Bi-Criteria Scheduling for Multistage Multiproduct Batch Plants with Due Dates and Setups

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Abstract

This paper presents a method for multistage multiproduct batch scheduling based on two criteria simultaneously: relative setup cost criterion and average orders utility criterion. Batch size is determined at the first operation and will not change further. During scheduling process batches are automatically grouped by product types for cost decreasing. Storing between operations is unavailable.
In this method, the concept of production intensity as a dynamic production process parameter is used. A software package allows scheduling for medium quantity of jobs. The result of software application is the set of non-dominant versions proposed to a user for making a final choice.

Keywords — *Batch production; dynamic scheduling; production intensity; Pareto-optimality.*

I. INTRODUCTION

Batch processes are widely used in production of many low-volume high-value-added products, such as pharmaceutical or food commodities. In multiproduct manufacturing the operation subsequence is the same for all products, and batches of initial raw through several operations turn into the batches of finished products. Size of a batch is usually determined by capacity of the machine assigned for the first operation.

Actually, at subsequent operations this volume may be changed, if a technological process requires some supplements, or after the operation, part of the batch may be sold as by-product. In this paper it is assumed that batch volume does not change at all technological operations.

There is a great number of papers dedicated to multistage multiproduct batch scheduling. Models for sequential facilities usually include assignment of tasks to processing units, sequencing between pairs of tasks assigned to the same unit, and timing of tasks [1]. Most of the published approaches formulate the problem as a mixed integer linear programming (MILP) or mixed integer non-linear programming (MINLP) model [2].

As far as the author knows, [3] proposed the earliest model for MILP using, which divides the time horizon into a certain number of even time intervals. These models provide relatively simple constraints, but need a large number of time points to achieve solution with reasonable quality. To reduce the number of binary variables, continuous-time approaches were developed [4], where the discretization of the time horizon is not equidistant. Further, [5] and [6] used various decomposition methods for decreasing of computations, in which at the first stage of decomposition they elaborated the schedules for “bottlenecks”. [7] developed a unit slot continuous-time model, which divides the continuous-time interval into unit slots different for specific machines. This model was useful for decision making in various scenarios considering different resources allocation profiles. The perfect review of the MILP papers and their classification is made by [8].

In [9] a genetic algorithm was proposed (GA) for online-scheduling of a multi-product batch polymer plant. It was seen that this approach essentially outperformed mathematic programming. The GA method was successfully applied by [10] for multistage batch scheduling of big size with criteria $C_{\max}$ or $F_{\max}$. In [11] the efficiency was demonstrated of the Max-Min Ant System (MMAS) algorithm for parallel unrelated machines scheduling and the criterion $C_{\max}$. In this method the subsequent construction of the feasible schedule is combined with local search of the best solution. A problem to apply genetic, simulated annealing, tabu search and other meta-heuristic methods is that it is difficult to get the initial feasible solution.

The multicriteria approach was proposed in [12] for multiproduct batch scheduling. This paper embeds principles from Life Cycle Analysis (LCA) for optimization model construction, which takes into account economical criteria and criteria of environmental safety. The similar approach was applied by [13], which elaborated the combination of genetic algorithm and local search. The proposed methodology was studied in a case concerning a multiproduct acrylic fiber production plant, where product changeovers are critical results. In [14] it was estimated the scheduling quality with economical criterion and environmental pollution criterion as well. This optimization model was solved with the ε-constraint method. The optimal solutions lead to a Pareto frontier construction for mentioned criteria.

The highest production efficiency may be achieved only when every batch is assigned to specific customer order at the moment of batch release into manufacturing. However, order size usually is not equal to machine capacity, so batch size usually is not equal to order volume as well. We have such coincidence only when there is one order and its volume is less then machine capacity. In other cases, the batch is assigned either for several orders or for the part of a single order.

Most papers dedicated to batch scheduling are based on the make-to-store mode of production. So, these methods do not take into account dependence between size of batches and their subsequence with the given set of orders. If the case takes due dates into account, for example [15], it is usually assumed that there is a special procedure for order distribution in batches, which has to be made before scheduling.

