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Scheduling batches in multi hybrid cell manufacturing system considering worker resources: A case study from pipeline industry

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A B S T R A C T

This study considers batch scheduling problem in the multi hybrid cell manufacturing system (MHCMS) taking into account worker resources. This problem consists of determining sequence of batches, finding the starting time of each batch, and assigning workers to the batches in accordance with some pre-determined objectives. Due to a lack of studies on the batch scheduling problem in the MHCMS, a binary integer linear goal programming mathematical model is developed for bi-objective batch scheduling problem in this study. The formulated model is difficult to solve for large sized problem instances. To solve the model, we develop an efficient heuristic method called the Hybrid Cells Batch Scheduling (HCBS) heuristic. The proposed HCBS heuristic permits integrating batch scheduling and employee (worker) timetabling. Furthermore, we construct upper and lower bounds for the average flow time and the total number of workers. For evaluation of the performance of the heuristic, computational experiments are performed on generated test instances based on real production data. Results of the experiments show that the suggested heuristic method is capable of solving large sized problem instances in a reasonable amount of CPU time.

A R T I C L E I N F O

Keywords:
Batch scheduling
Hybrid manufacturing cells
Hybrid cells batch scheduling
Goal programming
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1. Introduction

Cellular manufacturing (CM), described as the applications of the group technology principles in a manufacturing environment, is a production system in which the parts with similar processing requirements and machines are grouped in distinct manufacturing cells [1, 2]. The main advantages offered by CM are reduction in setup time, reduction in lead time, reduction in work-in-process inventory, enhanced visibility and quality, efficient material handling, simplified scheduling and production control, and an increase in flexibility [3, 4-7].

The problems in a CMS are classified mainly into design and operational aspects. Design problems contain formation of cells and layout planning of cells while operational problems involve assignment of workers (employees) and scheduling of parts/batches-groups into the cells [1]. Operational problems have not been considered extensively in the extant literature compared to design problems [8]. This paper considers the problem of batch scheduling in the MHCMS which is a type of CMS consisting of a number of parallel independent hybrid cells. Most of the real CMSs are composed of hybrid cells, and both automatic and manual operations are performed in these cells [9]. The importance of the worker assignment on batch scheduling problems comes to light more clearly especially in the hybrid cells. Worker involvement is not bounded in these cells and the number of workers in cells plays an important role and directly affects the cell cycle times. Due to the manual operations within the hybrid cells, cell cycle times vary from high to low and the flow times of the batches depend on the number of workers assigned to work on these batches. Therefore, the decisions must be made simultaneously for the batch scheduling problem in the MHCMS are the sequence of batches on each cell, the starting time of each batch and the workers assigned to operations of batches on cells.

In the current study, scheduling in multi hybrid manufacturing cells, which are arranged as flowline, is addressed. A goal-programming model has been developed for scheduling of batches within cells by considering worker resource. Two conflicting objectives are identified for the problem: minimization of the average flow time and minimization of the total number of workers in the system. Since the average flow time can be used as a performance indicator for resource utilization [10], it is determined as one of the conflicting objectives in this study. To the best of our knowledge, the batch scheduling problem for the MHCMS is examined here for the first time.

Due to the computational complexities, it is fairly challenging to obtain optimal solutions to scheduling problems in real sized problem instances with exact optimization methods [11]. As such, a heuristic method, namely the HCBS heuristic, is developed for this problem. Computational results show that the heuristic method presented in the paper has the capability of solving large sized problem instances with industrial pertinence efficiently. The motivation of this study is the batch scheduling problem arising in a real life CMS. Therefore, the study has the ability of adding value to industry in the way of effectively raising engineering control for scheduling activities in CMSs. In this context, the aim of the study is to propose a new batch scheduling method for multi hybrid cell manufacturing system under resource constraints and to verify this method on an industrial application. Furthermore, this study has the originality of proposing a novel goal programming model and a heuristic method via the parallel consideration of the total number of workers and the average flow time in the MHCMS.

The flow of this study is as follows: review of the relevant literature is included in Section 2. Problem definition, mathematical model and a numerical example are presented and explained in Section 3. The developed heuristic method is introduced in Section 4. The experimental data and the computational results of the proposed heuristic method are reported in Section 5. The conclusions and recommendations for future research are offered in Section 6.

2. Literature review

In this study, batch scheduling problem in the MHCMS is investigated by considering worker resource. Therefore, the literature is reviewed two headlines as the worker assignment and allocation problems in the CMS and the batch scheduling problem in multi cell manufacturing system.

Jensen [12] used the simulation method to examine performance advantages of labor flexibility for departmens, hybrid cells and strict cells. Askin and Huang [13] proposed a multi-objective model to improve the fitness of individual workers to tasks performed in cells, and to create effective teams. Norman et al. [14] examined the problem of allocating workers to cells to improve organizational effectiveness which is affected by productivity, quality and training cost. Süer and Dagli [15] examined cell loading and labor allocation problems. They created a three-stage structure and examined solutions to sequencing, labor allocation and cell loading problems. Cesani and Steudel [16] used the simulation method to investigate the effects of varied labor allocation policies on system performance. Their results show that balance in the number of workers is a significant determinant of system performance. Süer and Tummaluri [7] studied the problem of assigning operators to operations in labor intensive cells. They proposed a three-stage approach for the solution of the problem. Fowler et al. [17] examined differences between workers, in terms of their general cognitive ability (GCA), and developed a mathematical model to minimize worker-related costs over multiple periods. Davis et al. [18] used the simulation method to examine the relationship between cross training and workload imbalance, and found that workload imbalance increased the need for worker flexibility. Fan et al. [19] examined multi-objective cell formation and operator assignment problems. Süer and Alhawari [20] examined the use of two different operator assignment strategies (Max-Min and Max) in labor intensive manufacturing cells. Azadeh et al. [21] examined the problem of operator allocation in a CMS by combining fuzzy data envelopment analysis (FDEA) and fuzzy simulation techniques. Egilmez et al. [22] examined the problem of stochastic skill-based workforce assignment in a CMS where both operation times and demand are uncertain. Niakan et al. [23] developed a new bi-objective model of the cell formation problem to handle worker assignment and environmental and social criteria. Liu et al. [24] developed a decision model for employee assignment and production control in a CMS with considering learning and forgetting effects of employees.

