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Reactive Scheduling Addressing Unexpected Disturbance in Cellular Manufacturing Systems

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P A P E R I N F O

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A B S T R A C T

Most production environments face random, unexpected events such as machine failure, uncertain processing times, the arrival of new jobs, and cancellation of jobs. For the reduction of the undesirable side effects of an unexpected disruption, the initial schedule needs to be reformed partially or entirely. In this paper, a mathematical model is presented to address the integrated cell formation and cellular rescheduling problems in a cellular manufacturing system. As a reactive model, the model is developed to handle the arrival of a new job as a disturbance to the system. Based on the principle of resistance to change, the reactive model seeks a new solution with the minimum difference from the initial solution. This is realized through a simultaneous minimization of the total completion time and the number of displaced machines. For the investigation of the performance of the proposed model, some numerical examples are solved using the GAMS software. The results demonstrate the ability of the reactive model to obtain solutions resistant to unexpected changes.

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NOMENCLATURE

Sets and Indices			
$\boldsymbol{M}$	Set of machine types ($m \in \{1,2,\dots,M\}$)	TE_p	Intercellular transportation time for part p
$\boldsymbol{P}$	Set of parts in the initial plan ($p \in \{1,2,\dots,P\}$)	F_{kp}	Completion time of the k^{th} operation of part p in the initial plan
$\boldsymbol{P'}$	Set of parts in the reactive plan ($p' \in \{1,2,\dots,P'\}$)	X_{kpmjc}	A binary parameter that takes value 1 if, in the initial plan, the k^{th} operation of part p is processed on the j^{th} duplication of machine type m in cell c, and takes value 0 otherwise
$\boldsymbol{MS}_m$	Set of duplications of machine type m ($j, j' \in \{1,2,\dots,MS_m\}$)	D	The occurrence time of the disturbance (the unexpected arrival of a new job)
$\boldsymbol{C}$	Set of cells ($c, c' \in \{1,2,\dots,C_{max}\}$)	Y_{mjc}	A binary parameter that takes value 1 if, in the initial plan, the j^{th} duplication of machine type m is allocated to cell c, and takes value 0 otherwise
$\boldsymbol{K}_p$	Operation sequence of part p ($k, k' \in \{1,2,\dots,K_p\}$)	YY'_c	A binary variable that takes value 1 if cell c is formed after the disturbance, and takes value 0 otherwise
		$Z'_{kpk'p'mj}$	A binary variable that takes value 1 if the k^{th} operation of part p is processed after the disturbance before the k'^{th} operation of part p' on the j^{th} duplication of machine type m, and takes value 0 otherwise
$\boldsymbol{M}_{kp}$	Set of alterative machine types for the k^{th} operation of part p	v_{kp}	A binary parameter that takes value 1 if the starting time of processing the k^{th} operation of part p in the initial plan is before the occurrence of the disturbance, and takes value 0 otherwise
Parameters		**Decision Variables**	
C_{min}	Minimum number of cells that should be formed	F'_{kp}	Completion time of the k^{th} operation of part p (after the disturbance)
C_{max}	Maximum number of cells that should be formed	X'_{kpmjc}	A binary variable that takes value 1 if the k^{th} operation of part p is processed after the disturbance on the j^{th} duplication of machine type m in cell c, and takes value 0 otherwise
BL	Minimum number of machines in each cell	Y'_{mjc}	A binary variable that takes value 1 if the j^{th} duplication of machine type m is allocated after the disturbance to cell c, and takes value 0 otherwise
BU	Maximum number of machines in each cell	YY'_c	A binary variable that takes value 1 if cell c is formed after the disturbance, and takes value 0 otherwise
L	A large positive number	$Z'_{kpk'p'mj}$	A binary variable that takes value 1 if the k^{th} operation of part p is processed after the disturbance before the k'^{th} operation of part p' on the j^{th} duplication of machine type m, and takes value 0 otherwise
T_{kpm}	Processing time of operation k of part p on a machine of type m	Fy_{kp}	A binary variable that takes value 1 if the completion time of the k^{th} operation of part p in the reactive plan changes concerning that in the initial plan, and takes value 0 otherwise

