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Robust design for facility layout problem in cellular manufacturing systems with uncertain demand

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Abstract

Cellular manufacturing system (CMS) is one of the well-developed subjects in the manufacturing systems area due to its many advantages. This subject is categorized to four sub problem including cell formation, group layout, and group scheduling and resource assignment. Despite of the importance of facility layout in manufacturing productivity, layout design is less investigated compared to the other problems in CMS, especially while considering uncertain demand of the real world. Hence, ignoring this issue leads to inefficiency in the models. In this paper, a new mathematical modeling is proposed to design a robust facility layout in CMS in the presence of uncertainty. This model simultaneously minimizes the cost of inter-cell and intra-cell movements based on two robust approaches. In the first approach, the worst case scenario is minimized in absolute robustness criterion and deviation from the optimal solutions are minimized by the robust deviation in the second approach. Moreover, the integer nonlinear model is linearized in order to solve it by linear programing. Finally, the performance of the proposed model is evaluated through a numerical example.

Keywords: Cellular manufacturing system (CMS), facility layout problem, robust design, uncertain demand, inter-cell and intra-cell movement

1-Introduction

Global marketing and its results, the competitive markets, enforced producers to improve the quality of goods, decrease the prices and also increase the flexibility in production. In this condition, traditional manufacturing systems such as job shop and flow shop could not properly response to these new demands. Therefore, recently to tackle these requirements, some new approaches such as group technology (GT) are suggested. GT is one of the fundamental applied approaches of the just in time (JIT) philosophy. The facility layout aspect of GT is Cellular manufacturing system (CMS). Mainly advantages of CMS implementation could be highlighted as decreasing setup time, inventory on hand, transportation cost, direct and indirect worker cost; improving manufacturing quality, material flow, space utilization and employment spirit.

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Design of a CMS is classified to four subgroup problems including cell formation (CF), group layout (GL), group scheduling (GS) and resource assignment (RA). In the cell formation problem, different parts and machines are grouped to the part families based on the similarities in process, figures and some other criteria. Papaioannou and Wilson (2010) reviewed the most important studies in cell formation problem and presented trends of methodologies in this area. They also suggested some directions for future researches. Group layout is concerned about the layout of cells in the shop flour (inter-cell movement) and facilities within the cells (intra-cell movement). In group scheduling, part families are scheduled in such way that the production is finished with minimum time or delay. And resource assignment is allocating human resource and facilities to machines for achieving the minimum preparation costs. Table 1 summarized major researches in cellular manufacturing systems.

Table 1. Summarized researches in cellular manufacturing system

Authors	CF	GL	GS	RA	Solving method	
					Hierarchical	Simultaneously
Onwubolu and Mutingi (2001)	*					
Wang (2003)	*					
Defersha and Chen (2006)	*					
Tavakkoli-mogaddam et al. (2007)		*				
Wu et al. (2007)	*	*	*			*
Arkat et al. (2007)	*					
Jabal-Ameli and Arkat (2008a)	*					
Jabal-Ameli and Arkat (2008b)	*					
Safaei and Tavakkoli-Moghaddam (2009)	*					
Mahdavi et al. (2009)	*					
Satuglu and Suresh (2009)	*			*	*	
Mahdavi et al. (2010)	*			*		*
Tavakkoli-Moghaddam et al. (2010)	*		*			*
Krishnan et al. (2012)	*	*			*	
Arkat et al. (2011)	*	*	*			*
Jolai et al. (2012)	*	*				*
Kia et al. (2014)	*	*				*
Mohammadi and Forghani (2016)	*	*				*
Imran et al. (2019)	*					
Alimian et al. (2020)	*		*			