As the body of the literature addressing the worker assignment and allocation problems in the CMS ruled out up to the present the effect of number of workers on the flow time of batches on the cells, the present study moves in that direction.

Batch scheduling problem in CMS is also addressed in this study. Little research has been conducted on batch scheduling problem in multi-cell manufacturing system in the literature. The following is a review of studies that examine the batch scheduling problem in multi-cell manufacturing system.

Das and Canel [25] proposed a branch and bound solution method to seek solution to the problem of scheduling of batches in the multi-cell flexible manufacturing system (MCFMS). Celano et al. [26] used simulation method to analyze the batch scheduling problem within a manufacturing system consisting of multiple cells. Hachicha et al. [2] utilized simulation method to design a CMS consisting of multiple cells in which parts are produced in batches. Balaji and Porselvi [27] proposed a model for batch scheduling problem in a MCFMS having sequence dependent batch setup time with flowline structure.

When considering the large body of the extant literature, it is revealed that there have been studies in the literature that focus on the batch scheduling problem in CMSs having multi cells. However, there has not been any published study addressing the influence of assignment of workers on flow times of batches for the batch scheduling problem in the CMSs. This problem has been observed in a real cellular manufacturing system in the pipeline industry and it has not been addressed in the literature before. This study bridges this gap in the literature.

3. Descriptions of the problem and mathematical model

3.1 Description of the problem

In the current study, the batch scheduling problem in the hybrid cells having missing operations (some parts may skip some operations on some machines) is examined. The distinctive feature of this problem is the dependence of the batch flow times on the number of workers assigned to the main operations of batches on cells.

The hybrid cells need attendance of workers constantly. Because of the presence of manual operations, changing the number of workers assigned to the operations in this type of manufacturing cells causes changes in cell cycle times, which in turn changes flow times of batches on cells. An increment in the number of workers in cells results in a decreases in flow times of batches, and vice versa. For this reason, determination of number of workers, which are assigned to cells to perform operations of batches, is important in the hybrid cell scheduling studies. Therefore, when seeking solutions to the batch scheduling problem in a CMS which consists of parallel hybrid cells, it is necessary to consider the sequence of batches, the starting times of batches and the worker assignment to the batches.

There are K unrelated parallel labour-intensive hybrid cells in the CMS. The hybrid cells consist of M machines, designed as flowlines, dedicated to process I batches. The assumptions which have been made in the study are as follows:

- The cell compositions and the assignment of batches to cells are known in advance.
- Each machine in a cell corresponds to an operation, and these operations combine to form main operation. Pre-emption of operations and main operations is not allowed.

- Parts are produced in batches, and one-piece flow is applied within the cells. The flow is uni-directional and no back-tracking is allowed.
- Batches are processed from only one family in each cell and at most one batch can be processed in a cell at the same time.
- The batch sizes are equal to order sizes and batch splitting is not permitted.
- Batches are available for processing at time zero and processing times include setup times.
- Each worker has same multi-skills to perform all operations on cells.

3.2 Mathematical model

In this section, to describe the problem more clearly, a binary integer linear goal programming mathematical model is developed to address conflicting objectives which are the total number of workers and the average flow time. The purpose of the proposed mathematical model is to contribute to the apperception of the scheduling problem addressed in the study.

The indices, parameters, variables, deviational variables, decision variables and mathematical models are introduced in this section.

Indices

i,j – Indices of batches (i,j = 1,…, N)
z – Index of workers (z = 1,…, Z)
m – Index of machines (m = 1,…, M)
k,t – Indices of cells (k,t = 1,…, K)

Parameters

w_1 – Weight of the first objective (average flow time)
w_2 – Weight of the second objective (total number of workers)
$ak_{i,k}$ – If batch i is allocated to cell k, 1; if not, 0
$avewalking_k$ – Average walking time of workers in cell k
$totalwalking_k$ – Total walking time of workers in cell
$using_{i,k,m}$ – If machine m is used for operation of batch i on cell k, 1; if not, 0
$manualpro_{i,k,m}$ – Manual processing time for parts in batch i on machine m in cell k
$autopro_{i,k,m}$ – Automatic processing time for parts in batch i on machine m in cell k
$pt_{i,k,m}$ – Processing time of parts in batch i on machine m in cell k
$lpt_{i,k}$ – Longest processing time for parts in batch i on cell k
$FLT_{i,k}$ – Completion time for the first part in the batch i on cell k
$cycmin_{i,k}$ – Minimum cell cycle time for batch i on cell k
$cycmax_{i,k}$ – Maximum cell cycle time for batch i on cell k
q_i – Number of parts in batch i

Variables

$f_{i,k}$ – Flow time of batch i on cell k
$c_{i,k}$ – Completion time of batch i on cell k
$cyc_{i,k}$ – Cell cycle time for batch i on cell k
$time_{j,t}$ – Starting time of batch j on cell t
$workforce_{j,t}$ – Total number of workers at the start of main operation of batch j on cell l
mw – Maximum number of workers in the system
$wo_{z,i,k,m}$ – If worker z is assigned to machine m for main operation of batch i on cell k, 1; if not, 0
$x_{i,k}$ – Number of workers assigned for batch i on cell k
$g_{i,k,j,t}$ – If main operation of batch i on cell k and the main operation of batch j on cell t overlap in time, 1; if not, 0

Deviational Variables

$d1$-$d2$ – Positive deviational variables for the average flow time and the total number of workers, respectively

Decision variables

$w1_{z,i,k}$ – If worker z is assigned to main operation of batch i on cell k, 1; if not, 0

$b_{i,j,k}$ – If batch i is processed after batch j on cell k, 1; if not, 0
(Note that after does not necessarily means immediately after)

The mathematical formulation of the binary integer linear goal programming model is as follows:

Objective Function

$$\min objective = w1 \times (d1/(UP1 - LB1)) + w2 \times (d2/(UP2 - LB2)) \quad (1)$$

