$; 0 – non-preemptive; 1 – preemptive, re_r – resumability of operations, i.e. the possibility of stopping the operation when the station is unavailable, a break resulting from the calendar, $re_r = \{0, 1\}$; 0 – unresumbable; 1 – resumable,

An operation with a specified duration t_r must start and finish within a specified time frame between the earliest term of commencing a particular operation ES and the latest term of finishing the operation LF.

System limitations

The non-homogenous system discussed in this work functions under conditions of many limitations related to orders and resources. Production scheduling in this type of systems requires defining all the limitations:

- relative, i.e. requirements whose fulfilment is expected, but not necessary,
- absolute, i.e., requirements which must be taken into consideration and fulfilled.

Limitations related to resources:

a) absolute:
   - work in the system according to the agreed calendar, which cannot be changed due to formal reasons,
   - production of diverse assortment, adversely influencing the system productivity as each change of assortment requires long-lasting retooling,
   - limited possibility of make-to-stock production due to a changeable market demand for the product,
   - possibility of halting the process only on selected resources,
   - limitations related to the volume of a production batch.

b) relative:
   - bottleneck, which is one of resources in the system.

Limitations related to orders:

a) absolute:
   - execution of orders in various manufacturing systems: MTS, MTO, ETO, which is the reason why various methods of order scheduling are applied. The execution of orders is prioritized. In the considered model, ETO has the highest priority of execution, followed by MTO. MTS orders have the lowest priority of execution.
   - manufacturing of production batches of various sizes. Additionally, ETO orders, which usually involve producing a small quantity of materials for industrial tests, may be ahead of the remaining orders on resources,
   - market requirements regarding the necessity to fulfill orders within the shortest possible time.

b) relative:
   - specified term of MTO order completion (deadline),
   - specified earliest possible term of order commencement (ES) and latest possible term of order completion (LF) in the case of ETO orders,
   - specified term of MTS order commencement (supplementing the stocks).

Order model

Orders are all works which load the resources involved in the implementation of the production plan. In a non-homogenous system orders having different characteristics and priorities can be fulfilled concurrently. Production order ZP is a transformed order of an external customer in the case of MTO and ETO or of an internal customer in the case of MTS.

$$Z_P = \left\{P^k,\ P^m,\ P^l\right\} \tag{5}$$

where: P^k – MTO processes, P^m – ETO processes, P^l – MTS processes.

A few orders for the same product can be combined into one order, if they entered the system at the same time interval. The reception of products resulting from long-term orders implementation can be cyclical, e.g. on a quarterly basis.

MTS orders

The MTS process is described by four variables:

$$P^l = \{M^l, L^l, t_r^l, \Delta t_r^l\}, \quad l = 1, \ldots, L \tag{6}$$

where: L – number of MTS processes, P^l – p process corresponding to production-to-stock, M^l – process matrix, L – series volume, t – the earliest possible term of production process start-up, Δt – time interval between subsequent MTS start-ups.

The MTS process is described by the earliest possible date of starting a production order. It is dependent on the inventory turnover of a given assortment in the finished products warehouse and on marketing forecasts. This provides a basis for planning the production starting date and the volume of a particular assortment series. Thus, resource utilization resulting from orders execution is specified.

For MTS orders it is assumed that priority is given to orders that are characterized by the shortest *tpz* and/or the highest number of successors. It is characterized in the form of priority rules.

The earliest term of commencing order execution – NTR is described by:

$$P_l(t) = \min_l \{W_l(t) | W_l(t) = t_r^l;\ l = 1, \ldots, L\} \tag{7}$$

where: $W_l(t)$ – indicator of priority of 1th task at time t, t_r^l – term of commencing 1-th process.

The shortest possible setup time – NTZP:

$$P_l(t) = \min_l \{W_l(t) | W_l(t) = tpz^l, l = 1, \ldots, L\} \tag{8}$$

tpz^l – order setup time.