A careful look at the researches in this area reveals that the most of studies are in the cell formation problems and numerous works have been done on this subject. Nonetheless, as some researches in group layout problems, Wu et al. (2007) presented a conceptual framework and mathematical model which considered cell formation, group layout and group scheduling, simultaneously. Ahi et al. (2009) proposed a two stage method based on the multiple attribute decision making (MADM) concept to design concurrently cell formation, intracellular machine layout and cell layout in the CMS problem. A new mathematical model for designing a facility layout in a hybrid CMS is suggested by Ariafar et al. (2011a and 2011b). This model considers variation in demand during the planning horizon. Reference [15] proposed a hierarchical method to design a CMS. The proposed model solves a cell formation problem and group layout in three steps, separately. Leno et al. (2012) tried to design the Inter-cell layout and the flow path layout of the material handling system, simultaneously by means of a method named as genetic algorithm based meta-heuristic using simulated annealing (GASAA). This method is a local search tool which optimizes total material handling cost in CMS. A cell formation and group layout is designed for a dynamic CMS at the same time through mixed integer nonlinear programming model by Kia et al. (2012). They also considered some manufacturing features and solved this model by simulated annealing. The aim of this model is set a cell formation and facilities layout to minimize process time. Izui et al. (2013) investigated the design criteria for a robotic CMS layout design and proposed a multi-objective optimization method to obtain Pareto frontier. Kia et al. (2014) considered both cell formation and group layout simultaneously as the interrelated aspects of designing a CMS due to obtain an optimal design solution. Mohammadi and Forghani (2016) in their research proposed a novel S-shaped layout formulating an integerated bi-objective group layout and cell formation problem concurently. A mathematical model is formulated by Imran et al. (2019) to optimize cell formation by reducing the value added work in process using an integereated simulation and the genetic algorithm called Simulation integrated hybrid genetic algorithm (SHGA). To optimize the design of a CMS, cell formation, workload balancing and cell layout are considered simultaneously by developing a hybrid metaheuristic algorithm with genetic and bacterial operators (Mejía-Moncayo and Battaia, 2019). Production, and preventive maintenance planning are integerated with cell formation, and group scheduling in Alimian et al. (2020) research. To evaluate the model, numerical examples are examined by Bender’s decomposition pack in GAMS.

On the other hand, demand, production time and other parameters have uncertain nature in the real world. Variation in parameters degrades the performance of classic models. Hence, developing these models in the uncertain condition is inevitable. Tavakkoli-mogaddam et al. (2007) proposed a mathematical model for facility layout problem which considers stochastic demand. The objective function is minimizing the cost of intra-cell and inter-cell movements, all together. Ariafar et al. (2011a) offered a new mathematical model for group layout problem in CMS with considering the stochastic nature of demand. In this model, the both inter-cell and intra-cell material handling cost is minimized. Ariafar et al. (2012) studied the effects of uncertainty in demand on the group layout in CMS. To this aim, they formulated a mathematical model in which demand of products have normal distribution function. They also increase the application of this model by considering the transfer batch size and operation sequence of parts. Stochastic models have not received adequate attention compare to the certain models. To the best of our knowledge, there is no model which considers scenario base condition. In this paper, a new mathematical modeling is proposed to design a robust facility layout in cellular manufacturing system in presence of uncertainty. Note that the uncertainty in demand is characterized by different scenarios. Moreover, we do not know which scenario will occur in the future and also there is no information about the incidence probability of each scenario. To model robust facility layout design of CMS with uncertain demand, two robust scenario based approaches including min-max (absolute robustness) and robust regret (robust deviation) is developed. The objective of the first approach is minimizing the cost of worst-case scenario while deviation from the optimal solutions is decreased in the second one (robust deviation). The aim of this model is minimizing simultaneously the cost of inter-cell and intra-cell movement, based on the robust approach. Meanwhile, the integer nonlinear model is linearized and optimized by Branch and Bound (B&B) solver. Finally, the performance of the proposed model is evaluated through a numerical example.

The rest of the paper is organized as follows: in the next section, the proposed model as well as linearization method is described. Section 3 presents a numerical example to evaluate the performance of the model. Conclusion and some future researches will be introduced in section 4.