Naturally, when flow shop schedule is being elaborated, it is necessary to be guided by some optimization criteria, though they are not obvious. In the papers on batch plants scheduling optimization with a single criterion is usually made. It may be the production cost criterion, makespan $C_{\max}$, flow time $F_{\max}$ and so on. In such cases, the due dates are usually taken into account as some constraints. There are few papers [16], where tardiness is used as the main criterion. The known papers, which apply multicriteria approach, do not use a criterion of timeliness as well.

Wide spread occurrence of Just-in-Time Production methodology in scheduling requires to apply the criteria, which explicitly consider possible deviations of contractually agreed due dates. As a result, the aspiration for timely order fulfillment leads to necessity of frequent system changeovers.

During changeover from one product to another, an enterprise incurs losses owing to machine setups, machine cleaning, utilization of cleaning liquid and possible waste of some production. Besides, the line throughput diminishes. Therefore, we must attempt to make a minimal number of changeovers. However, reduction of changeovers leads to storing large quantity of some product types and shortage of others, which adversely impacts service level. This contradiction is known as the "dilemma of operation planning" [17], and its solution is in principle impossible with a single criterion concept.

This paper proposes a dynamic scheduling method, in which a user makes a final choice among the set of Pareto-optimal solutions. For scheduling quality assessment two criteria are used [18]: relative setup cost criterion and average orders utility criterion.

The remainder of this paper is organized as follows. Section 2 determines the function of current order utility and the function of setup losses. In Section 3, the scheduling algorithm for flexible multiproduct batch line with the given set of orders is described. The example of algorithm application is made in Section 4. Section 5 contains some concluding remarks

II. MAIN PROBLEM DEFINITIONS AND UTILITY FUNCTIONS

In this Section the main formulas for the scheduling criteria are given.

Notation

Indices

i = 1, 2 …I Index of order
j = 1, 2 ... J Index of operation
f = 1, 2… F Index of machine pool
h = 1, 2 …T_q Index of material arrival for product of type q
k = 1, 2 …K Index of performed operation in full list of operations
l = 1, 2 …K Index of operation execution tree level
m = 1, 2…M Index of specific machine in full list of machines
o = 1, 2… O Index of product type of the last machine setup
q = 1, 2… S Index of product type
χ = 1, 2… n_i Index of batch for order i
z = 1, 2… Z_l Index of decision tree node on a level l
u = 1, 2… L Index of machine pair at batch transfer for the operation

Parameters

d_i Due date of order i in work days
G Duration of plan period in work days
E Quantity of hours in a work day
α "Psychological" coefficient
p_{ij} Processing time of operation j for order i in hours
r_{qh} Release moment for material of type q
s_{oqm} Duration of setup from type o into type q for machine m in hours
T_t Normative time between operations in hours
w_i Weight coefficient for job i

K_{iq} Number of product of type q in order i
B_m Capacity of machine m
c_s Cost of setup hour
c Cost of a work day

Variables
p_i Process time of job i that remains until order completion in hours
N_i Remaining number of operations
g_{ij} Necessary release moment of operation j for order i in hours
a_i Number of the first unfulfilled operation for order i
A_{qi} Quantity of released product of type q in order i
b_{u1} Occupied volume of the first machine in pair u
b_{u2} Occupied volume of the second machine in pair u
C_{lz} Operation completion moment for tree node z at level l
C_m Last job completion moment on machine m
D_{qt} Quantity of material of type q, which is stored at moment t
n_i Number of batches for order i
$\gamma_{i\chi}$ Percent of order i completion in batch χ
t Current time
$t_{l+1,k}$ Start moment for operation k on the level $l+1$
I_l Set of operations planned to the moment $t_{l+1,k}$
H_i Current production intensity of order i
V_i Current utility of order i
V Current utility of all remaining operations
$\bar{V}_l$ Average utility of all jobs on the level l
$\bar{V}_{l+1,k}$ Average utility of all orders on the level $l+1$ for operation k
U_l Total relative costs at the level l

Criteria
$\bar{V}$ Average utility of all orders on the planning horizon
U Total relative setup costs on the planning horizon.