Constraints

$$\sum_{k=1}^{K}(maxc_k/maxc_k) - d1 = LB1 \quad (2)$$

$$mw - d2 = LB2 \quad (3)$$

$$c_{i,k} \geq (c_{j,k} + f_{i,k}) - M \times (1 - b_{i,j,k}) \qquad \forall i,j,k \quad (4)$$

$$c_{i,k} \geq f_{i,k} \qquad \forall i,k \quad (5)$$

$$maxc_k \geq c_{i,k} \qquad \forall i,k \quad (6)$$

$$b_{i,j,k} + b_{j,i,k} = ak_{i,k} \times ak_{j,k} \qquad \forall i,j,k \quad i \neq j \quad (7)$$

$$time_{j,t} = c_{j,t} - f_{j,t} \qquad \forall j,t \quad (8)$$

$$(c_{i,k} - f_{i,k}) - time_{j,t} \leq M \times (1 - ka_{i,k,j,t}) \qquad \forall i,k,j,t \quad (9)$$

$$time_{j,t} - (c_{i,k} - f_{i,k}) \leq M \times ka_{i,k,j,t} \qquad \forall i,k,j,t \quad (10)$$

$$time_{j,t} - c_{i,k} \leq M \times (1 - kb_{i,k,j,t}) \qquad \forall i,k,j,t \quad (11)$$

$$c_{i,k} - time_{j,t} \leq M \times kb_{i,k,j,t} \qquad \forall i,k,j,t \quad (12)$$

$$2 - (ka_{i,k,j,t} - kb_{i,k,j,t}) \leq M \times (1 - g_{i,k,j,t}) \qquad \forall i,k,j,t \quad (13)$$

$$(ka_{i,k,j,t} - kb_{i,k,j,t}) - 1 \leq M \times g_{i,k,j,t} \qquad \forall i,k,j,t \quad (14)$$

$$f_{i,k} = cyc_{i,k} \times (q_i - 1) + FLT_{i,k} \qquad \forall i,k \quad (15)$$

$$cycmin_{i,k} \leq cyc_{i,k} \qquad \forall i,k \quad (16)$$

$$\sum_{m=1}^{M} w_{z,i,k,m} \times (avewalking_k + manualpro_{i,k,m}) \leq cyc_{i,k} \qquad \forall i,k,z \quad (17)$$

$$\sum_{z=1}^{Z} w_{z,i,k,m} = using_{i,k,m} \qquad \forall i,k,m \quad (18)$$

$$\sum_{m=1}^{M} w_{z,i,k,m} \leq w1_{z,i,k} \times M \qquad \forall z,i,k \quad (19)$$

$$(w1_{z,i,k} + w1_{z,j,t}) - 1 \leq M \times (1 - g_{i,k,j,t}) \qquad \forall z,i,k,j,t \quad i \neq j\ , k \neq t \quad (20)$$

$$x_{i,k} = \sum_{z=1}^{Z} w1_{z,i,k} \qquad \forall i,k \quad (21)$$

$$x_{i,k} - y_{i,k,j,t} \leq M \times (1 - g_{i,k,j,t}) \qquad \forall i,k,j,t \quad (22)$$

$$y_{i,k,j,t} \leq M \times g_{i,k,j,t} \qquad \forall i,k,j,t \quad (23)$$

$$workforce_{j,t} = \sum_{i=1}^{N}\sum_{k=1}^{K} y_{i,k,j,t} \qquad \forall j,t \quad (24)$$

$$mw \geq workload_{j,t} \qquad \forall j,t \quad (25)$$

$$b_{i,j,k}\ 0\ or\ 1\ ;\ x_{i,k}\ integer\ ;\ d1 \geq 0\ ;\ d2 \geq 0 \quad (26)$$

The objective function (Eq. 1) involves two terms, one for each of the conflicting objectives, and presents a weighted average of deviations from developed lower bounds. The first term minimizes the deviation of the average flow time from *LB1* (Eq. 32). The second term attempts to minimize the deviation of the total number of workers from *LB2* (Eq. 34), and is in conflict with the first term. In Eq. 1, a zero-one normalisation scheme is used to scale all unwanted positive deviations (*d1* and *d2*) onto a zero-one range [28]. Eq. 2 and Eq. 3 are soft constraints which represent positive deviations from target levels ($LB1$ and $LB2$) for the average flow time and the total number of workers objectives, respectively. Eq. 4 ensures that each cell can process at most one batch at the same time. Eq. 5 implies that the completion time of a batch is greater than or equal to the flow time of this batch. Eq. 6 implies that the total completion time in a cell (C_k) is greater than or equal to the largest completion times of batches in this cell. Eq. 7 ensures that if batches i and j are allocated to the cell k, then $b_{i,j,k}$ or $b_{j,i,k}$ gets value equal to one. Eq. 8 represents the time points ($time_{j,t}$) at which the total number of workers can change, that is to say, the starting times of the main operations. Eqs. 9-14 are used to determine main operations which coincide with the time points ($time_{j,t}$) . Eq. 15 is used to calculate the flow times of the batches. Eq. 16 and Eq. 17 are used to determine the cell cycle time for each batch. Eq. 18 is used to assign workers to machines where the operations are performed. Eq. 19 ensures that worker assigned to machine for operation is also assigned to the cell that contains the machine in question. Eq. 20 prevents the assignment of the same worker to two main operations which overlap in time. Eq. 21 is used to calculate the number of workers assigned for operation of batch i on cell k. Eqs. 22-24 are used to calculate the total number of workers at each time point ($workforce_{j,t}$). Eq. 25 indicates that the total number of workers in the system is greater than or equal to the total number of workers at each time points. Eq. 26 is used for the binary, integer and sign bounds on the variables. The constant M in the equations should be sufficiently large. Since the mathematical model is developed considering the parallel cells in this study, the related studies involve parallel machine/cell scheduling problems and mathematical models constructed by Yang et al. [11] and Dalfard et al. [29] can be examined by interested readers to obtain comprehensive perspective. It is also important to emphasize that although Eqs. 17-19 are proposed to calculate the cell cycle times in case of dedicated assignment of workers to the hybrid cells. Eq. 27 is developed to obtain the cell cycle times. Since each worker has the same multi-skills in the MHCMS, theoretical values of the cell cycle times, which are the best values that can be reached, are calculated by using Eq. 27 and it is used in the solution of the model instead of Eqs. 17-19.