The largest number of operations – LNO:

$$P_l(t) = \max_l \{W_l(t) | W_l(t) = R^l, l = 1, \ldots, L\} \tag{9}$$

R^l – number of operations in 1^{th} process.

MTO orders

The process carried out in the case of an MTO order is described by four variables:

$$P^k \{M^k, L_M^k, t_i^k, t_d^k\}, \quad k = 1, \ldots, K \tag{10}$$

K – number of MTO processes, P^{MTO} – process corresponding to make-to-order production, M^k – process matrix, L_M^k – volume of series, t_i^k – date of order's entry into the system, t_d^k – order deadline.

In the case of MTO orders, a vitally important issue is the deadline restriction imposed by the customer. By using the "backwards" planning method, the order completion date and resource load are determined. In the case of a few MTO orders, the order with the earliest directive term of order completion and/or the highest workstation occupancy of the order is given priority.

The earliest directive term of task completion_NTD:

$$P_k(t) = \min_k \{W_k(t) | W_k(t) = t_d^k,\ k{=}1, \ldots, K\} \tag{11}$$

where $W_k(t)$ – indicator of priority of k-th task at time t, t_d^k – k-th order directive completion time.

The maximum total workstation occupancy of the order – MAXSTAN:

$$P_k(t) = \max_k \left\{ W_k(t) \middle| \ W_k(t) = \sum_{r=1}^{R} t_j^k, \right. \\ \left. k = 1, \ldots, K \right\} \tag{12}$$

where: R – number of operations in process route, k – process number, t_j^k – cycle time of r-th operation of k-th process.

ETO orders

ETO orders are subsequent milestones in the implemented project (Fig. 2). Due to the strictly specified period of time in which the order (production part of the project) is to be executed, it is characterized by four variables:

$$P^m\{M^m,\ L_M^m,\ t_r^m,\ t_d^m\}, \quad m = 1, \ldots, M \tag{13}$$

where: M – number of ETO processes, PETO – process corresponding to the project production stage, M^m – process matrix, L – series volume, t_r^m – the earliest possible time of production process start-up, t_d^m – the latest possible order completion term (deadline).

In the event a few ETO orders are placed at the same time, the rule based on the priority of the earliest directive task completion date – NTD (described above) should be followed.

Definitions that describe processes include the term of order's entry in the system t_i^k, i.e. the term of receiving information about a new order and starting

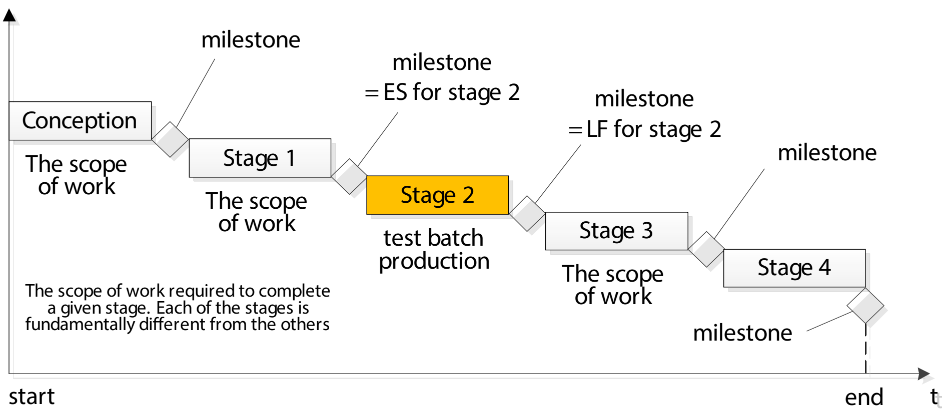

Fig. 2. Types of processes carried out in the system

to plan its fulfillment as well as order commencement date t_r^m which is the beginning of its execution. Therefore, the subject of planning is orders portfolio PZ, described by three variables:

$$\mathrm{PZ} = \big(\{M_l\},\ \{M_k\},\ \{M_m\}\big),$$
$$l = 1,\ldots,L,\quad k = 1,\ldots,K,\quad m = 1,\ldots,M \quad (14)$$

where: L – number of MTS orders, K – number of MTO orders, M – number of ETO orders.