If job execution is multistage, the process time of order i that remains until completion consists of process time on N_i of certain j operations

$$p_i = \sum_{j=a_i}^{N_i} p_{ij} . \quad (1)$$

Necessary release date of operation j for order i is defined as

$$g_{ij} = d_i - p_i /E + 1. \quad (2)$$

The manufacturer's attitude to the order changes with time, and the appropriate function is named production intensity. This function for multistage manufacturing and order execution without preemption (in a single batch) is [19] as

$$H_i = \frac{w_i[p_i + T_t(N_i - 1)]}{EG} \frac{1}{(d_i - t)/\alpha G + 1} \quad \text{at } d_i - t \geq 0$$

and (3)

$$H_i = \frac{w_i[p_i + T_t(N_i - 1)]}{EG}[(t - d_i)/\alpha G + 1] \quad \text{at } d_i - t \leq 0 .$$

The production intensity concept may be used for determination of the *current order utility function* V. This function is equal to the subtraction between production intensity value at the moment $t = d_i$ and current production intensity value at any moment t. For order i the current utility is defined as follows in [18]:

$$V_i = \frac{w_i p_i}{EG} - H_i . \quad (4)$$

The main property of both production intensity and order utility function is additivity property, owing to these parameters may be summed for different orders. Thus we can calculate the mean utility of the entire set of orders for a period:

$$V = \sum_{i=1}^{n} V_i = \frac{1}{G}\sum_{i=1}^{n} w_i p_i - \sum_{i=1}^{n} H_i . \quad (5)$$

The value of the function V changes in time, since the time reserve to the moment of scheduled execution changes. Besides, some orders are completed and new orders appear. If order preemption is possible (order execution in several batches), instead of formulas (3) we have:

$$H_i = \frac{w_i}{G} \sum_{x=1}^{n_i} \gamma_{i\chi} \frac{[p_\chi + a(N_\chi - 1)]}{(d_i - t)/\alpha G + 1} \quad \text{at } d_i - t \geq 0$$

and (6)

$$H_i = \frac{w_i}{G} \sum_{x=1}^{n_i} \gamma_{i\chi}[p_\chi + a(N_\chi - 1)]\,[(t - d_i)/\alpha G + 1] \quad \text{at } d_i - t \leq 0 .$$

In this case, operation time for batch χ is summarized from N_χ specific operations that remain until batch completion:

$$p_\chi = \sum_{j=1}^{N_\chi} p_{\chi j} . \quad (7)$$

This paper builds the multilevel tree of operation completion for multistage scheduling. Expediency of adding new tree nodes is considered at every level, and new nodes define both batches and machines to complete such operations. New tree branches, which grow from the node, may correspond to both a parent node machine and other machines.

Let us assume that a certain operation on the machine z corresponding to the node of the scheduling versions tree at the level l is completed at the moment of time C_{lz}. At the next level one of operations, which is not yet completed, has to be planned. Assume that this is the operation *j* for batch *k*, which may start at the moment t_k. Thus, the operation finishes at the moment $t_k + p_{kj}$.

As it was demonstrated in [19], the utility of the entire set of orders at any level of operation tree may be computed by one of two recurrent formulas, which are used, if the utility value is known at the previous level:

$$\overline{V}_{l+1,k} = \frac{1}{t_k + p_{kj}}\left(\overline{V}_l \times C_{zl} + \int_{C_{zl}}^{t_k+p_{kj}} V_k dt\right)$$

$$\text{at } t_k + p_{kj} \geq C_{zl}$$

and (8)

$$\overline{V}_{l+1,k} = \overline{V}_l + \frac{1}{C_{zl}} \int_{C_m}^{t_k+p_{kj}} V_k dt$$

$$\text{at } t_k + p_{kj} \leq C_{zl} .$$

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In (8) $\overline{V}_l$ is equal to the mean utility of the entire set of all orders during interval from $t = 0$ until the completion moment of the last scheduled operation C_{zl}; C_m – moment of completion of pre-planned batch on machine *m*; V_k – current (variable) utility of the set of orders that are not completed; $\overline{V}_{l+1,k}$ – the mean utility of the entire set of all orders during interval from $t = 0$ until the completion moment $t_k + p_{kj}$ of the next operation. Rules to compute the integrals and necessary tables are described in [20].

The value of relative direct costs in multistage production may be computed as the total sum of setup costs for all batches on the planning horizon :

$$U = \frac{1}{C}\sum_{i=1}^{n} \sum_{j=1}^{N_i} C_{ij} . \ (9)$$

III. DYNAMIC SCHEDULING ALGORITHM FOR FLEXIBLE MULTIPRODUCT BATCH LINE

As a rule, each technological operation needs specific equipment. If an operation may be performed on several machines, we have a flexible technological line. In Figure 1 the example of such a line, which is designed for four operations, is shown. From raw store M materials are carried by transport device or by tubes to the machine 1 or the machine 2 for operation 1. Generally, machine availability depends on production type.