$$cyc_{i,k} = \left(cycmax_{i,k}/x_{i,k}\right) \qquad \forall i,k \tag{27}$$

The parameters $cycmax_{i,k}$ and $cycmin_{i,k}$ are calculated using Eq. 28 and Eq. 29, respectively.

$$cycmax_{i,k} = \sum_{m=1}^{M}(totalwalking_k + manualpro_{i,k,m}) \qquad \forall i,k \tag{28}$$

$$cycmin_{i,k} = lpt_{i,k} \qquad \forall i,k \tag{29}$$

The longest processing time for parts on a cell is equal to maximum of processing times of machines in this cell. This fact is stated in Eq. 30. The processing time for parts on each machine is equal to sum of manual processing time and automatic processing time. This fact is stated in Eq. 31.

$$lpt_{i,k} = \max_{\forall m}(pt_{i,k,m}) \qquad \forall i,k \tag{30}$$

$$pt_{i,k,m} = manualpro_{i,k,m} + autopro_{i,k,m} \qquad \forall i,k,m \tag{31}$$

In this paper, we put forward lower and upper bounds for the average flow time and the total number of workers. The derivation of lower bound (*LB1*) and upper bound (*UP1*) for average flow time are expressed as follows:

$$LB1 = \left(\sum_{k=1}^{K}\sum_{i=1}^{N}\left(cycmin_{i,k} \times (q_i - 1) + FLT_{i,k}\right)/K\right) \tag{32}$$

$$UP1 = \left(\sum_{k=1}^{K}\sum_{i=1}^{N}\left(cycmax_{i,k} \times (q_i - 1) + FLT_{i,k}\right)/K\right) \tag{33}$$

The derivation of lower bound (*LB2*) and upper bound (*UP2*) for the total number of workers are expressed as follows:

$$LB2 = \sum_{k=1}^{K}\left(\min_{\forall i}\left(cycmax_{i,k}/cycmax_{i,k}\right)\right) \tag{34}$$

$$UP2 = \sum_{k=1}^{K}\left(\max_{\forall i}\left(cycmax_{i,k}/cycmin_{i,k}\right)^{+}\right) \tag{35}$$

3.3 Numerical illustration

To explain the problem considered in this paper, we present a MHCMS with missing operations (MO). In this system, batches between 1 and 6 are to be scheduled in the first cell and batches between 7 and 12 are to be scheduled in the second cell. The maximum and minimum cell cycle times for each batch, the batch sizes, the automatic and the manual processing times of parts of batches on machines and the total walking time in cells are presented in Table 1. As seen in this table, the operations on machine 3 are missing operations for batch 1 to batch 6 and the operations on machine 2 are missing operations for the batch 7 to batch 12. There is a worker pool which is consists of five different workers. The mathematical model was coded in the GAMS CPLEX software package for equal weights of objectives ($w1$ = 0.5; $w2$ = 0.5). The optimal solution was derived in 676 min. of computational time. The results of the CPLEX software are reported below. Fig. 1 illustrates optimum solution of this problem. In Fig. 1, the best sequence of batches on Cell 1 and Cell 2 is obtained as 1-4-3-5-2-6 and 9-8-7-10-11-12, respectively. The starting and completion times of each batch are shown in Fig. 1. The average flow time is equal to 1800, the total number of workers is equal to 3 and the objective function is equal to 0.26.

Table 1 Data for a 12-batch 2-cell batch scheduling example

		Cell Cycle Times		Batch Size	Machine1		Machine2		Machine3		Machine4		Total Walking
		Max	Min		Aut.	Man.	Aut.	Man.	Aut.	Man.	Aut.	Man.	
Cell 1	Batch 1	60	30	5	5	15	0	10	MO	MO	10	20	15
	Batch 2	80	30	10	0	20	0	15	MO	MO	0	30	15
	Batch 3	55	30	5	10	10	0	15	MO	MO	15	15	15
	Batch 4	35	35	10	20	0	0	10	MO	MO	25	10	15
	Batch 5	50	30	5	5	5	0	10	MO	MO	10	20	15
	Batch 6	80	30	10	0	20	0	15	MO	MO	0	30	15
Cell 2	Batch 7	75	30	5	15	15	MO	MO	0	30	20	10	20
	Batch 8	50	20	10	10	10	MO	MO	0	20	20	0	20
	Batch 9	40	20	5	10	0	MO	MO	0	20	20	0	20
	Batch 10	30	30	10	10	0	MO	MO	10	10	30	0	20
	Batch 11	50	30	5	5	5	MO	MO	0	10	10	20	15
	Batch 12	80	30	10	0	20	MO	MO	0	15	0	30	15

As seen in the numerical example, the model is difficult to solve in an acceptable amount of time even for small-sized problem instances. As the size of the problem increases, the computational time to find the optimum solutions increases, so optimum solutions cannot be found in a reasonable time. Therefore, developing a heuristic method is plausible to obtain good solutions even for the large-sized problem instances in an acceptable amount of computational time.