2-Problem formulation

In this section, a new mathematical model for designing simultaneously cells (inter-cell movement) and facilities (intra-cell movement) layout is formulated by considering the uncertainty in demand. The uncertainty in demand is characterized by different scenarios. Beside, to deal with variation in production demand, two robust design approaches is proposed. The assumptions of this model are described as follows:

- Cell formation stage is performed previously. It means number of cells, facilities in each cell and part families are known.
- Cost of handling the materials is specified by distance unit.
- Demand for each part is uncertain and estimated scenarios are known.
- Cells layout as well as facilities in cells are U shape.
- Facilities are considered in the same size.
- Only cells with the same sizes could change place.
- Figure 1 shows the layout scheme of modeled cellular manufacturing systems:

In the following, indices, parameters and decision variables are defined. Then, mathematical model is presented based on two robust approaches.

2-1-Indexing set

r	index for parts
s	index for scenarios
i, j	index for machine locations
k, l	index for machines
m, n	index for cells
o, p	index for cell locations

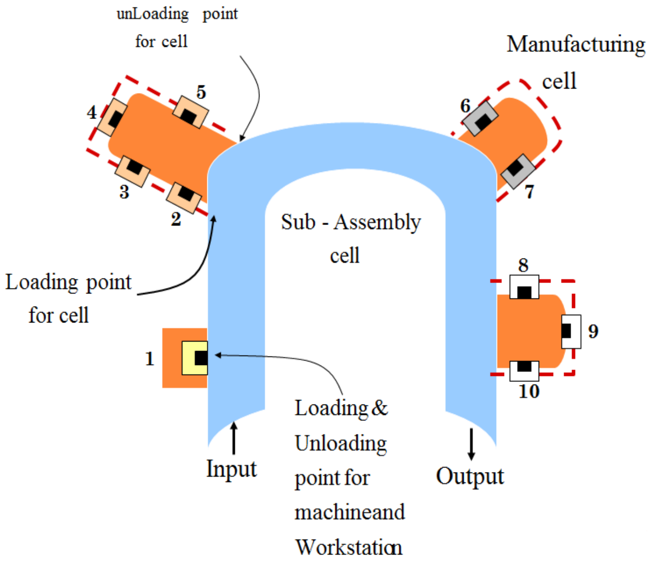

Fig 1. Layout scheme for a cellular manufacturing system

2-2-Parameters

nf	Number of machines and machine locations which are equal
nc	Number of cells and cell locations which are the same size
np	Number of parts
q	Number of scenarios
R_r	Operation sequence of part r
W_{kls}	Material flow between machines k and l in scenario s

c_{ij}	Cost unit for movement between locations *i* and *j*
d_{ij}	Distances between locations *i* and *j*
NMC_m	Number of machines in cell *m*
NLC_o	Number of locations in cell location *o*
$mc_{km} \epsilon (0,1)$	1 if machine k belongs to cell m, otherwise 0
$lc_{io} \epsilon (0,1)$	1 if location i belongs to cell location o, otherwise 0

2-3-Decision variables

$x_{ik} \epsilon (0,1)$	1 if machine *i* place in machine location *j*, otherwise 0
$y_{mo} \epsilon (0,1)$	1 if cell *m* place in cell location *o*, otherwise 0

2-4-Mathematical model

In uncertainty situation with scenarios, layout design which minimizes the cost function is usually different for each scenario. In another words, optimizing scenarios separately may lead to increasing in overall cost. The main issue is proposing an appropriate approach in obtaining overall optimal layout design for all scenarios. Hence, the proposed approach to cope with uncertainty is the robust design. In this paper, two approaches are considered as robust optimization. At the first approach, a possible objective function for absolute robust layout design can be written as the objective function (1). Through this objective, we want to minimize the maximum cost of all scenarios (the worst case of all scenarios) because we have no information which scenarios may happen. Note that z_s in this objective function is the cost of inter-cell and intra-cell movement for scenario s which is defined as equation (2). This criterion is suitable for the cases in which the risk is in a high level and the one who wants to design a layout has little tolerance to risk.