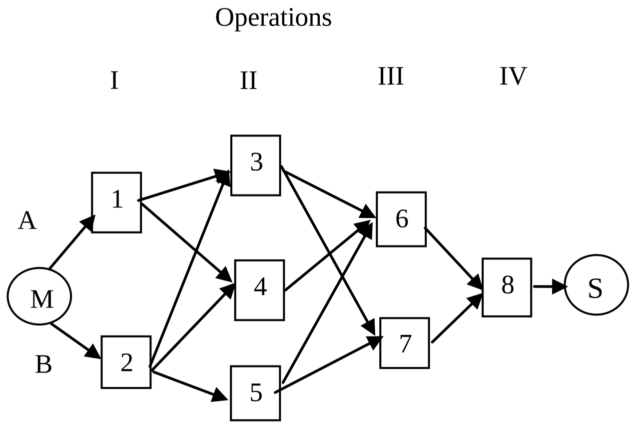

Fig. 1. Example of Flexible Multiproduct Batch Line

Let us assume that it is possible to manufacture two different products A and B in parallel on the line. In Figure 1, it is shown that for the operation 2 with the product A we can assign machines 3 and 4; for product B all machines 3, 4, 5 may be used. Availability of product transfer from specific machine of operation 2 to a machine of operation 3 depends on product type. Apparently, the machine 5 is only for the product B, but in machines 3 and 4 both products are available.

Assume that at the operation 3 it is impossible to manufacture the product A in the machine 7, but in the machine 6 both products are available. Accordingly, here the case is shown, when the product B is in the machine 3, and the product A in the machine 4. Only one machine 8 is available for the operation 4, so both products may be completed in it. The products are then transferred to the store S of finished production.

The assumptions for the line in Figure 1 are below.

a) There are no reservoirs for product storage between operations.

b) The operation sequence is the same for any job.

c) For every order the priority coefficient may be applied.

d) Each operation may be performed on some unrelated machines of a certain pool.

e) The processing time for each operation is known and deterministic.

f) At the beginning all product batches on all machines are known.

The problem, in accordance with the well-known three-part scheduling classification, is as follows:

$$FF \mid batch, r_q, d_i, s_{qkm} \mid U, \bar{V} \quad (10)$$

where *FF* – flexible flow production; *batch* – batch size, which is determined on the first operation and will not change further.

There are two target functions in this case, and they may both be improved only within certain limits. The Pareto compromise curve serves as such limit, because in its points the criterion U improvement (diminution) means the criterion $\bar{V}$ deterioration (diminution). For solving the problem (10), similar to [19], it makes sense to apply the method, based on the MO-Greedy approach [21].

For Pareto front determination by beam search the tree with nodes of intermediate solutions is constructed. For the nodes corresponding to the first operation the single constraint is

$$K_{qi}\gamma_{i\chi} / 100 \le Min(D_{qt}, K_{qi} - A_{qi}, B_m). \quad (11)$$

In the left part of the inequation (11) we have quantity of product q for order i, which may be released in batch x. This quantity is always less than available stock of necessary materials D_{qt}, the rest of uncompleted order i and the machine capacity B_m.

Apart from the constraint (11), in order to build tree nodes, it is necessary to take into account some constraints related to machine capacity. First, possibility of transfer from machine performing the previous operation to machine performing the following operation depends on current filling of these machines. Therefore for construction of tree nodes it is necessary to fix not only a machine, which performs the corresponding operation, but also a machine, from which the batch is transferred.

For this goal in the paper all possible machine pairs *u*, which have to be used in product transfer, are enumerated. When each tree node is built, the pairs from the list are selected, for which some constraints are met.

Let us assume that for transfer of a batch from the first machine in the pair to the second it is necessary to have some product in the first machine, and the second machine has to be empty:

$$b_{u12} > 0 \quad \text{and} \quad b_{u21} = 0. \quad (12)$$

Besides, the second machine capacity has to be adequate:

$$b_{u1} \le B_2. \quad (13)$$

At each subsequent step, some versions of possible and non-dominated solutions are selected by the algorithm below.