Plan and schedule generation method referred to as the PZSN procedure

As mentioned before rules are assigned to each of order groups putting them in order inside the group. Moreover, the priority of execution has been established in accordance with the following sequence relationship: ETO before MTO, ETO before MTS, MTO before MTS. The plan takes into account the variety of orders executed in the system, and, thus: different methods of their planning and criteria of their evaluation, the importance of tasks belonging to particular groups, but also priorities of tasks in each group.

Step 1. Initial evaluation of resources availability

It involves defining a calendar of the availability of resources required to perform operations, which is defined by the working time fund. The calendar is independent from resources, particular resources can use the same calendar (Kalinowski, 2013). The calendar results from the system of work adopted in an enterprise: the number of "working" hours during the day, the number of working days in a week, public holidays, breaks related to predictive actions. The calendar of a particular resource "n" consists of a list of periods of resource availability and unavailability. In a given planning horizon there may be cyclically repeating periods of availability or unavailability or non-cyclical periods of availability and unavailability.

$$Ka_n = \mathrm{COD}_n/\mathrm{CON}_n \cup \mathrm{NOD}_n/\mathrm{NON}_n \quad (15)$$

where:
- Ka_n – work time calendar for resource n,
- COD_n – cyclical period of availability (resulting from the system of work in a given enterprise),
- CON_n – cyclical period of unavailability (resulting from the system of work in an enterprise),
- NOD_n – non-cyclical period of availability (resulting from incidental overtime work),
- NON_n – non-cyclical period of unavailability (resulting e.g. from a machine service inspection).

Step 2. MTS orders planning

The first to be taken into consideration are MTS orders, for which there is a stable demand in the considered time frame. The monthly volume of series (L_M^l) results from the average demand for a given assortment established on the basis of marketing forecasts. The average is divided into production batches, the size of which depends on the technological line capacities. The date of starting another production batch (t_r^l) is specified by planners. In MTS orders the term of completion for a given batch is not specified and depends on "more important" MTO and ETO orders, which have a scheduling priority. Then, if orders with a higher priority (MTO and ETO), requiring a bigger production capacity than the current one, appear in the system, the procedure requires withholding the MTS execution. Usually, the production of a few assortments "to stock" is carried out. According to the adopted priority rules, priority is given to orders which have the shortest preparatory-end time. If this issue does not resolve the conflict, priority is granted to the process that has the biggest number of successors, e.g. it carries out the process on the basis of the longest process route.

Step 3. Analysis of system production capacities

In enterprises with non-homogenous production, a strategic issue is the level of initially reserved production capacities for executing all kinds of orders. This is an initial estimation of demand for production capacities:

$$P_p = \sum_{l=1}^{L} L_M^l \cdot \left(\sum_{r=1}^{R} p_{2r}^{\mathrm{MTS}} \right) + \sum_{k=1}^{K} L_M^k \cdot \left(\sum_{r=1}^{R} p_{2r}^{\mathrm{MTO}} \right) + \sum_{m=1}^{M} L_M^m \cdot \left(\sum_{r}^{R} p_{2r}^{\mathrm{ETO}} \right) \tag{16}$$

where:

P_p – production potential of the system,
L_M^l – volume of MTS orders series,
L_M^k – volume of MTO orders series,
L_M^m – volume of ETO orders series,
P_{2r}^{MTS} – cycle time of operation r on a resource from the matrix of MTS production,
P_{2r}^{MTO} – cycle time of operation r on a resource from the matrix of MTO production,
P_{2r}^{ETO} cycle time of operation r on a resource from the matrix of ETO production.

Production potential is a demand for resources in the system for completing tasks in a given time frame. An arbitrarily maximum value of production capacities reservation to be used for MTS orders is assumed. Its estimation takes into account costs involved in the maintenance of finished products warehouse and the type of activities. It may have various values. For the case of ICIMB, this value is 20%.