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1. INTRODUCTION

Scheduling is a decision problem that plays a crucial role in manufacturing and service systems. In today's competitive environment, it seems inevitable to have a scheduling process and an efficient operation sequence, a necessity for survival in the commercial space. For example, companies are required to adhere to the pre-promised delivery times, and failure to comply with them can lead to loss of significant profit. They should also plan their jobs so that they can utilize the available resources most properly. Scheduling addresses resource allocation over specific time frames and is aimed at optimizing one or more specified variables. Many researchers often assume that manufacturing systems operate in static environments in which no unexpected events occur. However, many manufacturing systems are in dynamic and random conditions, and at any moment, they may encounter unexpected events such as machine failure, the arrival of new jobs into the system, cancellation of jobs, delay in the arrival or shortage of materials, and change in the job priority. This leads to the non-optimality and infeasibility of the initial schedule. In order to address unexpected disruptions in a manufacturing system, an appropriate approach must be adopted. A framework of strategies for rescheduling manufacturing systems has been presented by Vieira et al. [1]. Wojakowski and Warzolek [2] presented a classification of scheduling problems under production uncertainty. Scheduling can provide better coordination in manufacturing systems to increase efficiency and reduce operating costs. Ideally, the manufacturing system should follow the schedule as far as possible; however, unexpected events can change the status of the system and affect its performance.

In general, there are three approaches for addressing random disturbances, as listed below. (1) Proactive approach. This approach attempts to provide a schedule that minimizes the negative effects of disturbances, which will occur in the future by predicting the occurrence of unexpected events and incorporating them into the initial schedule. (2) Reactive schedule. This approach first provides the initial schedule regardless of the effects of unexpected disturbances, and as soon as unexpected events occur, it modifies the initial schedule given the reactive measures that need to be taken. In general, these reactions are divided into two categories. One involves reactions that seek to modify and improve the initial schedule and the other concerns reactions that attempt to provide a completely new schedule. A dispatching rule is a reactive model that schedules jobs based on a predefined criterion. Rescheduling is another reactive approach, which modifies the initial schedule in order to adapt the status of the system to the disturbance that has occurred. Most conducted studies have generated the modified schedule based only on workshop performance criteria. When operators process jobs based on an initial schedule, the other parts of the system, such as the inventory control, are also planned based on the initial schedule. The modified schedule may be completely different from the initial one. Hence, since the other activities of the system have been planned according to the initial schedule, it has a significant effect on the activities of the other departments, which leads to infeasibility or non-optimality in the system. For this reason, the corrective measures must be taken such that minimal changes are required in the system while workshop criteria are considered. (3) Proactive-reactive approach. This approach is a combination of the above two and consists of two stages. At the first stage, it provides an initial schedule, like the proactive approach. At the second stage, which is the reactive stage, a new schedule is presented as soon as an unexpected event occurs.

The pace of change in customer needs has increased, and in such a competitive environment, manufacturers are forced to produce a wide variety of products in different volumes. Under such conditions, manufacturing systems should, on the one hand, have high flexibility to produce a wide range of products, as in a job shop system, and, on the other hand, produce high volumes of products over short periods, as in a flow shop system. Group technology (GT) and its relevant manufacturing systems are an accepted solution to the problem of semi-mass production of various products. Cellular manufacturing system (CMS), the most well-known application of group technology, attempts to identify manufacturing similarities of parts, based on which part families are formed and produced using relatively independent production units called machine cells. Some of the important benefits of CMSs are that they can simplify and reduce material transportation, reduce material flow in manufacturing, reduce setup and production time and costs, improve production control, and increase flexibility. The process of CMS design consists of four main steps: (1) cell formation (CF) (e.g., Sakhaii et al. [3] and Soolaki and Arkat [4]), (2) cellular layout (e.g., Arkat et al. [5] and Rahimi et al. [6]), (3) cellular scheduling (Arkat and Ghahve [7]), and (4) resource assignment (e.g., Mehdizadeh and Rahimi [8] and Bagheri et al. [9]).