Step 1. *(Initial computation of utility functions)*

At the initial level number l=0 the initial expense function value is U_0=0; the initial orders utility function V_0 may be computed by the formula (5); number of nodes Z_0=1.

External cycle

Step 2. *(Determination of possible operations at next levels)*

For each node z of the constructed tree at the level l all possible operations are determined, and values g_{ijz} are computed by formulas (1,2).

Intermediate cycle

Step 3. *(Determination of necessary machines at next levels)*

For each operation k, which is possible at the moment C_{lz} and is not yet completed, the necessary machine pairs *u* are determined, according to the constraints (12,13).

Internal cycle

Step 4. *(Utility function computation at next (levels*

For each machine pair u values $U_{l+1,z,k,m}$ and $\bar{V}_{l+1,z,k,m}$ are computed using the formulas (9) and (8) with account of the moment of its potential release.

End of internal cycle

End of intermediate cycle

Step 5. *(Determination of dominated tree nodes)*

If the level $l+1$ is not last, then for domination on the level $l+1$ of the tree node y with a job i over the tree node x it is sufficient to comply with the following inequations

$$U_{l+1,y} \le U_{l+1,x},\ U_{l+1,y} \le U_{l+1,x} \text{ and}$$
$$g_{l+1,y} < g_{l+1,x}, \quad (14)$$

besides, the first or the second inequations is strong.

Otherwise: on the last level $l+1$ domination is possible, if

$$U_{l+1,y} \le U_{l+1,x},\quad U_{l+1,y} \le U_{l+1,x}. \quad (15)$$

Step 6. *(Transition to the next level or stopping)*

If the level is more than the last (all operations are completed), then STOP.

Otherwise: level number increment $l+1$ and go to Step 2.

End of external cycle

IV. EXAMPLE OF ALGORITHM APLLICATION FOR SCHEDULING

Consider a flexible flow line completing 4 operations consists of 8 machines (Table 1).

Machine number	Machine pool number (operation number)	Physical capacity, cubic meter	Cost of setup hour	Engage mark
1	1	50	2	1
2	1	40	2.5	1
3	2	45	2	1
4	2	50	1.8	1
5	2	50	2.8	1
6	3	50	2.5	1
7	3	40	3.5	1
8	4	50	1.8	1

Table 1: Machine Parameters

Cost of setup hour includes the total setup costs, consisting of machine cleaning, utilization of cleaning liquid and possible waste of some production. Let us assume that 6 types of products are to be manufactured on the line (Table 2) for 20 orders (Table 3). If a machine may not be used for a product, in Table 2 number -1 is input.

Product type	Gravity Kg/liter	Process time, hours							
		Machine 1	Machine 2	Machine 3	Machine 4	Machine 5	Machine 6	Machine 7	Machine 8
1	1.5	4	6	3	5	4	7	6	2
2	2	12	12	10	15	9	10	14	5
3	1.7	5	6	7	-1	10	8	8	4
4	1.5	-1	5	10	12	10	8	10	6
5	2	5	3	-1	-1	4	4	2	3
6	1.8	6	6	4	4	5	10	12	3

Table 2: Product Parameters

Orders in the Table 3 may be delayed: for example, the order 1 has to be completed one day earlier than the schedule starts, so we have initial tardiness. For each order, we can assign the weight (priority) coefficient, which usually is equal to 1. Order size in Table 3 varies from 20 to 90 tons, so a single batch may be assigned for some orders, and in a contrary, a single order may be completed in several batches.

For scheduling, it is necessary to fill in a matrix of setup norms for each machine on various product types, to mark working days on the scheduling period, to get information on available raw quantity for each product and the forecast of its arrival on the scheduling horizon. Besides, we need in information about the machine state at the moment of scheduling to make a new plan. Such information includes the product type, the product volume in a machine and the percent of operation readiness. Below the case of initial line release is considered, and it is assumed that all machines are adjusted for product type 3. All information is recorded into the MS Excel sheet.

