A mathematical programming model with present value method for optimum design of flexible cellular manufacturing systems

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ABSTRACT

In this article, an integer mathematical programming model for the design problem of flexible cellular manufacturing systems is proposed. The developed mathematical programming model whose objective function is to minimize total design cost including cost of operating parts on machines, cost of using tools on machines, and cost of assigning employees to cells, also contains the present value method. Thus, it is ensured that the operational costs that occur along a certain time period are also taken into account. LINGO 19.0 optimization program software is used for the optimum solution of the integer mathematical programming model with the present value method whose objective function is to minimize the total design cost. In this article, the application of the model and the analysis related to the model are shown using a developed example problem. In addition, by ensuring the optimum design of flexible cellular manufacturing systems, the results of which alternative routes are used for processing parts, which machines are located in which cells, and which employees are assigned to which cells, are obtained. Then, a sensitivity analysis is presented to show the importance of alternative routes of parts.

Keywords: Flexible cellular manufacturing systems; Alternative routings; Optimization; Mathematical programming model; Present value method.

INTRODUCTION

The concept of flexible manufacturing characterizes a type of manufacturing system that is taken into consideration to increase flexibility, productivity, and quality (Chen and Adam, 1991), as well as to reduce flow time and various cost items such as operation cost, tooling cost, setup cost, quality control cost, labor cost and intracellular/intercellular movement cost. Flexible manufacturing systems aim to provide manufacture flexibility without reducing the quality of products (Sivarami Reddy et al., 2022). The concept of cellular manufacturing, basically, is based on the processing of part families formed by similar parts in cells formed by machines. Thus, flexible cellular manufacturing systems which play an important role in achieving the above-mentioned gains, are manufacturing systems which generally contain more than one cell, the ability of machines to process different parts based on automation, that is flexible machines, and various other flexibility concepts such as routing flexibility for parts. By using alternative routings for parts in the system, that's, routing flexibility, it is possible to transfer the parts to other machines and hence to process the parts on other machines without wait in production in case of disruptions such as machinery breakdown and maintenance. This article also considers alternative routings for parts. Some studies from the literature that includes alternative routings for parts in the design or redesign of flexible or dynamic cellular manufacturing systems are as follows: Saxena and Jain (2011), Yılmaz and Erol (2015), Feng et al. (2017), Kheirkhah and Ghajari (2018), Rabbani et al. (2019).

The design of flexible cellular manufacturing systems is a complex and difficult problem because it includes the various concepts mentioned above. Some studies from the literature related to the design or redesign of flexible or dynamic cellular manufacturing systems are as follows: Renna and Ambrico (2015) present an approach that includes three mathematical models for the design, redesign, and scheduling of cellular manufacturing systems, taking into account fluctuations in market conditions. Yılmaz and Erol (2015) are interested in when and how to reconfigure existing flexible manufacturing cells. In order to decide when to reconfigure the flexible manufacturing cells, they consider the lower and upper limits for the utilization rates of the machines, which is one of the system performance measurements, and the time limits regarding the cycle times of the machines, which are the other system performance measurement. In their study, they propose a mathematical programming model that minimizes the total reconfiguration cost in order to make optimal reconfiguration decisions. Niakan et al. (2016) propose a bi-objective mathematical model for the dynamic cell formation problem that considers worker assignment, and environmental and social criteria. Bagheri et al. (2019) deal with the multi-period cell formation problem which takes into account grouping efficacy, total costs, and worker factors in a dynamic environment. Xue and Offodile (2020) propose a nonlinear mixed integer programming model integrating dynamic cell formation and hierarchical production planning. Kia (2020) presents a mixed integer nonlinear programming model for designing a cellular manufacturing system under a dynamic condition and making aggregate planning decisions simultaneously.

The present value method is one of the methods specified within the scope of engineering economics, and as stated by Tolga and Kahraman (1994), is generally used to calculate incomes or expenses according to the present value, using a certain time horizon. Thus, it is possible to recognize the amount of income or expense that may occur in the future. In the literature, few studies related to flexible or cellular manufacturing systems that consider the present value method are found. Some studies related to this issue are as follows: Bokhorst et al. (2002) discuss the investment evaluation in flexible automation technologies, computer numerically controlled machines. The optimality criterion in their work is concerned with maximizing the net present value over a given planning horizon. Karsak and Özogul (2005) are interested in the evaluation of expansion flexibility in flexible production system investments. These evaluations also include the net present value. Ghosh and Offodile (2016) examine a firm's transition to cellular manufacturing using a simulation methodology and an approach that also includes net present value.