Step 4. ETO orders planning

Another step of the procedure involves including ETO orders, which are a part of a bigger project (i.e. a research one in Fig. 2), in the production plan. The planner knows in advance about the arrival of this type of orders. This task is granted priority in the allocation of resources. However, it must be carried out in the time frame between the earliest possible date of commencement (ES) and the latest possible term of order completion (LF), resulting from the project schedule.

The completion time is usually relatively short, but from the point of view of the company functioning strategy these are the most important types of orders executed in the system. It has been assumed that ETO orders have priority before MTS orders, which at this stage of implementing the procedure in question are already taken into account in the production plan. If the time of ETO orders execution interferes with the schedule of MTS orders executed before, i.e. during the planned execution of an ETO order, the resources are engaged in the execution of MTS processes, the schedule of MTS orders allocation is corrected so that the resources can be made available to ETO orders.

Step 5. MTO orders planning

MTO orders appear in the system suddenly and utilize the resources for a short time, hence there is the possibility of using short idle statuses between orders that have been already accepted for execution (steps 2 and 4). These orders have a precise deadline for completion, specified by the customer, so the adopted method is that of “backward” scheduling. MTO orders are given priority in relation to MTS orders, but they do not influence the scheduling of ETO orders execution.

In the event the MTO execution deadline specified by the customer interferes with an ETO order, the availability of resources is searched for before the term, and if this is also impossible, planning is changed to the “forward” mode; this way the term of possible execution is determined (Fig. 3). However, it will be delayed compared to the directive term.

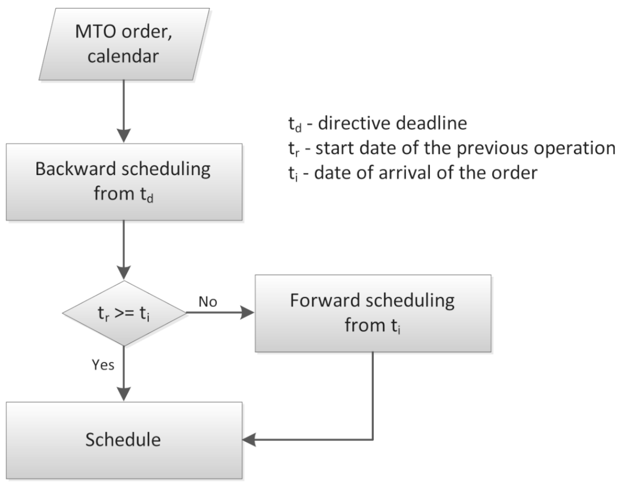

Fig. 3. ETO Scheduling of MTO tasks in the event they have to compete for resources with an ETO order

Step 6. Evaluation of the obtained schedule

The established schedule is subjected to qualitative evaluation. The assessment is based on indicators evaluating the schedule of a given order in terms of flow and completion deadlines. Schedule assessment indicators, similarly to the priority rules established for the system, are determined for a particular enterprise while taking into consideration the operating strategy. The following schedule evaluation criteria have been adopted for the considerations contained in this work. The indicator of order untimeliness is:

$$W_j^l = \frac{\sum_l t_{rz}^l - t_d^l}{l}, \quad l = 1, \dots L \tag{17}$$

The order flow time (F) is a period between the effective date of completing the order and the date of its entry into the system.

$$F = t_{rz} - t_r \tag{18}$$

where: t_{rz} – effective date of order completion, t_r – release date of order.

The time of order stay in the system (Fs) is a period between the effective completion date and the order commencement date.

$$Fs = t_{rz} - t_i \tag{19}$$

where: t_i – date of order entry into the system (the order commencement date).

The derivative of these indicators are costs involved in the carrying out of production based on a given schedule (e.g. the volume of ongoing works). This aspect is important from the managerial point of view and the economics of business activity, as it must be remembered that the aim of the procedure is to increase the probability of the company's success, i.e. obtaining a positive financial result.