A comprehensive review of published articles in the field of the CMS scheduling problem has been presented by Feng et al. [10]. Given the unexpected disruptions in production systems, which lead to the reduction of system efficiency, an appropriate approach should be adopted to address these disruptions in CMSs. Rahmani and Ramezanian [11] have presented a comprehensive literature review in the field of dealing with random disturbances in scheduling problems. In the area of CMSs, few studies have examined addressing unexpected disturbances, most of which have presented a knowledge-based approach. Olumolade [12] proposed a reactive approach to solve the CMS scheduling problem when machine failure occurs. They assumed that the CMS did not include additive machines. Weckman [13] presented a framework for reactive scheduling in the cellular manufacturing environment using the notions of neural networks, genetic algorithms, and simulation in such a way that the neural network was used to generate the initial solution to the genetic algorithm. The solution obtained by the genetic algorithm was applied to the simulation model for the specification of the efficiency of the scheduling based on the performance criteria. Li and Murata [14] presented a mixed-integer programming model for the reactive scheduling problem for waiting jobs in a CMS against occurrences of machine failure. They proposed a hybrid binary particle swarm optimization algorithm and simulated annealing algorithm for solving the problem. When the initial schedule changes, the workforce resists against the change directly or indirectly. In other words, after each disruption, the operators and internal parts of the system prefer to process jobs based on the initial schedule and to process new ones at the end. Therefore, they resist any changes in the initial plan. The research conducted in this area by Caruth et al. [15], Giangreco, and Pecci [16], and Rahmani and Ramezanian [11] shows that worker dissatisfaction and resistance to change may increase processing time.

The implementation benefits of CMSs include reduction of setup times, reduction of material transportation, reduction of the work-in-process inventory, better production efficiency, and higher-quality, shorter response times to the customer requirements. Of course, it is worth noting that the benefits of implementing a CMS for a company arise when the implemented CMS is based on the results of solving models that properly consider all the features of the system. Most of the CMSs considered in previous studies postulate an initial set of jobs to be processed in the manufacturing system, while a new, unexpected job may arrive in the manufacturing system during the program execution for which there is no predetermined plan. The purpose of this research is to investigate how to handle the arrivals of new, unexpected jobs in the CMS, events that lead to changes in the system parameters, and, consequently, non-optimality of the optimal solution found for normal conditions. For specification of how to address unwanted changes in input parameters, a reactive model is presented for the conditions that hold after the occurrence of a disturbance. The primary purpose of the model is to determine how to change the decisions (concerning cell formation and cell scheduling) so that the system is encountered with the slightest consequences in terms of costs and time. In order to consider the cost and time consequences, the reactive planning approach is formulated in such a way that the decision variables in the initial plan are considered as the parameters of the reactive model. Moreover, the notion of resistance to change (RTC) in the reactive scheduling problem, which has received little attention, is introduced.

2. PROBLEM STATEMENT AND MATHEMATICAL MODEL

In this section, a cellular manufacturing system is investigated, where there is the feasibility of processing non-sequential operations of parts on identical machines. These parts are referred to as reentrant parts. It is also possible to process some of the operations of the parts using several alternative machines. Here, the number of formed cells is unknown a prior and considered as a decision variable. Each machine has several identical copies, and each part has a number of alternative process routings. The number of machines in each cell and the number of cells each have a known minimum and maximum. Intercellular transportation time is assumed to be constant, and processing times include setup times. With an initial plan outlining machine grouping and part process routings, as well as the cellular scheduling, the goal is to make appropriate changes to address the situation where a part is added as a new order. Since a new, unexpected job may arrive in the system during the execution of the initial plan, we present a modified model to provide a new plan considering the original workshop criterion and the stability criterion. The proposed mathematical model seeks to present a plan which is not only minimizes the main criterion of the workshop (total completion time of parts) but also makes the slightest changes as compared to the initial plan. For this purpose, the notion of resistance to change is used, which increases in processing time. We apply the RTC concept creatively by combining it with the concept of system stability.

For this purpose, the set of parts in the plan on the arrival of a new job is indicated by $\boldsymbol{P}'$. The following sets of parameters and decision variables are also introduced.

The mathematical model of the problem is as follows:

$$min \sum_{p\epsilon \boldsymbol{P}'} F'_{K_p,p} \quad (1)$$

$$min \sum_{m\epsilon \boldsymbol{M}} \sum_{j\epsilon \boldsymbol{MS}_m} \sum_{c\epsilon \boldsymbol{C}} \left| Y'_{mjc} - Y_{mjc} \right| \quad (2)$$