In the second approach, a possible objective function for robust deviation layout design can be written as objective function (3). Note that z_s^* in this objective function is the minimum cost of inter-cell and intra-cell movement for scenario *s* which is obtained by optimizing the mathematical model using objective min z_s. By applying this criterion, we want to select the design which has smallest deviation from the optimum solution of each scenario. Hence, first it is needed to obtain minimum cost for each scenario as a certain condition. So this approach is applicable when we are going to find the amount of improvement in layout design

$$\min Z_1 = \max\left\{z_1, \ldots, z_s, \ldots, z_q\right\} \tag{1}$$

$$z_s = \sum_{i=1}^{nf}\sum_{j=1}^{nf}\sum_{k=1}^{nf}\sum_{l=1}^{nf}\sum_{m=1}^{nc}\sum_{n=1}^{nc}\sum_{o=1}^{nc}\sum_{p=1}^{nc} w_{kls} d_{ij} c_{ij} x_{ik} x_{jl} y_{mo} y_{np} mc_{km} mc_{ln} lc_{io} lc_{jp} \tag{2}$$

$$\min Z_2 = \max\left\{\left(z_1 - z_1^*\right), \ldots, \left(z_s - z_s^*\right), \ldots, \left(z_q - z_q^*\right)\right\} \tag{3}$$

Subjected to:

$$\sum_{i=1}^{nf} x_{ik} = 1\ ;\ \forall k = 1, \ldots, nf \tag{4}$$

$$\sum_{k=1}^{nf} x_{ik} = 1\ ;\ \forall i = 1, \ldots, nf \tag{5}$$

$$\sum_{m=1}^{nc} y_{mo} = 1\ ;\ \forall o = 1, \ldots, nc \tag{6}$$

$$\sum_{o=1}^{nc} y_{mo} = 1\ ;\ \forall m = 1, \ldots, nc \tag{7}$$

$$\sum_{i=1}^{nf}\sum_{k=1}^{nf}\sum_{m=1}^{nc} x_{ik} y_{mo} mc_{km} lc_{io} = NLC_o\ ;\ \forall o = 1, \ldots, nc \tag{8}$$

$$\sum_{i=1}^{nf}\sum_{k=1}^{nf}\sum_{o=1}^{nc} x_{ik}\, y_{mo}\, mc_{km}\, lc_{io} = NMC_m \;\; ; \forall m = 1,\dots,nc \tag{9}$$

$$x_{ik}\;, y_{mo} \in \{0,1\} \tag{10}$$

Equation (2) calculates inter-cell and intra-cell movement cost. In this equation when all decision variables are 1 then weight of movement between assigned machines are multiplied in distances between them and cost of movement per unit. Constraints (4) and (5) ensure that each machine placed in one machine cell and each place assign to one machine, respectively. Constraints (6) and (7) ensure that each cell location only to one cell and each cell only assigned to each cell location, respectively. Constraints (8) and (9) ensure that machine locations assigned to correct cell location and machines assigned to right cells. And constraint (10) is for determining kind of decision variables.

2-5-Linearization of the mathematical model

In this subsection, the nonlinear inequalities are linearized in some steps. First, objective function (1) are linearized by defining a new variable u. This objective function is replaced by following equations:

$$\min Z_1 = u \tag{11}$$

$$z_s \le u \;\; ; \forall s = 1,\dots,q \tag{12}$$

Since z_s is still nonlinear, this inequality is linearized by defining a new binary variable $b_{ikjlmonp}$ to following equations:

$$\sum_{i=1}^{nf}\sum_{j=1}^{nf}\sum_{k=1}^{nf}\sum_{l=1}^{nf}\sum_{m=1}^{nc}\sum_{n=1}^{nc}\sum_{o=1}^{nc}\sum_{p=1}^{nc} w_{kls}\, d_{ij}\, c_{ij}\, b_{ikjlmonp}\, mc_{km}\, mc_{ln}\, lc_{io}\, lc_{jp} \le u ; \forall s = 1,2,\dots,q \tag{13}$$