An innovative approach to multi-criteria analysis is an analysis of indicators separately for each of the order groups, i.e. MTS, MTO and ETO. Bearing in mind the assumed strategy of operation, and, in consequence, allocation of various indicators of priority for particular groups of orders it seems pointless to analyse the obtained indicators for all the orders as such evaluation could lead to wrong planning decisions.

KbRS and PZSN

KbRS supports scheduling and rescheduling in systems characterized by discreet production flow (Kalinowski, 2013). It among others supports taking decisions in the following scope:

- scheduling of production process operations (orders), choice of process routes, alternative resources, establishing the number of staff etc.,
- recording and control of orders execution,
- correcting the course of production,
- pre-simulation and testing of the system efficiency as well as the choice of the most adequate package of orders.

Application of KbRS for scheduling in non-homogenous systems in accordance with the PZSN procedure required making certain modifications. The changes were among others related to:

- defining the types of orders and assigning an adequate planning strategy to them. According to the work assumptions, all the orders executed in the system are divided into three groups: MTS, MTO and ETO. In the planned execution of orders from particular groups, different priorities and terms characteristic of a given group are taken into consideration. The program provides for the possibility of assigning an appropriate manner of "forward" planning to MTS orders, or "backward" planning to MTO and ETO orders. Additionally, in KbRS, the term of order's entry into the system t^k (it is not equivalent to the term of task commencement) is taken into consideration, whereas in the case of ETO, t^m, i.e. the earliest possible date of project commencement can be taken into account.
- assigning priorities to particular orders. In the process of particular groups planning, different priority rules are taken into consideration. The program provides for the possibility of reading orders from .xls and .csv files, in which orders are sorted in accordance with the rules adopted for a given method. In the PZSN procedure, in line with the adopted assumptions, orders are listed in the following sequence: ETO, MTO and MTS. Next, within particular groups of orders, they are sorted according to the priority rules adopted for a given group.

Case study

Production of monolithic materials is characterized by the fact that operations are carried out on subsequent resources. However, a certain group of resources or all of them can be used for particular processes.

Three processes are performed on eight resources in this system.

$$S = (\{Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8\}, \{P_1, P_2, P_3\}) \qquad (20)$$

The diagram of processes has been shown in Fig. 4.

The process route of monolithic material production Pr_1 is described by matrix M_{P1}:

$$M_{P1} = \begin{bmatrix} Z_1 & Z_2 & Z_3 & Z_4 \\ 15 & 20 & 15 & 60 \\ 3 & 0 & 3 & 9 \end{bmatrix} \qquad (21)$$

The process route of pre-fabricated elements production Pr_2 is described by matrix M_{P2}:

$$M_{P2} = \begin{bmatrix} Z_1 & Z_2 & Z_3 & Z_4 & Z_5 & Z_6 & Z_7 & Z_8 \\ 15 & 20 & 15 & 60 & 60 & 120 & 2880 & 60 \\ 3 & 0 & 3 & 9 & 7 & 7 & 120 & 0 \end{bmatrix} \qquad (22)$$

The process route of prefabricated elements production Pr_3 is described by matrix M_{P3}:

$$M_{P3} = \begin{bmatrix} Z_5 & Z_6 & Z_7 & Z_8 \\ 60 & 120 & 2880 & 60 \\ 7 & 7 & 120 & 0 \end{bmatrix} \qquad (23)$$

In the considered case of a non-homogenous system there are different mechanisms of analyzing and starting-up processes involved in customers' orders which is illustrated in Fig. 5.