In this article, a mathematical programming model including also present value method is developed for optimum design of flexible cellular manufacturing systems. In the next main section, the developed mathematical programming model containing the present value method is explained in detail. Then, after an illustrative sample problem and related sensitivity analysis are presented, finally, conclusions and future research suggestions are shown in this article.

MATERIAL AND METHOD

In this article, an integer mathematical programming model is developed for the design problem of flexible cellular manufacturing systems including routing and machine flexibilities. The objective function of this developed model minimizes the total design cost. The cost of operating parts on machines, cost of using tools on machines, and cost of assigning employees to cells forms the total design cost in the model. The developed model also contains the present value method. Considering a certain planning horizon, it is possible to calculate operational costs that occur because of processing parts on machines, according to the present value. Thus, it is ensured that the sum of the operational costs that may occur along a certain time period is considered in the optimal design of the flexible manufacturing cells.

In the developed model, it is assumed that the processing times of parts are deterministic. The factors related to employees such as skill levels and training of employees are not taken into account while assigning the employees to the cells in the system. Moreover, the capacities of tool magazines are not taken into account while using the tools on the machines in the system.

Developed mathematical programming model

First, the notation showing the indices, input parameters and the decision variables of this developed model, and next, the objective function and the constraint equations of this developed model are as follows:

Notation:

Indices:

p: part types	$p = 1,..,P$	where P is the number of parts.
a: alternative routes	$a = 1,..,A$	where A is the number of alternative routes.
h: manufacturing cells	$h = 1,..,H$	where H is the number of manufacturing cells.
m: machine types	$m = 1,..,M$	where M is the number of machine types.
t: tool types	$t = 1,..,T$	where T is the number of tool types.
i: employees	$i = 1,..,I$	where I is the number of employees.

Input parameters:

op_{pm}: annually unit operation cost of part p on machine m

$matrix_{pam}$: 1 if part p according to alternative route a is processed on machine m; 0 otherwise

pt_{pam}: annual unit processing time of part p on machine m according to alternative route a

de_p: annual demand amount of part p

tn_{pamt}: number of tools of type t that need to use on machine m according to alternative route a of part p

tco_{mt}: cost for using one tool of type t on machine m

cap_m: annual time capacity of one machine m

mlb_h: lower bound for cell h in terms of total numbers of machines

mub_h: upper bound for cell h in terms of total numbers of machines

ico_{hi}: cost for assignment of employee i to cell h

$imin_h$: minimal number of employees in cell h

$imax_h$: maximal number of employees in cell h

$hmax_i$: maximal number of cells to which an employee i can be assigned

Decision variables:

x_{pa}: 1 if alternative route a of part p is chosen; 0 otherwise.

y_{hm}: 1 if machine m is assigned to cell h; 0 otherwise.

z_{hi}: 1 if employee i is assigned to cell h; 0 otherwise.

op_{pm}, tco_{mt}, ico_{hi} stated in the above notation have the same currency unit. pt_{pam} and cap_m specified in the above notation have the same time unit.

Objective function:

The objective function of the developed integer mathematical programming model is as seen in Equation (1). This equation, which expresses the optimum total design cost, consists of the sum of operation, tool usage and employee assignment costs, respectively.

$$\text{Min} \begin{Bmatrix} \sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{m=1}^{M} x_{pa} matrix_{pam} pt_{pam} de_p op_{pm} + \sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{m=1}^{M}\sum_{t=1}^{T} x_{pa} tco_{mt} tn_{pamt} + \\ + \sum_{h=1}^{H}\sum_{i=1}^{I} z_{hi} ico_{hi} \end{Bmatrix} \quad (1)$$

Subject to:

The constraint equations of this study are as follows:

$$\sum_{a=1}^{A} x_{pa} = 1 \qquad \forall p, \quad p = 1, \dots, P \qquad (2)$$

$$\sum_{m=1}^{M} y_{hm} \geq mlb_h \qquad \forall h, \quad h = 1, \dots, H \qquad (3)$$

$$\sum_{m=1}^{M} y_{hm} \leq mub_h \qquad \forall h, \quad h = 1, \dots, H \qquad (4)$$

$$\sum_{h=1}^{H} y_{hm} = 1 \qquad \forall m, \quad m = 1, \dots, M \qquad (5)$$

$$\sum_{p=1}^{P}\sum_{a=1}^{A} x_{pa} matrix_{pam} pt_{pam} de_p \leq cap_m \qquad \forall m, \quad m = 1, \dots, M \qquad (6)$$