Order number	Due date	Product type	Quantity, ton	Weight coefficient
1	-1	3	20	1
2	1	2	30	3
3	2	1	40	1
…	…	…	…	…
19	14	1	20	1
20	15	5	50	1

Table 3: Fragment of order Set for Line

To search for non-dominated solutions on the basis of the criteria U and $\bar{V}$, the program using the VBA language for MS Excel has been designed. The calculation result for this example is shown in Figure 2 with records in the MS Excel sheet. The result consists of two non-dominated versions of batch distribution for machines in different sequence. Each pair of numbers divided by "/" corresponds to a batch; the first number designates the minimal order number in this batch, the second number – the maximum order number. Except for these two orders, a batch includes the product, which is assigned for all orders with intermediate numbers and the same type as recorded orders. The entire set of batches for all twenty orders is equal to sum of batches, which are planned for the machine 1 and the machine 2 on the operation 1. In the case, this set is equal to 16. Version 1 differs from version 2 only on operation 3. In the version 1 the batches 3/20 and 20/20 of product 5 are processed in machine 7, but in the version 2 these batches are processed in machine 6.

Numbers in brackets form groups of lots with jobs of identical type, which do not require any setup, i.e. technological batch. For instance, in both schedule versions for machine 1 at first the group, which includes two batches of product 3, is planned. The first batch of this group is assigned for several orders from order 1 until order 10. In the second batch processing of the product 3 for orders from 10 until 12 continues.

In Figure 3 the Gantt diagrams for machines of the line are shown.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Version 1 Machine 1: (1/10, 10/12), 2/6, 12/14, 13/20											
2	Version 1 Machine 2: (3/5, 5/9, 9/19), (15/15, 15/15), (11/11, 11/17), 6/16, (14/18, 18/18), 20/20											
3	Version 1 Machine 3: 5/9, (14/18, 18/18)											
4	Version 1 Machine 4: (3/5, 9/19), (15/15, 15/15), (11/11, 11/17)											
5	Version 1 Machine 5: (1/10, 10/12), (2/6, 6/16), 12/14, (13/20, 20/20)											
6	Version 1 Machine 6: (1/10, 10/12), (3/5, 5/9, 9/19), (15/15, 15/15), (11/11, 11/17), (2/6, 6/16), 12/14											
7	Version 1 Machine 7: (14/18, 18/18), (13/20, 20/20)											
8	Version 1 Machine 8: (1/10, 10/12), (3/5, 5/9, 9/19), (15/15, 15/15), (11/11, 11/17), (2/6, 6/16), (14/18, 12/14, 18/18), (13/20, 20/20)											
9	Version 2 Machine 1: (1/10, 10/12), 2/6, 12/14, 13/20											
10	Version 2 Machine 2: (3/5, 5/9, 9/19), (15/15, 15/15), (11/11, 11/17), 6/16, (14/18, 18/18), 20/20											
11	Version 2 Machine 3: 5/9, (14/18, 18/18)											
12	Version 2 Machine 4: (3/5, 9/19), (15/15, 15/15), (11/11, 11/17)											
13	Version 2 Machine 5: (1/10, 10/12), (2/6, 6/16), 12/14, (13/20, 20/20)											
14	Version 2 Machine 6: (1/10, 10/12), (3/5, 5/9, 9/19), (15/15, 15/15), (11/11, 11/17), (2/6, 6/16), 12/14, (13/20, 20/20)											
15	Version 2 Machine 7: (14/18, 18/18)											
16	Version 2 Machine 8: (1/10, 10/12), (3/5, 5/9, 9/19), (15/15, 15/15), (11/11, 11/17), (2/6, 6/16), (14/18, 12/14, 18/18), (13/20, 20/20)											