$s.t.$

$$F'_{kp} \geq F_{kp} - M * (1 - \nu_{kp}) \qquad \forall p\epsilon \boldsymbol{P}, k\epsilon \boldsymbol{K}_p \quad (3)$$

$$F'_{kp} \leq F_{kp} + M * (1 - \nu_{kp}) \qquad \forall p\epsilon \boldsymbol{P}, k\epsilon \boldsymbol{K}_p \quad (4)$$

$$\sum_{c\epsilon \boldsymbol{C}} Y'_{mjc} \leq 1 \qquad \forall m\epsilon \boldsymbol{M}, j\epsilon \boldsymbol{MS}_m \quad (5)$$

$$\sum_{c\epsilon\boldsymbol{C}}\sum_{m\epsilon\boldsymbol{M}_{kp}}\sum_{j\epsilon\boldsymbol{MS}_m}X'_{kpmjc}=1-\nu_{kp}\quad\forall p\epsilon\boldsymbol{P}',k\epsilon\boldsymbol{K}_p \tag{6}$$

$$X'_{kpmjc}\le Y'_{mjc}\quad\forall m\epsilon\boldsymbol{M},c\epsilon\boldsymbol{C},p\epsilon\boldsymbol{P},k\epsilon\boldsymbol{K}_p,j\epsilon\boldsymbol{MS}_m \tag{7}$$

$$BL\,.YY'_c\le\sum_{m\epsilon\boldsymbol{M}}\sum_{j\epsilon\boldsymbol{MS}_m}Y'_{mjc}\le BU\,.\,YY'_c\quad\forall c\epsilon\boldsymbol{C} \tag{8}$$

$$YY'_c\ge YY'_{c+1}\qquad\forall c\epsilon\boldsymbol{C}-\{C_{max}\} \tag{9}$$

$$\sum_{c\epsilon\boldsymbol{C}}YY'_c\ge C_{min} \tag{10}$$

$$t_{p,k,k+1}=\frac{TE_p}{2}.\sum_{c\epsilon\boldsymbol{C}}\Big|\sum_{m\epsilon\boldsymbol{M}_{k+1,p}}\sum_{j\epsilon\boldsymbol{MS}_m}\big(X'_{k+1,pmjc}.(1-\nu_{k+1,p})+X_{k+1,pmjc}.\nu_{k+1,p}\big)-\sum_{m\epsilon\boldsymbol{M}_{k,p}}\sum_{j\epsilon\boldsymbol{MS}_m}\big(X'_{kpmjc}.(1-\nu_{kp})+X_{kpmjc}.\nu_{kp}\big)\Big|\quad\forall p\epsilon\boldsymbol{P},k\epsilon\boldsymbol{K}_p-\{K_p\} \tag{11}$$

$$F'_{1p}\ge\sum_{c\epsilon\boldsymbol{C}}\sum_{m\epsilon\boldsymbol{M}_{1p}}\sum_{j\epsilon\boldsymbol{MS}_m}T_{1pm}.\left(X_{1pmjc}.\nu_{1p}\right)+T'_{kpm}.\left(X'_{1pmjc}.(1-\nu_{1p})\right)\quad\forall p\epsilon\boldsymbol{P}' \tag{12}$$

$$F'_{k+1,p}\ge F'_{kp}+\sum_{c\epsilon\boldsymbol{C}}\sum_{m\epsilon\boldsymbol{M}_{k+1,p}}\sum_{j\epsilon\boldsymbol{MS}_m}T_{k+1,pm}.\left(X_{k+1,pmjc}.\nu_{k+1,p}\right)+T'_{k+1,pm}.\left(X'_{k+1,pmjc}.(1-\nu_{k+1,p})\right)+t_{p,k,k+1}\quad\forall p\epsilon\boldsymbol{P}',k\epsilon\boldsymbol{K}_p-\{K_p\} \tag{13}$$

$$Z'_{kpk'p'mj}+Z'_{k'p'kpmj}=\sum_{c\epsilon\boldsymbol{C}}\big(X'_{kpmjc}.(1-\nu_{kp})+X_{kpmjc}.\nu_{kp}\big).\big(X'_{k'p'mjc}.(1-\nu_{k'p'})+X_{k'p'mjc}.\nu_{k'p'}\big)\quad\forall p,p'\epsilon\boldsymbol{P}',k\epsilon\boldsymbol{K}_p,k'\epsilon\boldsymbol{K}_{p'},p=p'\,and\,k=k'\,are\,incompatible;\ \forall j\epsilon\boldsymbol{MS}_m,m\epsilon\boldsymbol{M}_{kp}\cap\boldsymbol{M}_{k'p'},c\epsilon\boldsymbol{C} \tag{14}$$