$$\sum_{i=1}^{I} z_{hi} \geq imin_h \qquad \forall h, \quad h = 1, \dots, H \qquad (7)$$

$$\sum_{i=1}^{I} z_{hi} \leq imax_h \qquad \forall h, \quad h = 1, \dots, H \qquad (8)$$

$$\sum_{h=1}^{H} z_{hi} \leq hmax_i \qquad \forall i, \quad i = 1, \dots, I \qquad (9)$$

$$x_{pa} \in \{0,1\} \qquad \forall p, a, \quad p = 1, \dots, P \text{ and } a = 1, \dots, A \qquad (10)$$

$$y_{hm} \in \{0,1\} \qquad \forall h, m, \quad h = 1, \dots, H \text{ and } m = 1, \dots, M \qquad (11)$$

$$z_{hi} \in \{0,1\} \qquad \forall h, i, \quad h = 1, \dots, H \text{ and } i = 1, \dots, I \qquad (12)$$

Equation (2) provides the selection of optimal route as a result of considering all alternative routes for each part. Using Equation (3), it is determined how many machines each cell can contain at least. Equation (4) indicates how many machines each cell can contain at most. Equation (4) states that the layout area must not be assumed to be unlimited. In addition, it is stated by Equations (3) and (4) that each cell can contain the minimum and maximum numbers of machines in different numbers. The constraint stated that a machine can be assigned to only one cell is provided by Equation (5). Equation (6) shows that the capacities of the machines are not unlimited and also cannot be exceeded. Employees can be assigned to flexible manufacturing cells due to processes such as controlling cells. Equations (7) and (8) show the minimum and maximum numbers of employees that can be assigned to each cell, respectively. Using Equations (7) and (8), it is stated that each cell can contain the minimum and maximum numbers of employees in different numbers. Equation (9) indicates how many cells each employee can be assigned to at most, in other words, how many cells each employee can deal with at most. Equations (10), (11), and (12) state that the decision variables x_{pa}, y_{hm}, and z_{hi} are binary integer variables, in other words, 0 or 1.

Inclusion of present value method in the developed mathematical programming model

The present value method is one of the methods used in engineering economics, and the general purpose of the present value method, as also stated by Tolga and Kahraman (1994), is to calculate future incomes or expenses according to present value. In this section of this article, by including a certain planning horizon, the situation of determining the operational costs that occur by processing parts on machines, taking into account the present value, is considered. Thus, it is possible to include the sum of the operational costs that may occur after a few periods in the optimal design of the flexible manufacturing cells aimed in the study. In the present value method model of this article, it is assumed that the operating costs are annual, in other words, they occur at the end of the year. It is also assumed that the demands of parts do not change over the planning horizon. In this section, if the planning horizon is shown as pl years, it is known that the operating costs of the parts increase at a certain rate, $rate$, for each year. The operational costs for each year are calculated using this $rate$ value, and then these calculated values are summed up at present value with a certain real interest rate shown as ri. Figure 1 represents the present value method in this study for the operating costs of parts. Then there is the formulation of the mathematical programming model also including the present value method in this study.

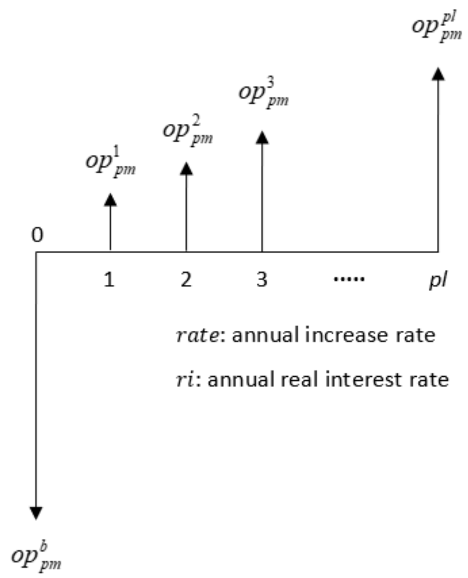

Figure 1. Representation of the present value method for operating costs of parts.