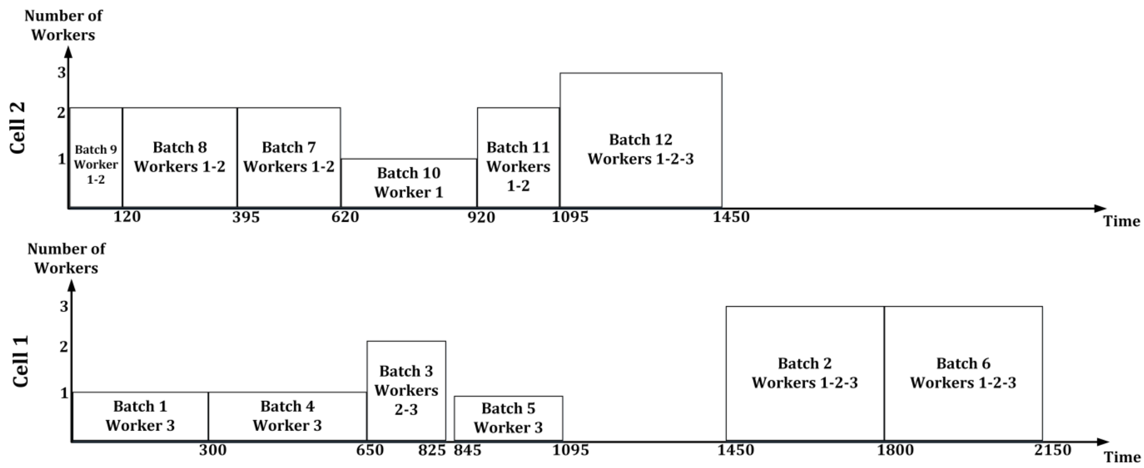


Fig. 1 Numerical example

4. A hybrid cells batch scheduling (HCBS) heuristic

The scheduling problems in CMS are evaluated as NP-hard and seeking the optimal solutions to these problems are computationally extensive [10, 27, 30-31]. Since the scheduling problems in CMS are regarded to be NP-hard, our problem is also NP-hard in the strong sense. Since it is hard to seek the solutions for this problem with exact methods, we developed a heuristic method to obtain near optimal solutions in a reasonable computational time. In order to analyse the effectiveness of our heuristic, we also constructed lower and upper bounds both for the average flow time and the total number of workers.

This section presents a heuristic method, namely the HCBS heuristic, for finding good solutions to the bi-objective batch scheduling problem with respect to the sequence of batches, starting times of batches and worker assignment to each batch.

The following terms and equations are used in the heuristic:

$ave.wor._{i,k}$ – Average number of worker for batch i on cell k

$$ave.wor._{i,k} = \left(\left(cycmax_{i,k}/cycmin_{i,k}\right)/2\right)^{+} \qquad \forall i,k \tag{36}$$

seq_k and $sequence_k$ – Sequence of batches on cell k
$sequence_{k,t}$ – Sequence of batches obtained at iteration r
$newx_{i,k}$ – Auxiliary variable for $x_{i,k}$

$$newx_{i,k} = x_{i,k} \pm 1 \qquad \forall i,k \tag{37}$$

$w1_{z,i,k,r}$ – If worker z is assigned to main operation of batch i on cell k at iteration r, 1; if not, 0
rn_k – Uniformly distributed random number for cell k
$newcyc_{i,k}$ – Auxiliary variable for $cyc_{i,k}$

$$newcyc_{i,k} = max\left(\left(cycmax_{i,k}/newx_{i,k}\right); cycmin_{i,k}\right) \qquad \forall i,k \tag{38}$$

$newp_{i,k}$ – Auxiliary variable for $f_{i,k}$

$$newf_{i,k} = newcyc_{i,k} \times (q_i - 1) + FLT_{i,k} \qquad \forall i,k \tag{39}$$

$dif_{i,k}$ – Difference between $f_{i,k}$ and $newf_{i,k}$

$$dif_{i,k} = \left|f_{i,k} - newf_{i,k}\right| \qquad \forall i,k \tag{40}$$

$alt_{i,k}$ – If the number of workers for batch i on cell k is increased or decreased, 1; if not, 0
$workerset_k$ – Set of workers for cell k
alt_k – Sum of the values of $alt_{i,k}$ for batch k

$$alt_k = \sum_{i=1}^{N} alt_{i,k} \qquad \forall k \tag{41}$$

$newobj_{i,j,k,t}$ – Auxiliary variable for *objective* in case of position of batch i and batch j is swapped and mode of starting time of batch i is equal to t in cell k
$starting_{i,j,k,t}$ – Possible starting time alternatives (modes) for batch i in case of position of batch i and batch j is swapped on cell k
$starting_{i,k,r}$ – Starting time of batch i on cell k at iteration r
$starting_{i,k}$ – Starting time of batch i on cell k
objective – Objective function value (Eq. 1)
$objective_t$ – Objective function value obtained at iteration t

As stated earlier, the HCBS heuristic is developed to determine the sequence of batches and the number of workers for each batch by minimising the weighted average of deviations of the average flow time and the total number of workers from lower bounds. The flowchart of the HCBS heuristic is given in Fig. 2.