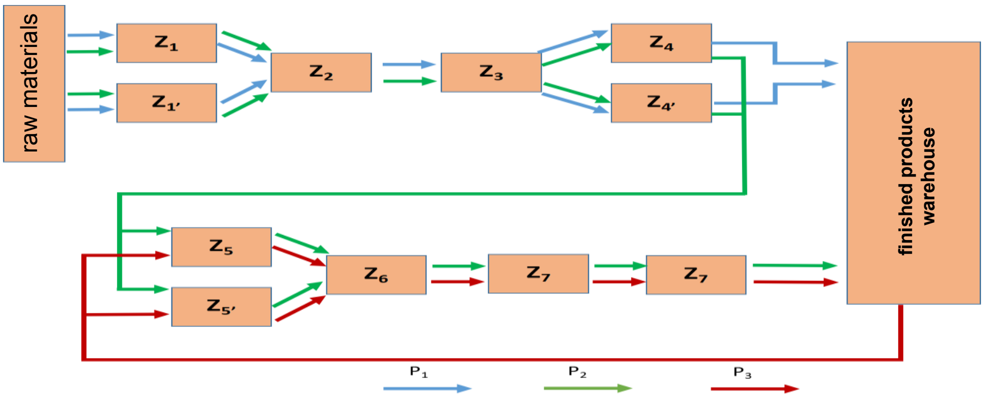

Fig. 4. Types of processes carried out in the system

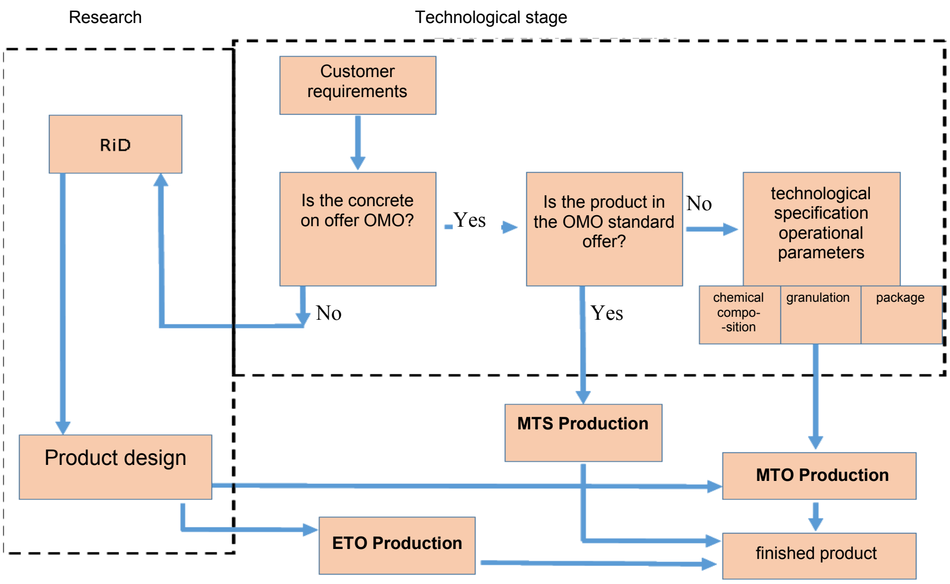

Fig. 5. Order analysis procedure at Łukasiewicz – ICIMB

Step 1. Initial estimation of resources availability

The system works in a mixed system. Resources Z_1–Z_6 and Z_8 work in a one-shift system from Monday to Friday – Calendar_1. Resource Z_7, which is the system bottleneck, works in a continuous system, i.e. 24h/7 days in a week, i.e. 10 080 minutes weekly (Calendar 2). Using KbRS, these two calendars were prepared for a period of 12 months.

Step 2. MTS orders planning

Processes related to MTS orders execution are started on the basis of historical data as well as trends and marketing forecasts. These orders have the lowest priority indicator, and their execution can be postponed so as to ensure timely completion of MTO and ETO orders which suddenly appear in the system.

MTS production plan is prepared for 12 months. This plan is frequently modified due to changes in the market expectations and a lack of possibilities to sell the produced materials. For the considered case, the following were qualified for MTS production:

- mix NGB-150. Planned monthly production "to stock" will reach 20 tons.
- castable BOS-145. Planned monthly production "to stock" will be 40 tons.
- castable BAN-160. Planned monthly production "to stock" will be 18 tons.