The expression of the notation stated in Figure 1 is as follows:

op_{pm}^{b}: present value of pl years unit operating costs of part p on machine m

op_{pm}^{1}: unit operating cost of part p on machine m for the first year

op_{pm}^{2}: unit operating cost of part p on machine m for the second year

op_{pm}^{3}: unit operating cost of part p on machine m for the third year

op_{pm}^{pl}: unit operating costs of part p on machine m for the pl. year

The operating costs of each year indicated in Figure 1 and the notation above are calculated using Equations (13), (14), and (15):

$$op_{pm}^{2} = op_{pm}^{1}(1 + rate)^{1} \quad (13)$$

$$op_{pm}^{3} = op_{pm}^{1}(1 + rate)^{2} \quad (14)$$

$$op_{pm}^{pl} = op_{pm}^{1}(1 + rate)^{pl-1} \quad (15)$$

The following Equation (16) is used to calculate the present value of the operating costs for pl years:

$$op_{pm}^{b} = \frac{op_{pm}^{1}}{(1+ri)^{1}} + \frac{op_{pm}^{2}}{(1+ri)^{2}} + \frac{op_{pm}^{3}}{(1+ri)^{3}} + \ldots + \frac{op_{pm}^{pl}}{(1+ri)^{pl}} \quad (16)$$

Tolga and Kahraman (1994) also calculate the present value of an income or expense amount occurred at the end of a certain period using a similar way. For example, they use a similar way to the second item of the equation above, $\frac{op_{pm}^{2}}{(1+ri)^{2}}$, to calculate the present value of an income or expense amount occurred at the end of the second period.

In that case, if the planning period is taken into account as pl years, in other words as more than one year, the objective function equation of the developed mathematical programming model for the handled problem in this article is expressed as in Equation (17):

$$\text{Min} \begin{Bmatrix} \sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{m=1}^{M} x_{pa} matrix_{pam} pt_{pam} de_{p} op_{pm}^{b} + \sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{m=1}^{M}\sum_{t=1}^{T} x_{pa} tco_{mt} tn_{pamt} + \\ + \sum_{h=1}^{H}\sum_{i=1}^{I} z_{hi} ico_{hi} \end{Bmatrix} \quad (17)$$

The constraint equations of the developed mathematical programming model with the present value method are Equations (2)-(12).

RESULTS AND DISCUSSION

In this section, the application of the developed mathematical programming model, which also includes the present value method, on a developed sample problem is included. In this developed sample problem, five different parts with alternative routes, five different machines, two cells, three different tools and three workers are considered. Table 1 shows the data for parts such as demands of parts, alternative routes of parts, and according to these alternative routes of parts, unit processing times of parts on five different machines. In Table 2, the unit operation costs of each part on the machines in terms of currency unit, and the time capacity information of each machine are given. Table 3 specifies the varying machine-tool combinations, the required number of each tool type according to the alternative routes of the parts and the unit cost of using tool on machines in terms of currency unit according to tool type.

Table 1. Data for parts.

Part	Demand	Alternative route	Processing times on machines				
			Machine 1	Machine 2	Machine 3	Machine 4	Machine 5
1	10	1	5	4	8	0	0
		2	0	3	6	4	0
		3	2	0	8	0	6
2	40	1	0	0	4	4	8
		2	0	2	10	0	0
		3	0	4	0	4	3
3	30	1	6	0	8	0	0
		2	5	7	0	2	0
4	50	1	0	0	0	3	6
		2	2	0	3	0	6
5	25	1	0	0	4	6	2
		2	0	0	0	7	3
		3	0	0	2	0	8

Table 2. Unit operating costs of parts on machines and capacities of machines.

Part	Machine 1	Machine 2	Machine 3	Machine 4	Machine 5
1	25	26	24	20	29
2	28	32	25	29	20
3	29	25	33	22	24
4	24	26	21	28	25
5	34	27	24	25	22
Capacities of machines	2100	2400	3800	3200	2800

Table 3. Machine-tool data.

Part	Alternative route	Machine 1			Machine 2			Machine 3			Machine 4			Machine 5		
		Tools			Tools			Tools			Tools			Tools		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1	1	5	3	4	4	0	5	0	2	2	-	-	-	-	-	-
	2	-	-	-	6	1	4	0	3	2	0	0	4	-	-	-
	3	4	6	1	-	-	-	1	4	2	-	-	-	3	4	3
2	1	-	-	-	-	-	-	4	4	6	2	4	2	3	3	6
	2	-	-	-	5	2	6	5	4	5	-	-	-	-	-	-
	3	-	-	-	3	0	3	-	-	-	1	2	4	3	2	4
3	1	6	2	3	-	-	-	4	2	5	-	-	-	-	-	-
	2	5	4	4	4	2	1	-	-	-	3	0	4	-	-	-
4	1	-	-	-	-	-	-	-	-	-	4	6	0	6	5	2
	2	0	3	2	-	-	-	3	3	4	-	-	-	7	2	1
5	1	-	-	-	-	-	-	6	2	0	4	0	1	3	2	0