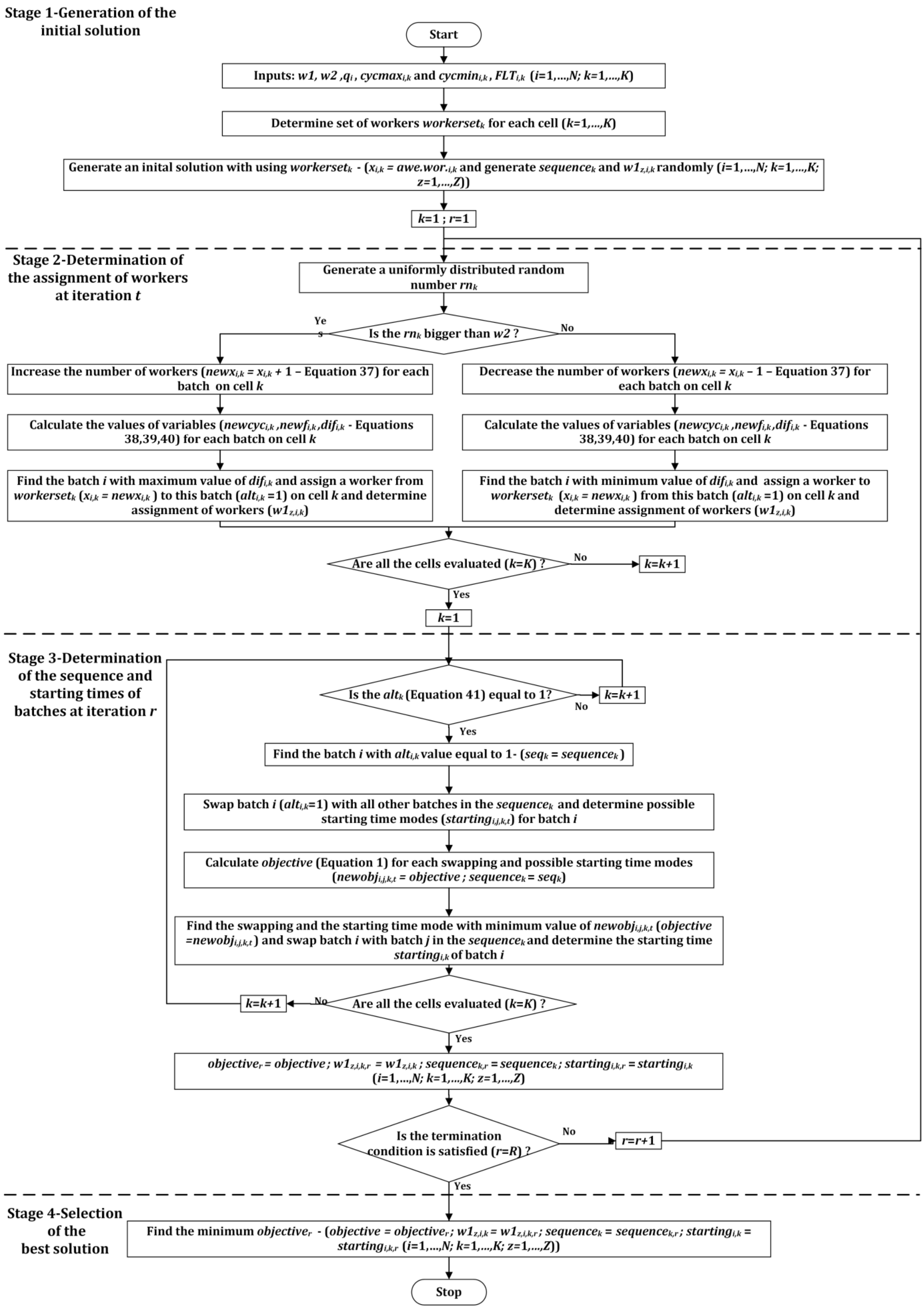


Fig. 2 The flowchart of HCBS heuristic

The input data for the HCBS heuristic is: the weights $w1$ and $w2$ of the objectives, the size q_i of batch i, the maximum and minimum cell cycle times, namely $cycmax_{i,k}$ and $cycmin_{i,k}$, for batch i on cell k, and the completion time $FLT_{i,k}$ for the first part in the batch i on cell k. The heuristic gives output such as the sequence of batches on each cell k, namely $sequence_k$, the starting time of batch i on cell k, namely $starting_{i,k}$, the assignment of workers to each batch, namely $w1_{z,i,k,r}$, and the *objective* (Eq. 1) .

The HCBS heuristic consist of four stages: (1) Generation of the initial solution; (2) determination of the assignment of workers for each batch at iteration r ; (3) determination of the sequence and starting times of batches for each cell at iteration r ; (4) selection of the best solution.

The first is related with the generation of the initial solution. This is provided by creating $workerset_k$ for each cell and assigning $ave.wor._{i,k}$ workers (Eq. 36) from $workerset_k$ for each batch on each cell. In this manner, assignment of the same worker to two or more main operations overlap in time is prevented. Sequences of batches on cells are first randomly generated. Then, Stage 2 and Stage 3 are executed for each iteration until the termination condition is satisfied. Stage 2 begins with evaluating the alternative scenarios of increasing or decreasing the number of worker for the first cell. In the following step, the effect of increase/decrease in the number of workers on flow time is computed for each batch (Eq. 40). Then, the decision about the change in number of workers is made with respect to pre-computed effect values. The $workerset_k$ is used when the number of workers assigned to the batch is changed. Then, Stage 2 is repeated for the following cells. Stage 3 of the heuristic tries each of the possible pairwise swaps and starting time modes $starting_{i,j,k,t}$ between the batch where the change in the number of workers is made in the previous stage and the other batches in the first cell. The heuristic generates starting time alternatives (modes) by means of allowing waiting times for batches so as to provide trade-off between number of workers and flow time. Waiting times are computed by considering the finishing time of current batches in other cells. The swap and starting time mode which yield the highest improvement in the objective function (Eq. 1) is executed. Consequently, the solution and objective function value for the iteration are recorded. Similar to Stage 2, Stage 3 scans each of the following cells respectively. Meanwhile, cells where the number of workers does not change in Stage 2 are excluded for swap operations. When the termination condition is met, the heuristic records the best solution through iterations as the final solution in Stage 4.

Table 2 Cell cycle times, batch sizes, processing time and total walking time

Cells	Number of batches (NB)		Cell cycle times Max ($cycmax_{i,k}$)	Min ($cycmin_{i,k}$)	Batch size (BS)	Processing time (s/unit) – $pt_{i,k,m}$ Roller Manual	TIG Welding Manual	Horizontal forming Manual	Horizontal forming Automatic	Vertical forming Manual	Reel Manual	Cutting Manual	Closing Manual	Total walking time ($totalwalking_k$)
Cell 1	DN 25	1-Floating flange	957	450	5	16	150	MO	MO	450	155	108	62	16
		2-Fixed flange	622	468	4	16	150	110	358	MO	160	108	62	16
	DN 32	3-Floating flange	915	432	10	15	144	MO	MO	432	148	105	55	16
		4-Fixed flange	590	455	5	15	144	100	355	MO	152	105	58	16
	DN 40	5-Floating flange	887	420	15	15	140	MO	MO	420	145	96	55	16
		6-Fixed flange	555	438	8	15	140	88	350	MO	145	96	55	16
	DN 50	7-Floating flange	741	319	15	12	135	MO	MO	319	130	84	45	16
		8-Fixed flange	508	355	5	12	135	75	280	MO	138	84	48	16
Cell 2	DN 65	9-Floating flange	626	250	10	9	120	MO	MO	250	117	71	44	15
		10-Fixed flange	436	272	10	9	120	60	212	MO	117	71	44	15
	DN 80	11-Floating flange	472	155	15	8	108	MO	MO	155	88	66	32	15
		12-Fixed flange	363	186	9	8	108	26	160	MO	102	66	38	15
Cell 3	DN 100	13-Floating flange	525	182	12	8	115	MO	MO	182	95	71	40	14
		14-Fixed flange	414	210	8	8	115	50	160	MO	112	71	44	14
	DN 125	15-Floating flange	617	226	14	11	131	MO	MO	226	102	85	48	14
		16-Fixed flange	469	258	8	11	131	58	200	MO	120	85	50	14
	DN 150	17-Floating flange	755	318	10	14	145	MO	MO	318	115	94	55	14
		18-Fixed flange	541	360	5	14	145	80	280	MO	134	94	60	14
Cell 4	DN 200	19-Floating flange	940	431	5	18	153	MO	MO	431	139	118	65	16
		20-Fixed flange	653	490	15	18	153	120	370	MO	155	118	73	16
	DN 250	21-Floating flange	1070	485	10	25	168	MO	MO	485	163	135	78	16
		22-Fixed flange	739	545	8	25	168	135	410	MO	175	135	85	16
	DN 300	23-Floating flange	1202	528	10	34	185	MO	MO	528	188	161	90	16
		24-Fixed flange	857	607	5	34	185	147	460	MO	211	161	103	16