$$F'_{kp}-F'_{k'p'}+L\,.\left(1-Z'_{k'p'kpmj}\right)\ge T_{kpm}\,.\nu_{kp}+T'_{kpm}.\left(1-\nu_{kp}\right)\quad\forall p,p'\epsilon\boldsymbol{P}',k\epsilon\boldsymbol{K}_p,k'\epsilon\boldsymbol{K}_{p'},p=p'\,and\,k=k'\,are\,incompatible;\ \forall j\epsilon\boldsymbol{MS}_m,m\epsilon\boldsymbol{M}_{kp}\cap\boldsymbol{M}_{k'p'},c\epsilon\boldsymbol{C} \tag{15}$$

$$F'_{kp}+L\,.\nu_{kp}\ge D+\sum_{c\epsilon\boldsymbol{C}}\sum_{m\epsilon\boldsymbol{M}_{kp}}\sum_{j\epsilon\boldsymbol{MS}_m}T'_{kpm}.X'_{kpmjc}\,,\ \forall p\epsilon\boldsymbol{P}',k\epsilon\boldsymbol{K}_p \tag{16}$$

$$\left|F'_{kp}-F_{kp}\right|\le L\,.Fy_{kp}\qquad\forall p\epsilon\boldsymbol{P}',k\epsilon\boldsymbol{K}_p \tag{17}$$

$$T'_{kpm}=T_{kpm}+\alpha.\,Fy_{kp}\,.T_{kpm}\quad\forall p\epsilon\boldsymbol{P}',k\epsilon\boldsymbol{K}_p,m\epsilon\boldsymbol{M}_{kp} \tag{18}$$

$$Y'_{mjc},X'_{kpmjc},Z'_{kpk'p'mj},YY'_c,Fy_{kp}\epsilon\{0,1\} \tag{19}$$

The objective function (1) minimizes the total completion time of parts. The objective function (2) minimizes the total number of displacement machines in the reactive plan as compared to that in the initial plan. Constraints (3) and (4) show that the completion times of operations, the processing of which has started before the occurrence of the disturbance, do not change in the reactive plan. Constraint (5) indicates that each machine should be allocated maximally to one cell. Constraint (6) guarantees that if the processing of each operation of a part has not started before the disturbance, it will be processed on one machine in a specific cell. Constraint (7) ensures that operations assigned to a specific cell are processed on machines allocated to that cell. Constraint (8) set the number of machines in each cell. Constraint (9) indicates that cells are formed sequentially according to their numbers; *i.e.*, cell 1 is first formed, cell 2 is formed next, and the following cells are formed in the same order if needed. Constraint (10) applies the lower bound of the number of formed cells. Equation (11) calculates the transportation time between k^{th} and $(k+1)^{th}$ operations of part p. Constraint (12) guarantees that the completion time of the first operation of part p is as large as its processing time. Constraint (13) indicates the precedence relationships among the operations of each part. Constraint (14) defines the precedence relation between operations of two different parts or two different operations of the same part on a machine. Constraint (15) guarantees that maximally one part is processed on each machine at a time. Constraint (16) shows that the completion time of operation, the processing of which has not started, is at least as large as its processing time as well as the disturbance time. The pair of Constraints (17) and (18) are considered to calculate the processing times of operations of parts after the disturbance. This means that if the completion time of each part changes with respect to that in the initial plan, its processing time will increase. Constraint (19) shows the range of the decision variables.

The mathematical model presented is nonlinear. It has been reformulated as a linear model in order to solve the problem with exact methods.

3. COMPUTATIONAL RESULTS

For validation and verification of the proposed model, two numerical examples are presented. These problems are solved using the GAMS software on a PC with an Intel Core i5 processor 1.6 GHz and a 6-GB RAM. In the following, the numerical examples are presented first. Then, we assume that we have an initial plan for the presented examples that are used at the presented mathematical model. Finally, it is assumed that a new job arrives during the execution of the initial plan, and the presented model is used to present the reactive plan for addressing the disturbance. Given that the model of the reactive plan is bi-objective, we use the normalized weighted sum method in this paper, and in order to present one of the solutions, we select the same weight for the objective functions.

Numerical example 1

The first example includes seven parts and six machine types, and the upper and lower bounds are 2 and 3, respectively. Machine type 5 has two duplications, and the other types have only one. Other data for this example is shown in Table 1.

Table 1 shows the information concerning the operation sequence of parts, processing times on alternative machines, and intercellular transportation times of parts for the first example. Also, Table 2 illustrates the optimal solution for the initial plan, which its information is presented in Table 3.