Step 3. Analysis of system production capacities

An analysis was conducted for resource load related to the execution of 324 MTS orders. Table 1 contains estimated resource load with MTS. The resource load indicators do not exceed 20% in relation to the calendar referred to in step 1.

Step 4. ETO orders planning

Research and development is the basic activity of Refractory Materials Branch . For this reason ETO orders have priority despite the fact that from the economic point of view they are not profitable. Their timely completion is extremely important in the context of the timeliness of the entire research project. In industrial plants there is a strictly defined time interval in which a material can be installed and subjected to industrial tests. In the event the manufacturing of the test batch is delayed, completion of the whole project can be postponed even by 12 months, i.e. until the next overhaul shutdown.

Delayed completion may result in a negative evaluation of the enterprise as a research centre as well as financial consequences. Therefore, ETO orders have been granted the highest priority compared to all the remaining orders executed in the system. In the year 2018 the number of completed ETO tasks reached 15.

Step 5. MTO orders planning

The Institute fulfills mostly MTO orders due to the fact that most of the assortment contains alumina cement with a specified expiry date. Monolithic materials' quality parameters deteriorate over time. Additionally, grain size distribution, the manner of packing, marking etc. are agreed at the stage of accepting an order from the customer. Therefore, focusing production capacities on MTO orders completion results from the nature of products and the changeable demand on the market. In the year 2018, the Institute completed 832 MTO orders.

Step 6. Evaluation of the obtained schedule

In accordance with the PZSN procedure, a schedule was created for a period of 12 months. A fragment of this schedule, as of 22/03/2018, with the course of selected tasks marked, is presented in the Gantt chart in Fig. 6.

To evaluate their effectiveness, another schedule (so-called baseline schedule) was prepared. In this case, task planning is similar to that currently carried out in the Institute. It is based on the following assumptions:

- planning is done according to the sequence of orders in the system,
- all orders are planned "forward".

Table 1
MTS Estimated resource loads related to MTS execution

Id (according to KbRS)	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Code (according to model)	Z1	Z1′	Z2	Z3	Z4	Z4′	Z6	Z6′	Z7	Z7′	Z8	Z9
% share t	1.2	1.2	1.0	0.8	4.7	4.7	0.2	0.2	0.3	0.3	9.6	0.9
% share $t + tpz$	1.2	1.2	1.0	0.9	4.9	4.9	0.2	0.2	0.3	0.3	10.0	0.9