5. Computational experiments

In this section, a set of instances was generated based on the original production data obtained by a manufacturing company in the pipeline industry for performance evaluation of the HCBS heuristic. The focused company produces many types of expansion joints, and also fills custom orders. The present study examines the producing of axial metal bellowed expansion joint parts. These parts are divided into two main categories of fixed and floating flange joints.

The manufacturing system of the company consists of four parallel hybrid manufacturing cells and a functional layout. In this study, functional layout was not taken into consideration. Part families produced in the cells differ by their nominal diameters. There are four part families with different diameters. These are part families with nominal diameters DN 25-32-40-50, DN 65-80, DN 100-125-150 and DN 200-250-300. There are seven different types of machines in the cells: roller, TIG welding, horizontal forming, vertical forming, reel, cutting and closing machines. The minimum and the maximum cell cycle times for the batches, the size of the batches and the processing time of machines are given in Table 2. The missing operations are represented as MO in Table 2.

The heuristic was coded in MATLAB software and tested on the same computer, a 2.4 GHz Intel(R) Core™ i7-3630QM CPU with 16 GB of RAM.

5.1 Experimental data

Since there are no benchmark instances which consider batch scheduling problems in the MHCMS, problem instances were generated via experimental design based on real production data in Table 2. The experimental factors and their levels are presented in Table 3. Moreover coefficients for objective function is evaluated under three combinations, namely labour dominant ($w_1 = 0.2$; $w_2 = 0.8$), equally weighted ($w_1 = 0.5$; $w_2 = 0.5$) and flow time dominant ($w_1 = 0.8$; $w_2 = 0.2$). A total of 3×3×3×3 = 81 test problems are generated and solved for each of the combinations of the weights. Each experiment is repeated ten times. Hence, the number of runs in the experimentation amounted to 2430 (81×3×10). After a series of repetitive experiments, 50-iteration is found to be appropriate as termination condition for HCBS heuristic.

The performance of heuristic is evaluated in terms of the objective function value, the total number of workers, the average flow time and the CPU time. Note that deviation from LB for objective function has the same numerical value with objective function itself since the related LB is zero.

Table 3 The experimental factors and their levels

	Levels		
Number of batches on each cell (NBEC)	Low $[0{,}7\times NB]^+$	Medium [NB]	High $[1{,}5\times NB]^+$
Batch size on each cell (BSEC)	Low $[0{,}7\times BS]^+$	Medium [BS]	High $[1{,}5\times BS]^+$
Processing time (MPT)	Low $[0{,}7\times pt_{i,k,m}]$	Medium $[pt_{i,k,m}]$	High $[1{,}3\times pt_{i,k,m}]$
Total walking time in each cell (TWEC)	Low $[0{,}7\times totalwalking_k]$	Medium $[totalwalking_k]$	High $[1{,}3\times totalwalking_k]$

5.2 Results and discussions

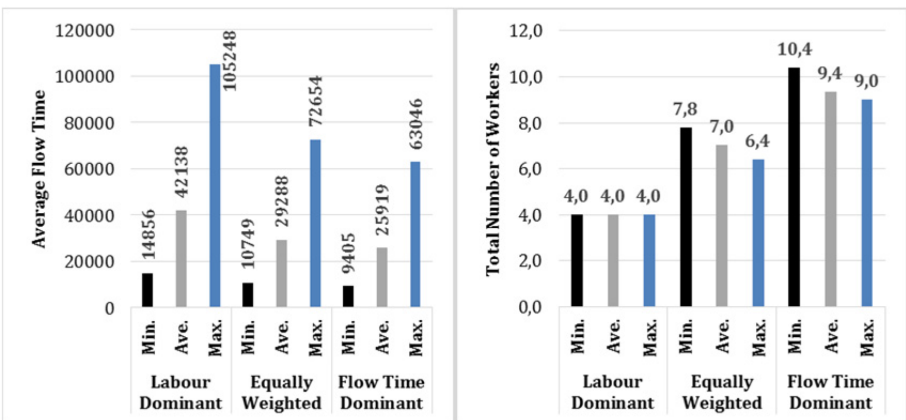
As can be understood from Table 4, the HCBS heuristic yielded satisfactory results with respect to deviation from lower bounds. Best objective function values are reached under flow time dominant configuration. When computation time is considered, it is concluded that the proposed heuristic has the capability of solving test problems efficiently (maximum = 23.63 s).