Now, we assume that a new job arrives in the system for processing during the execution of the presented plan. We refer to this part as part 8. We assume that the new part includes four operations on machines 4, 6, 3, and 2 with processing times 5, 9, 8, and 12, respectively, and that the intercellular transportation time is 9. We modify the initial schedule using the model presented for the reactive plan. Given that the disturbance time is also important in the presentation of the reactive plan, we examine the reactive plan at different disturbance times (the arrival time of a new job D). Below, we first examine the reactive plan concerning $D = 13$. Based on the solution to the reactive model, the results shown in Tables 2 and 3 are updated as Tables 4 and 5.

Based on the results obtained from the sensitivity analysis of the values of the arrival time of new jobs (D), as shown in Table 6, the higher the arrival time of a new job at the initial times, the higher the required computational time. On the other hand, it is observed that the values of the objective functions change as does the arrival time of a new job, and this change can also be due to the initial plan changes in terms of the starting time, the formed cells, or both.

TABLE 1. Production data for the first numerical example

Part	Machine type m (T_{kpm})					TE_p
	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	
1	1(8)	4(12)	5(3)	3(7), 5(14)	2(5), 4(15)	6
2	3(6), 5(4)	4(12), 6(10)	5(5)			9
3	3(8)	2(4)	6(7)	3(5)		12
4	2(2)	3(4)	6(14)			5
5	1(2), 2(3)	4(5), 6(6)				11
6	1(3)	3(5), 5(3)				8
7	4(3)	5(5)	1(7)	5(6)	4(4), 6(7)	10

TABLE 2. The initial plan for the first numerical example

Cell	Machine Type	Part						
		2	3	4	1	5	6	7
1	2		2	1	5			
	3		1,4	2	4			
	5	1,3			3			
	6	2	3	3				
2	1				1	1	1	3
	4				2	2		1,5
	5*						2	2,4

* This represents the second copy of machine type

TABLE 3. Operations starting and completion times for the initial plan of the first numerical example

Part	Starting time and Completion time of part operations F_{kp}				
	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$
1	5,13	13,25	31,34	34,41	41,46
2	0,4	4,14	14,19		
3	0,8	8,12	14,21	21,26	
4	0,2	8,12	21,35		
5	0,2	3,8			
6	2,5	5,8			
7	0,3	8,13	13,20	20,26	26,30

TABLE 4. Results concerning the reactive plan for the first numerical example

Cell	Machine Type	Part							
		2	3	4	8	1	5	6	7
1	2		2**	1**	4	5			
	3		1**, 4	2**	3	4			
	5	1**, 3				3			
	6	2**	3	3	2				
2	1					1**	1**	1**	3
	4				1	2	2**		1**, 5
	5*							2**	2**, 4

** This represents the operations of parts that their processing has been started before arriving new job

TABLE 5. Operations starting and completion times for the reactive plan for the first example

Part	Starting time and Completion time of part operations F_{kp}				
	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$
1	5,13	13,25	31,34	34,41	41,46
2	0,4	4,14	14,19		
3	0,8	8,12	14,21	21,26	
4	0,2	8,12	21,35		
5	0,2	3,8			
6	2,5	5,8			
7	0,3	8,13	13,20	20,26	30,34.06
8	25,30	39,48	48,56	56,68	

TABLE 6. Sensitivity analysis on the arrival time of the new job

D	Z1	Z2	Time
5	236	0	0.464
10	239.645	0	0.519
15	244.06	0	0.291
20	244.06	0	0.306
25	231.225	4	0.16

Numerical example 2

The second numerical example includes 10 part types and 8 machine types, and the upper and lower bounds are 3 and 4, respectively (*i.e.*, $P = 10, M = 8, C_{min} = 3\ and\ C_{max} = 4$). The machine types 5 and 6 have two duplications (*i.e.*, $MS_5 = MS_6 = 2$), and the other types of machines have only one duplication. The information generated on this problem is shown in Table 7. Besides, $BL = 2, BU = 5$. (The numerical example has been taken from Feng et al. [10].)

Table 7 shows the information concerning the operation sequence of parts, processing times on alternative machines, and intercellular transportation times of parts for the second numerical example.