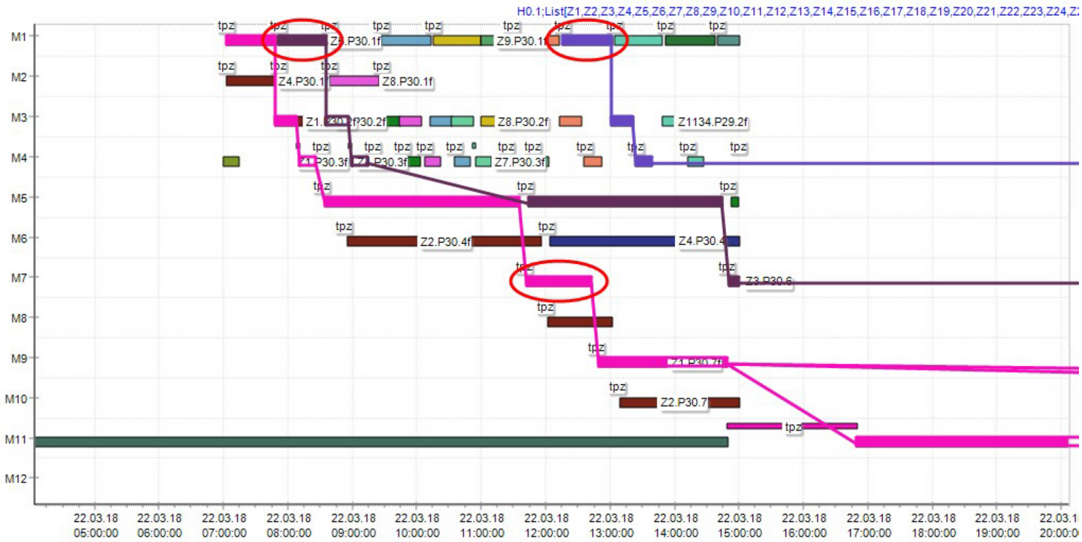

Fig. 6. Gantt chart of the production schedule on 22.03.2018

Two schedules were prepared, i.e. PZSN and baseline schedule, on the basis of actual data from the Łukasiewicz Research Network – Institute of Ceramics and Building Materials Refractory Materials Division. The PZSN and baseline schedules were prepared using the KbRS program and subjected to multiple-criteria analysis. The obtained results have been given in Table 2.

A comparative analysis of the PZSN and baseline schedules confirmed the enhanced timeliness of pro-

Table 2
List of indicators of baseline and PZSN schedules

Indicator		MTS	MTO	ETO
Number of tasks		324	832	15
Number of delayed tasks U [pcs]	Baseline	19	460	15
	PZSN	89	115	5
Maximum untimeliness Lmax [h]	Baseline	130.2	145.5	38.5
	PZSN	81.9	38.6	28.3
Average untimeliness Lav[h]	Baseline	61.7	11.0	23.6
	PZSN	33.1	1.4	12.9
Maximum delay Tmax [h]	Baseline	14.6	145.7	38.5
	PZSN	77.4	38.5	10.3
Average delay Tav [h]	Baseline	0.43	9.87	23.6
	PZSN	8.9	0.7	1.8
Maximum flow time Fmax [h]	Baseline	71	146.1	69.7
	PZSN	183.7	127.6	22.9
Average flow time Fav [h]	Baseline	18.7	20.5	44.2
	PZSN	64.2	12.0	11.4
Maximum time of stay Fsmax [h]	Baseline	70.4	138	70
	PZSN	183.1	47.6	22.8
Average time of stay Fsav [h]	Baseline	14.6	12.5	11.3
	PZSN	51.8	1.44	11.3

duction orders according to the PZSN procedure developed in this work. It allowed for decreasing the total number of delayed orders from 494 to 209. In the group of priority tasks related to project completion (ETO), the number of delayed orders dropped from 15 to 5 orders, and in the group of MTO tasks from 460 to 115 orders.

The bottleneck of the system, i.e. roaster (M_{11}), makes it impossible to eliminate delays completely. The method allowed for reducing the delays in ETO and MTO orders groups. The improvement was at the cost of increased delays in MTS orders. However, this is consistent with the Institute's strategy, as MTS delays do not influence the image of the company and no financial penalties are incurred as a result of failure to meet the obligations. In all delayed orders the maximum untimeliness was reduced. This applied mostly to MTO orders, i.e. from 145.7 to 38.5 h.

The question of resource use optimization will be the subject of further investigations. In the systems where multi-assortment production is carried out, there is a possibility of limiting the preparatory-end time by grouping similar orders. The defining of similarity criteria and correcting the PZSN procedure accordingly is an interesting and significant issue from the point of view of enterprises engaged in a similar production.

Summary

The main subject of this work concerned the development of a method to support the decision-making process in planning and scheduling tasks in heterogeneous production systems. The developed method supports the planning process at different organizational levels and allows the determination of production plans in a different time perspective.

The obtained schedule evaluation indicators, i.e. timeliness of task implementation confirmed the effectiveness of the proposed method. The research will be continued so as to optimize the effectiveness of resource use in non-homogenous systems. It can be done by grouping similar orders and consequently reducing the preparation and finishing time in the total resource usage.

Heterogeneous systems are becoming more and more common, and tools supporting management processes are an indispensable element of everyday business operations. The indicated method is of implementation character, and its assumptions can be broadly modified, taking into account the requirements of a given class of systems or the specifics of the company's operations.

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