$$x_{ik} + x_{jl} + y_{mo} + y_{np} \le 4 b_{ikjlmonp} \;\; ; \forall i,k,j,l,m,o,n,p \tag{14}$$

$$b_{ikjlmonp} \in \{0,1\} \tag{15}$$

Similarly, the second objective function is linearized by defining a new binary variable v and replacing the following equations:

$$\min Z_2 = v \tag{16}$$

$$z_s - z_s^* \le v \;\; ; \forall s = 1,\dots,q \tag{17}$$

Likewise, since equation (17) is still nonlinear, this inequality is linearized by defining a new binary variable $b_{ikjlmonp}$ to following equations:

$$\left(\sum_{i=1}^{nf}\sum_{j=1}^{nf}\sum_{k=1}^{nf}\sum_{l=1}^{nf}\sum_{m=1}^{nc}\sum_{n=1}^{nc}\sum_{o=1}^{nc}\sum_{p=1}^{nc} w_{kls}\, d_{ij}\, c_{ij}\, b_{ikjlmonp}\, mc_{km}\, mc_{ln}\, lc_{io}\, lc_{jp}\right) - z_s^* \le v ; \forall s = 1,2,\dots,q \tag{18}$$

$$x_{ik} + x_{jl} + y_{mo} + y_{np} \le 4 b_{ikjlmonp} \;\; ; \forall i,k,j,l,m,o,n,p \tag{19}$$

$$b_{ikjlmonp} \in \{0,1\} \tag{20}$$

Finally, constraints (8) and (9) are linearized by defining a new binary variable a_{ikmo}. These constraints are replaced by following equations:

$$\sum_{i=1}^{nf}\sum_{k=1}^{nf}\sum_{m=1}^{nc} a_{ikmo}\, mc_{km}\, lc_{io} = NLC_o \;\; ; \forall o = 1,\dots,nc \tag{21}$$

$$\sum_{i=1}^{nf}\sum_{k=1}^{nf}\sum_{o=1}^{nc} a_{ikmo}\, mc_{km}\, lc_{io} = NMC_m \;\; ; \forall m = 1,\dots,nc \tag{22}$$

$$x_{ik} + y_{mo} \le 2 a_{ikmo} \;\; ; \forall i,k,m,o \tag{23}$$

$$a_{ikmo} \in \{0,1\} \tag{24}$$

2-6-Solution procedure

First based on operation sequence of each part, to-from matrix are computed for each scenario. Then, to obtain robust layout design based on the first approach, objective function (11) is considered as well as constraints in equations (4) to (7), (10), (13) to (15) and (21) to (24). Before applying the second approach, it is needed to obtain the minimum cost for each scenario. Then, the objective function (16) can be optimized subjected to the constraints (4) to (7), (10) and (18) to (24).

3-Numerical example

In this section, the performance of the proposed model are validated and proven through a numerical example which are solved by branch and bound (B&B) method. Note that the large sized examples cannot be optimally solved within a reasonable computational time. The input parameters of the example are summarized in the following tables. Table 2 shows production parts along with their operation sequence in machines which indicated by machine numbers, three different demand scenarios and cost of movement per unit distance for each part.

Table 2. Input parameters

Parts	**Operation sequence**				**Demand scenarios**			**Cost of movement per unit distance**
	1	**2**	**3**	**4**	**#1**	**#2**	**#3**	
	Machine number							
1	#3	#1	#2	#4	24	24	24	1
2	#1	#3	#5	#4	10	10	10	1
3	#1	#2	#3		6	6	6	1
4	#4	#5	#7		16	16	16	1
5	#2	#3	#6	#7	8	8	8	1
6	#3	#2	#1	#7	6	6	6	1
7	#2	#4			0	26	0	1
8	#1	#7			20	0	0	1
9	#5	#2			15	0	0	1

As mentioned in assumptions, cell formation stage has been done before. Table 3 displays results of this stage. Number of machines which grouped in cells as well as capacity of each cell location is reported in this table.