The information in Table 8 shows that three cells have been formed. The machines 2, 3, 6, 7, and 8 have been assigned to cell 1, machines 1 and 4, and the second copy of machine 5 have been assigned to cell 2, and machines 5 and the second copy of machine 6 have been assigned to cell 3. Moreover, for operations that can be processed with more than one machine type, one of the machines is selected for processing. For example, both machine types 3 and 5 can process the first operation of part 3, and, based on the results, the first copy of machine 5, which has been assigned to cell 3, is selected for processing. Many parts are processed without intercellular movements and in single cells totally, while other parts are processed in two or more cells, where the intercellular transportation time of the part is needed. For example, the fourth operation of part 2 is processed in cell 1 on machine type 6, while its fifth operation is processed on machine type 5 in cell 3. In this case, the intercellular transportation time of part 2 between cells 1 and 3 is needed. The information in Table 9 specifies the starting and completion times of the parts. For example, the first operation of part 1 is started on machine 1 in cell 2 at time 3, and it is completed at time 11, given the time required for processing the operation.

TABLE 7. Production data for the second numerical example

Part	Machine type (T_{kpm})					TE_p
	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	
1	1(8)	4(12)	5(3)	3(7), 5(14)	4(15), 8(5)	6
2	3(5)	8(10)	3(4)	6(7)	5(6)	9
3	3(6), 5(4)	6(10), 8(12)	5(5)			12
4	2(2)	7(4)	6(14)			5
5	4(15)	1(5)	5(6)			11
6	3(8)	8(4)	6(7)	3(5)	5(10), 7(5)	8
7	6(8), 8(10)	2(11)	7(5)			10
8	1(2), 2(3)	6(6), 8(5)				12
9	1(3)	3(5), 5(3)				11
10	4(3)	5(5)	1(7)	5(6)	6(7), 8(4)	10

TABLE 8. The initial plan for the second numerical example

Cell	Machine Type	Part									
		2	4	6	7	8	1	5	9	10	3
	2		1		2	1					
	3	1,3		1,4			4				
1	6	4	3	3	1						
	7		2	5	3						
	8	2		2		2	5			5	
	1						1	2	1	3	
2	4						2	1		1	
	5*						3	3	2	2,4	
3	5	5									1,3
	6*										2

* This represents the second copy of machine type

TABLE 9. Operations starting and completion times for the initial plan of the second numerical example

Part	Starting time and Completion time of part operations F_{kp}				
	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$
1	3,11	18,30	30,33	39,46	46,51
2	0,5	8,18	18,22	31,38	38,44
3	0,4	4,14	14,19		
4	3,5	5,9	9,23		
5	3,18	18,23	24,30		
6	5,13	18,22	23,30	30,35	35,40
7	0,8	8,19	19,24		
8	0,3	3,8			
9	0,3	3,6			
10	0,3	6,11	11,18	18,24	34,38

Now, we assume that a new job arrives in the system for processing during the execution of the presented plan. We refer to this part as part 11. We assume that the new part includes four operations on machines 5, 8, 4, and 3 with processing times 10, 4, 8, and 13, respectively, and that the intercellular transportation time is 9. Below, we examine the reactive plan concerning $D = 13$. Based on the solution to the reactive planning model, the results obtained in Tables 8 and 9 are updated, as shown in Tables 10 and 11.

TABLE 10. Results concerning the reactive plan for the second numerical example

Cell	Machine Type	Part										
		4	7	8	5	9	10	1	2	3	6	11
1	2	1*	2*	1*								
	7	2*	3								5	
2	1				2	1*	3*	1*				
	5**				3	2*	2*,4					
	6	3*	1*				5					
3	3							4	1*,3		1*,4	4
	4				1*		1*	2				3
	5							3	5	1*,3		1
	6*								4	2*	3	
	8			2*				5	2*		2	2

** This represents the second copy of machine type

* This represents the operations of parts that their processing has been started before arriving new job

TABLE 11. Results concerning the starting and completion times of the part operations for the reactive plan for the second numerical example

Part	Starting time and Completion time of part operations F'_{kp}				
	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$
1	3,11	18,30	30,33	37,44	44,49
2	0,5	8,18	27,31	32,39	39,45
3	0,4	4,14	14,19		
4	3,5	5,9	9,23		
5	3,18	18,23	24,30		
6	5,13	21,25	25,32	32,37	45,50
7	0,8	8,19	19,24		
8	0,3	3,8			
9	0,3	3,6			
10	0,3	6,11	11,18	18,24	24,31
11	19,29	29,33	36,44	44,57	

Through a comparison of the results obtained for the reactive plan with those for the initial plan, it is observed that some changes have occurred in cell formation and selection of alternative machines for the numerical example. As observed, machine 6 is displaced from cell 1 into cell 2, machines 3 and 8 from cell 1 into cell 3, and machine 4 from cell 2 into cell 3. The fifth operation of part 10 is processed on the other alternative machine, *i.e.*, machine 6, in cell 2 rather than on machine 8. The new job arriving into the system has also been assigned to a machine for processing. Moreover, it is observed through a comparison of Tables 9 and 11 that jobs are processed according to the initial plan, and the processing of the operations of parts is started earlier or later in some cases. Furthermore, the job having arrived newly in the system starts its processing at time 19 on machine 5 in cell 3, and its following operations are started at times 29, 36.345, and 44.345 on machines 8, 4, and 3, respectively.