Fig. 2: Versions of Batch Distribution over the Machines

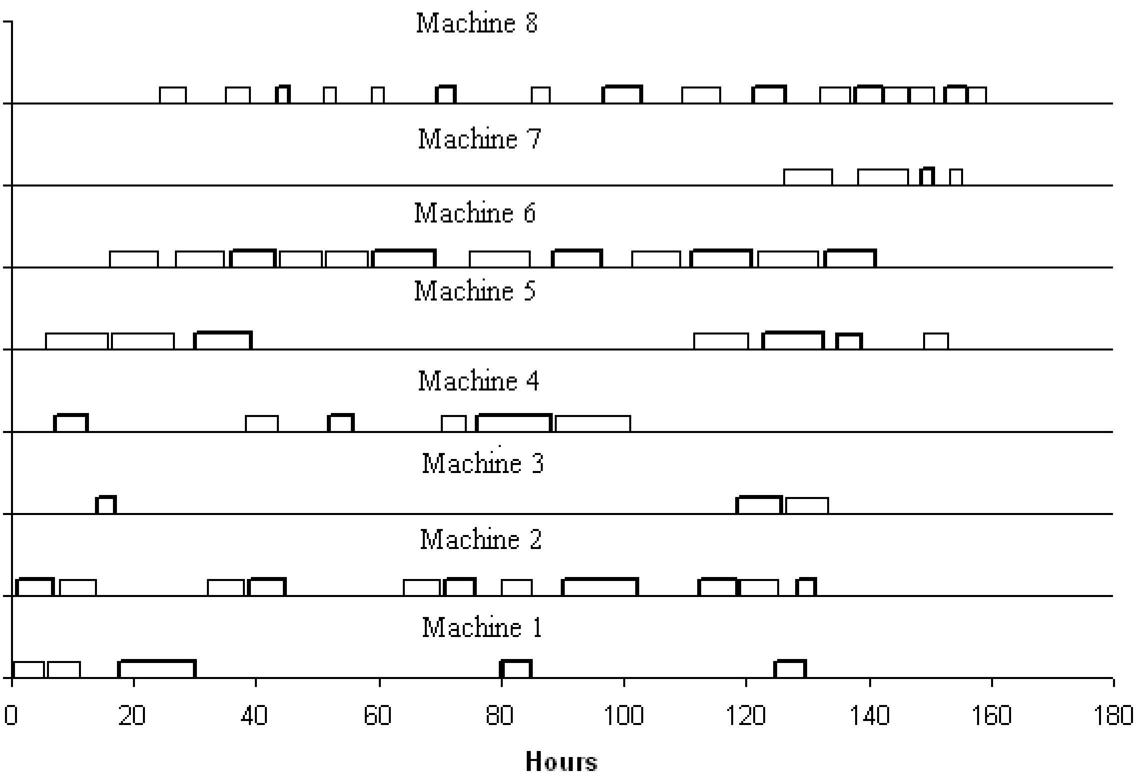

Fig. 3: Gantt Diagrams for Machines of the Line in Schedule Version 1

As it follows from Gantt diagrams in Figure 3, the described algorithm is loading the parallel machines on the same operation sometimes equally, but often – unequally. For instance, machines 3, 4 and 5 performing the operation 2 have similar charge value. By the same time, only five batches are planned for operation 1 on machine 1, and other eleven batches are planned on machine 2. This result derives through the difference in a physical machine capacity (Table 1). The machine 2 has capacity 40 cubic meters, machine 3 – essentially greater capacity 50 cubic meters, and such capacity is difficult to charge when there is material shortage.

The operation 3 may be performed on the machines 6 and 7. Since batch size on operations after the first does not change, setup cost value is here the main factor. Setup cost for the machine 6 is equal 2.5, which is considerably less than setup cost 3.5 for the machine 7. Therefore, only 4 batches are planned for the machine 7, and other 12 batches for the machine 6.

Batches with setups are depicted in the Gantt diagrams by bold lines. From Figure 3 it follows that the schedule is elaborated in a mode, which does not need setups in most batches.

In Figure 4 the batch list with order distribution is shown. A batch description in Figure 4 consists of two number groups. In the first group there is the product type number, then (through slash) batch size in cubic meters, and the completion moment in hours. Brackets include the list of orders, for which this batch is produced, and (through slash) the completion percent for each order.

If machine capacity is large and material quantity is enough, a batch may embrace several orders. For example, the batch 1 supplies 100% for orders 1, 4, 7 and 25% for order 10. When there is material shortage, a batch may be less than machine capacity and be equal to a part of the order. For example, the batch 6 volume for product type 6 is equal 22.2 cubic meters; it is considerably less than machine capacity and supply only 80% of order 15. When the necessary material arrives, the batch 7 will be processed for the rest of the order 15.

As it follows from Figure 4, the batches are grouped in the schedule for each product. For instance, at the first are processed two batches of products 3, then – 3 batches of product 1, and batches of products 6, 4, 2 are processed in twos. Then the final machine of the line has to be again adjusted for three batches of type 3. In finish two batches of type 5 are completed. Batch grouping essentially decreases production expenses.