2	-	-	-	-	-	-	-	-	-	6	1	4	4	3	0
3	-	-	-	-	-	-	2	2	7	-	-	-	4	4	2
Unit costs of using tools on machines	18	10	9	10	12	14	6	8	9	12	11	9	14	13	10

The minimum and maximum numbers of machines that each cell can contain are 1 and 3, respectively. The minimum and maximum numbers of employees that each cell can contain are 1 and 2, respectively. The unit costs of assignment of employees 1, 2 and 3 to cell 1 are 3000, 3500, and 3250 in terms of currency unit, respectively. The unit costs of assignment of employees 1, 2 and 3 to cell 2 are 2900, 3600, and 3100 in terms of currency unit, respectively. The maximum numbers of cells that employees 1, 2, and 3 can be assigned to are 1, 2, and 2, respectively.

The optimum solution of the example problem given above is obtained in a very short time, in less than 1 second, using a branch and bound algorithm under LINGO 19.0 optimization program software on a personal laptop including Intel(R) Core(TM) i5 CPU @ 2.40GHz 2.40GHz 4 core processor and 8.00GB RAM. The optimum total design cost is found to be 50864 currency units. The cost elements that form the optimum total design cost are shown in Table 4 in terms of currency unit.

Table 4. Cost elements of the optimum total design cost.

Operation cost	43400
Cost of using tools	1364
Cost of assignment of employees	6100
Optimum total design cost	50864

In the obtained optimum solution, its alternative route 2 for part 1, its alternative route 3 for part 2, its alternative route 2 for part 3, its alternative route 1 for part 4 and its alternative route 3 for part 5 are chosen as the optimum routes for parts. As a result of the optimum solution, machines 3, 4 and 5, and employee 1 are assigned to cell 1, and machines 1 and 2, and employee 3 are assigned to cell 2.

In the example problem above, the planning horizon is selected as 1 year. If the planning horizon is chosen as more than 1 year, for example 3 years, the optimum solution including the present value method for the problem is obtained as follows: It is assumed that the annual increase rate, $rate$, is 0.10 and the annual real interest rate, ri, is 0.05. First, using the present value method and hence Equations (13)-(16), the 3-years present values of the operational costs stated in Table 2 are calculated. Then, using the calculated 3-years present values of the operational costs, the optimum solution is found. The optimum solution of the problem, which also includes the present value method, is obtained in a very short time, in less than 1 second, using a branch and bound algorithm under LINGO 19.0 optimization program software on same personal laptop stated previously. For this problem, the optimum total design cost and the related cost elements are shown in Table 5 in terms of currency unit.

Table 5. The optimum total design cost elements for the problem with present value method.

Operation cost	129998.5
Cost of using tools	1364
Cost of assignment of employees	6100
Optimum total design cost	137462.5

In the optimum solution of the problem involving the present value method, the optimum routes of the parts, and the contents of the cells in terms of machines and employees are the same as in the previous optimum solution.

Sensitivity analysis in terms of the importance of alternative routes of parts

A sensitivity analysis is performed on the example problem, also including the present value method, to show the effect of alternative routes of parts on the optimum total design cost. If the alternative routings obtained according to the optimum solution are not available, it is seen in Table 6 that there are increases in the optimum total design cost.

Table 6. Impact of alternative routes on the optimum total design cost (as currency unit).

	All alternative routings are available for all parts	Alternative route 2 is not available for part 1	Alternative route 3 is not available for part 2	Alternative route 2 is not available for part 3	Alternative route 1 is not available for part 4	Alternative route 3 is not available for part 5

Optimum total design cost	137462.5	140992.2	138725.6	144086.2	141523.2	138660.5

CONCLUSION AND SUGGESTIONS

In this article, a mathematical programming model is presented for the optimum design of flexible cellular manufacturing systems. This developed model aims to minimize the total design cost that include cost of operating parts on machines, cost of using tools on machines, and cost of assigning employees to cells. In addition, this developed model includes the present value method, in other words, based on a certain planning horizon, the model provides the optimization of the design of flexible cellular manufacturing systems considering the operational costs that occur along the planning horizon and the present values of these costs. This study also considers alternative routes of parts, in other words, routing flexibility. The importance of alternative routings for the optimum total design cost of flexible cellular manufacturing systems is seen in the sensitivity analysis, and when alternative routings are not available, the increases in the optimum total design cost occur.

The study can be advanced by including different objective function elements such as the cost of purchasing machines, the cost of maintenance of machines, the cost of intercell and intracell movements of parts. Moreover, this study can be advanced by including various sustainability factors such as minimizing energy-related costs and carbon emissions.

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