4. CONCLUSION AND SUGGESTIONS FOR FUTURE RESEARCH

Since manufacturing systems operate in dynamic, uncertain conditions, unexpected events often take place in these systems. The occurrence of unexpected events in manufacturing environments may lead to the infeasibility and non-optimality of the initial plan. In order to overcome unexpected disturbances, the initial schedule needs some modifications. In this paper, we considered a cellular manufacturing system, including many design features, the objective of which is to minimize the total completion time of parts. First, we assume that we have an initial plan in the cellular manufacturing system. Then, we presented a mathematical model in order to react to new arrivals of jobs into the system. The presented reactive model has been designed such that it considers both the classical scheduling criterion (total completion time of parts) and two new criteria (stability in the system and resistance to changes). In the presented mathematical model, machines are allocated to manufacturing cells, processing routes are selected for parts, and the sequence of operations are processed on machines in such a way that the total completion time of parts is minimized as the first objective function. The total number of replacements of machines in the reactive plan is minimized as compared to that in the initial plan as the second objective function. For validation of the proposed model, some numerical examples were generated and solved using the GAMS software. The results of the numerical examples show that the reactive plan is sensitive to the disturbance time, and the closer this time to that at the beginning of the plan, the greater the computational time. Moreover, changes in the occurrence time of disturbance change the values of the objective function and the optimal solution. Finally, suggestions for future studies are made below.

- Given that machine failure and unavailability is another unexpected disturbance in the manufacturing system, it can provide an appropriate area of research to present a reactive planning model in addressing unexpected failures of machines in cellular manufacturing systems.
- Given the importance of the operator assignment problem in cellular manufacturing systems, it can provide an appropriate topic for continuing the present study to investigate the new model (initial planning model and reactive planning model) by considering the operator assignment problem.
- Given the importance of production planning in manufacturing systems and its dependence on the cell formation problem, it can provide an appropriate research area to integrate it with the problem under review in this paper.
- The arrival of a new job into a cellular manufacturing system as an unexpected disturbance was investigated in this paper. The reverse may also take place, where a customer cancels one or more jobs, the operation of which has not been started. It can be another future research area to investigate this state.

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Persian Abstract

چکیده

اغلب محیط‌های تولیدی با حوادث تصادفی و غیرمنتظره مانند خرابی ماشین، زمان‌های پردازش غیرقطعی، ورود کارهای جدید و از دستور کار خارج شدن کارها مواجه هستند. به منظور کاهش اثر اختلالات غیرمنتظره، زمان‌بندی اولیه نیازمند اصلاحاتی است. در این مقاله، یک مدل ریاضی عدد صحیح مختلط ارائه می‌شود تا مسائل تشکیل سلول و زمان‌بندی مجدد را در یک سیستم تولید سلولی در نظر بگیرد. در مدل ریاضی ارائه شده، فرض می‌شود کاری جدید جهت پردازش به عنوان یک اختلال وارد سیستم می‌شود. براساس اصول مقاومت در برابر تغییر، مدل واکنشی، راه‌حل جدیدی با کمینه تغییرات از جواب اولیه را جستجو می‌کند. به منظور برخورد با این اختلال، یک مدل واکنشی جدید ارائه می‌شود. مدل واکنشی ارائه شده به‌گونه‌ای عمل می‌کند که به صورت همزمان معیار کلاسیک زمان‌بندی (مجموع زمان‌های تکمیل قطعات) و تعداد جابجایی‌های ماشین‌ها را کمینه کند. به منظور اعتبارسنجی مدل پیشنهاد شده، تعدادی مثال عددی به کمک نرم‌افزار GMAS حل می‌شوند. نتایج، توانایی مدل واکنشی را در دستیابی به راه‌حل های مقاوم در برابر تغییرات غیرمنتظره نشان می‌دهد.