Table 3. Machine grouping

Cells	**Number of Machines**	**Machines**	**Cell location**	**Number of locations**	**Locations**
1	3	1, 2, 3	1	2	1, 2
2	2	4, 5	2	3	3, 4, 5
3	2	6, 7	3	2	6, 7

Table 4 released distance between machine locations which considers distances between cells as well.

Table 4. Distance between machine locations

From	**To**						
	1	2	3	4	5	6	7
1	0	2	6	9	12	17	18
2	2	0	4	7	10	15	16
3	6	4	0	3	6	11	12
4	9	7	3	0	3	8	9
5	12	10	6	3	0	5	6
6	17	15	11	8	5	0	1
7	18	16	12	9	6	1	0

To solve the mathematical model based on the robust regret or robust deviation approach, (second approach) optimum solution for each scenario should be computed. Hence, we optimized each scenario separately and obtained the optimum layout design and cost. The results are given in table 5. Moreover, the costs of other scenarios under single scenario optimization are reported in order to use in next comparisons. As seen in this table optimum layout for each scenario is different from the others. It means, if one chooses one of them as a final decision, overall cost may be increased when other scenarios happened. Therefore, applying an appropriate approach to deal with uncertainty is inevitable.

Table 5. Results of layout design for three scenarios separately

Optimum scenario	Inter-cell layout	Intra-cell layout	Scenario cost
#1	2-1-3	cell 1: 4-5	#1: 1154*
		cell 2: 2-3-1	#2: 1150
		cell 3: 7-6	#3: 994
#2	2-1-3	cell 1: 5-4	#1: 1206
		cell 2: 2-1-3	#2: 1060*
		cell 3: 7-6	#3: 956
#3	3-1-2	cell 1: 6-7	#1: 1170
		cell 2: 3-1-2	#2: 1070
		cell 3: 4-5	#3: 940*

After obtaining the optimum layout design for each scenario separately, the robust mathematical model is solved by B&B method and the layout design which are optimum for all scenarios are obtained. Consequently the results of layout design by applying the two proposed robust approaches are computed and the results are given in table 6 as follows:

Table 6. Results of the robust layout design approaches

Approach	Inter-cell layout	Intra-cell layout	Scenario cost
Absolute robust	2-1-3	cell 1: 4-5	#1: 1154*
		cell 2: 2-3-1	#2: 1150
		cell 3: 7-6	#3: 994
Regret deviation	3-1-2	cell 1: 6-7	#1: 1170
		cell 2: 3-1-2	#2: 1070
		cell 3: 4-5	#3: 940

As an example for explanations about the results, in absolute robust approach cells 2, 1 and 3 assigned to 1, 2 and 3 cell locations, respectively. Then, machines 4 and 5 are correspondingly assigned to 1 and 2 machine location. Similarly, machines 2, 3 and 1 to machine locations 3, 4 and 5. Likewise, machines 7 and 6 are belongs to machine locations 6 and 7, in that order. Meanwhile, the overall costs for layout design when each scenario occurs are reported in the last column of this table. As shown in table 6, maximum of cost functions in the absolute robust approach (1154) is less than the regret deviation (1170) approach. In addition, the maximum differences deviation from the optimum layout design in each scenario in the robust deviation approach is less than the absolute robust approach. These results can show the efficiency of the proposed approach.

4-Conclusion

This paper focuses on group layout design of cellular manufacturing system under uncertain condition by robust approaches. To compute the layout design, a new mathematical modeling is proposed and the absolute robust and robust deviation approaches are applied. Uncertainty in this problem is defined by different scenarios and the robust solutions scenarios are obtained. Through a numerical example, a comparison between two proposed robust approaches was done which showed the superiority of the robust approaches in the terms of expected criteria. Finally, the validity of the proposed model is investigated by using a numerical example. This model can easily extended in a large size scale and using evolutionary algorithm for solving the proposed model is suggested as a future research.

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