Table 4 Results under different objective function coefficient configurations

		Labour dominant	Equally weighted	Flow time dominant
Deviation from LB for objective function	Average	0.15	0.25	0.12
	Maximum	0.16	0.26	0.14
	Minimum	0.14	0.23	0.11
CPU time (s.)	Average	7.25	11.59	7.12
	Maximum	13.25	23.63	12.14
	Minimum	3.94	5.44	3.90

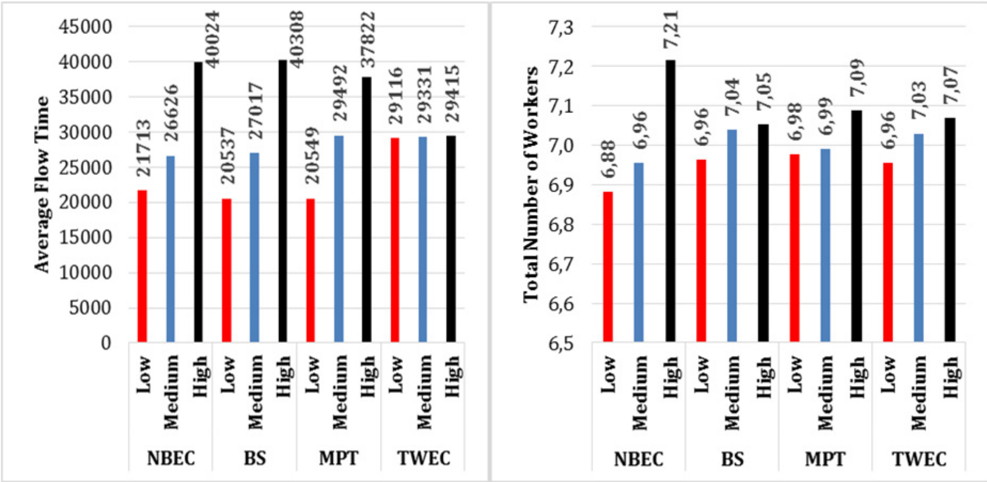
In addition, results of Fig. 3 indicated the sensitivity of average flow time and total number of workers performance to objective function configurations. It can be seen from Fig. 3(b), the maximum, the minimum and the average values of the number of workers are equal under labour dominant configuration. For the other configurations, changes in these values are low compare with values of average flow time in Fig. 3(a). The reason for this fact is that the total number of workers has not shown high sensitivity to different objective function coefficient combinations. The mathematical formulation of the total number of workers limits its sensitivity level. Hence, a new formulation related with the total number of workers can be developed to enhance the sensitivity level.

Furthermore, MANOVA is conducted to analyse the effect on the independent variables of NBEC, BSEC, MPT and TWEC (sources of variations) on the dependent variables of average flow time (AFT) and total number of workers (TNW). Statistical analysis is executed at 5 % significance level via SPSS 13.0 software. Note that, results for only equally weighted configuration is included to the analysis where main effects are investigated. According to the results, the effect of NBEC on the average flow time (p = 0.000) and the total number of workers (p = 0.001) are found to be statistically significant. In addition, BSEC (p=0.000) and MPT (p = 0.000) have significant effects on the average flow time. However, these factors do not have statistically significant effect on the total number of workers (p = 0.576 and p = 0.393, respectively). TWEC has been dominated by other factors with respect to their effects (p = 0.958 for AFT and p = 0.784 for TNW). Although NBEC, BSEC and MPT have a statistically significant effect on at least one dependent variable, TWEC has not a statistically significant effect on any dependent variables. BSEC and NBEC can be considered as the most influential factors on the average flow time and the total number of workers, respectively. With this information, it is concluded that the inputs related with batches, such as BSEC and NBEC, have a strong effect on the performance of the HCBS heuristic (R Squared = 0.930 and Adjusted R Squared = 0.922 for AFT; R Squared = 0.714 and Adjusted R Squared = 0.706 for TNW). It is also concluded that the factors are sufficient to explain significant percentage of variability in both AFT and TNW. Therefore, the independent variables determined in this study can be evaluated as the main factors which affect the operational efficiency in the MHCMS.



(a) (b)

Fig. 3 Results for average flow time (a), and total number of workers (b)



(a) (b)

Fig. 4 Results for average flow time (a), and total number of workers (b)

The average flow time and the total number of workers for different levels of factors are provided in Fig. 4. According to this figure, the average flow time is crucially increasing with the rising level of the NBEC, BSEC and MPT. The observed trend of TWEC can be regarded as consistent with Table 4. The average flow time reaches its maximum value when the level of BSEC is high and its minimum value when the level of BSEC is low. Also, the total number of workers reaches its maximum value when the level of NBEC is high and its minimum value when the level of NBEC is low. As far as the total number of workers is concerned, slight differences among different levels have been observed for each factor. The results also show a non-monotonic trend of BSEC, MPT and TWEC in respect of the total number of workers. The reason for the small changes in total number of workers along with different levels of factors is that the sensitivity of the total number of workers to different level of factors is quite low compared to sensitivity of average flow time. As mentioned before, a new mathematical formulation can be developed and used in the method to increase the sensitivity level of the total number of workers to the factor levels.

Table 5 Multiple comparisons among factor levels

Factor	Dep. var.	I	J	Mean difference (I-J)	Sig. (p)	Factor	Dep. var.	I	J	Mean difference (I-J)	Sig. (p)
NBEC	AFT	Low	Medium	-4413.296*	0.000	MPT	AFT	Low	Medium	-8943.148*	0.000
			High	-18311.111*	0.000				High	-17272.704*	0.000
		Medium	High	-13897.815*	0.000			Medium	High	-8329.556*	0.000
	TNW	Low	Medium	-0.074	0.415		TNW	Low	Medium	0.007	0.935
			High	-0.333*	0.000				High	-0.104	0.255
		Medium	High	-0.259*	0.005			Medium	High	-0.111	0.223
BSEC	AFT	Low	Medium	-6479.741*	0.000	TWEC	AFT	Low	Medium	215.481	0.839
			High	-19770.778*	0.000				High	-83.778	0.937
		Medium	High	-13291.037*	0.000			Medium	High	-299.259	0.778
	TNW	Low	Medium	-0.015	0.870		TNW	Low	Medium	-0.111	0.223
			High	0.074	0.415				High	-0.074	0.415
		Medium	High	0.089	0.329			Medium	High	0.037	0.683

(*)The mean difference is significant at the 0.05 level.