	A	B	C	D	E	F
1	Batch 1: 3/50/28.7 (1/100% 4/100% 7/100% 10/25%)					
2	Batch 2: 3/50/39.3 (10/75% 12/44%)					
3	Batch 3: 1/40/45.7 (3/100% 5/50%)					
4	Batch 4: 1/40/53.3 (5/50% 8/100% 9/50%)					
5	Batch 5: 1/23.3/61 (9/50% 19/100%)					
6	Batch 6: 6/22.2/72,8 (15/80%)					
7	Batch 7: 6/5.6/88,3 (15/20%)					
8	Batch 8: 4/40/103.2 (11/86%)					
9	Batch 9: 4/19.9/115.8 (11/14% 17/100%)					
10	Batch 10: 2/50/126.7 (2/100% 6/88%)					
11	Batch 11: 2/39.8/137.3 (6/12% 16/100%)					
12	Batch 12: 3/40/142.3 (14/13% 18/78%)					
13	Batch 13: 3/50/146.7 (12/56% 14/87%)					
14	Batch 14: 3/10.4/151 (18/22%)					
15	Batch 15: 5/30/156 (13/100% 20/80%)					
16	Batch 16: 5/5/159.3 (20/20%)					

Fig. 4: Batches and Their Distribution by Orders

Let us determine a group coefficient at machine m is equal to ratio of batch number at this machine n_m to setup number o_m

$$W_m = \frac{n_m}{o_m}. \quad (16)$$

The highest group coefficient (Figure 3) is at the most loaded machine 8 and is equal to 16 / 6 = 2.7. At other machines, which are less loaded, the group coefficient is much less and is in limits 1.7-2.2.

If product orders are jointed into batches, a deviation between the order completion date and the order due date arises inevitably. In Figure 5 the distribution density of order completion in dependence of tardiness is depicted. Since the line load in the case isn't large and averages 40%, most orders are completed early. As it follows from Figure 5, the peak of completion is approximately 3 working days earlier than the due date.

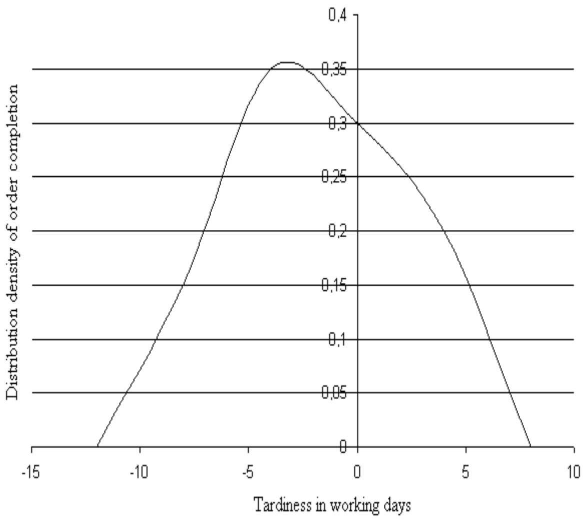

Fig. 5: Distribution of Order Completion Days

V. CONCLUSION

The above results show that the scheduling approach for batch plants, based on applying the criterion of relative setup cost and the criterion of average orders utility, made it possible to compute the satisfactory schedule versions. The logic of solving a problem with the MO-Greedy algorithm provided for designing a search tree starting from the initial system state, where the bound of tree nodes domination on each tree level is determined by the criteria U, $\bar{V}$ and values of the necessary order start time g. The software using the VBA language for MS Excel was designed, the example of software application is described.

In comparison with other known methods of flexible flow shop scheduling, the suggested method provides for automatic grouping of jobs with identical type for all engaged machines. Simultaneously, order due dates are taken into account as well. The method reveals the most loaded machines automatically and provides for grouping of most batches for these machines particularly.

For scheduling a set of Pareto-optimal solutions on planning horizon is constructed. The method makes it possible for a user to choose a plan version on the basis of his or her experience. However, actually, it is not possible to affirm that any version is the best in the set of computed versions, or in the set of all possible versions as well. In any case, the selected version may be considered as a starting-point for further improvement in a direction, which is desirable for the user.

Scheduling is a regular process that repeats with certain, but not always constant cycle. For this purpose it is convenient to use new MS Excel sheets, where information from previous sheets may be contained. By changing or inserting of new data the user can correct the previous plan or design a new one.

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