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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 objective function of the developed mathematical programming model is to minimize the total design cost, including the costs of operating parts on machines, using tools on machines, and assigning employees to cells; this model also incorporates the present value method. Thus, the operational costs that occur during a certain period are also considered. LINGO 19.0 optimization 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 is illustrated and the related analysis is shown using a developed example problem. In addition, by ensuring the optimum design of flexible cellular manufacturing systems, the results indicating 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. Finally, a sensitivity analysis is presented to demonstrate 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 applied to increase flexibility, productivity, and quality (Chen and Adam, 1991), as well as to reduce flow time and various costs such as operation, tooling, setup, quality control, labor, and intracellular/intercellular movement costs. Flexible manufacturing systems aim to provide manufacturing flexibility without reducing the product quality (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 that 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 is, by providing routing flexibility, it is possible to transfer the parts to other machines and process the parts on these machines without delays in production in case of disruptions such as machinery breakdown and maintenance. This study also considers alternative routings for parts. Some studies in 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), and Rabbani et al. (2019).

The design of flexible cellular manufacturing systems is a complex and difficult problem because it involves the various concepts mentioned above. Some studies in 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, considering fluctuations in market conditions. Yılmaz and Erol (2015) examined the topic of when and how to reconfigure existing flexible manufacturing cells. 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. Furthermore, they propose a mathematical programming model that minimizes the total reconfiguration cost to make optimal reconfiguration decisions. Niakan et al. (2016) propose a bi-objective mathematical model for the dynamic cell formation problem, considering worker assignments as well as environmental and social criteria. Bagheri et al. (2019) address the multi-period cell formation problem, considering 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 while simultaneously making aggregate planning decisions.

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. Few studies have been conducted related to flexible or cellular manufacturing systems that consider the present value method. Some studies related to this issue are as follows: Bokhorst et al. (2002) discuss investment evaluation in flexible automation technologies and computer numerically controlled machines. The optimality criterion in their work is concerned maximizing the net present value over a given planning horizon. Karsak and Özogul (2005) evaluates 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 includes net present value.

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

MATERIAL AND METHOD

In this study, an integer mathematical programming model is developed to design flexible cellular manufacturing systems, including routing and machine flexibilities. The objective function of this model minimizes the total design cost. The costs of operating parts on machines, using tools on machines, and assigning employees to cells form the total design cost of the model. The model also includes the present value method. Considering a certain planning horizon, the operational costs of processing parts on machines can be calculated according to the present value. Thus, the sum of operational costs that may occur during a certain period is ensured to be considered in the optimal design of flexible manufacturing cells.

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

Developed mathematical programming model

The notation showing the indices, input parameters, and decision variables of the developed model, followed by the objective function and constraint equations of this 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}: annual 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 for part p

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

tco_{mt}: cost of 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 the total numbers of machines

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

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

$imin_h$: minimal number of employees in cell h

$imax_h$: maximum number of employees in cell h

$hmax_i$: maximal number of cells to which 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} in the above notation have the same currency unit. pt_{pam} and cap_m in the above notation have the same time unit.

Objective function:

The objective function of the developed integer mathematical programming model is given by Equation (1). This equation, which expresses the optimum total design cost, consists of the sum of the 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:

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

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

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

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

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

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

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

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

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

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

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

Equation (2) provides the selection of the optimal route by considering all alternative routes for each part. The number of machines each cell can contain at least is determined using Equation (3). Equation (4) indicates the maximum number of machines that each cell can contain. Equation (4) indicates 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 expressed in Equation (5) indicates that a machine can be assigned to only one cell. Equation (6) indicates that the capacities of the machines are not unlimited and cannot be exceeded. Employees can be assigned to flexible manufacturing cells because of processes such as controlling cells. Equations (7) and (8) show the minimum and maximum numbers, respectively, of employees that can be assigned to each cell. 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 the maximum number of cells that each employee can be assigned to; in other words, how many cells each employee can deal with. Equations (10), (11), and (12) state that the decision variables x_{pa}, y_{hm}, and z_{hi} are binary integer variables, that is, 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, by including a certain planning horizon, the problem of determining the operational costs incurred by processing parts on machines, considering 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 examined in the study. In the present value method model of this study, it is assumed that operating costs are annual; that is, they occur at the end of the year. It is also assumed that the demands for the 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 the present value with a certain real interest rate shown as ri. Figure 1 illustrates the present value method in this study for the operating costs of parts. Then there is the formulation of this mathematical programming model also including the present value method.

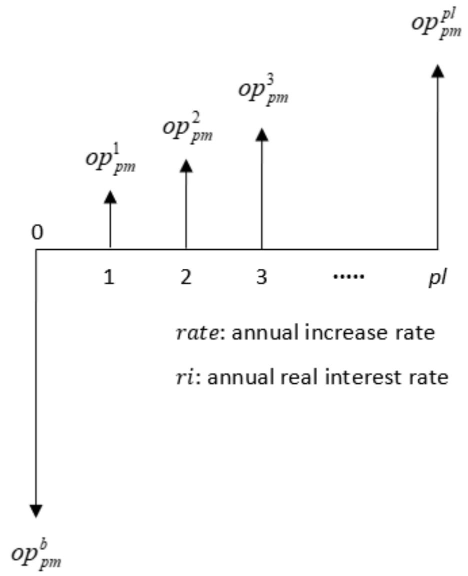

Figure 1. Representation of the present value method for operating costs of parts.

The notation stated in Figure 1 is described as follows:

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

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

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

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

op^{pl}_{pm}: unit operating cost of part p on machine m for the $pl.$ year

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

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

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

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

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

$$op^b_{pm} = \frac{op^1_{pm}}{(1+ri)^1} + \frac{op^2_{pm}}{(1+ri)^2} + \frac{op^3_{pm}}{(1+ri)^3} + \ldots + \frac{op^{pl}_{pm}}{(1+ri)^{pl}} \quad (16)$$

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 an approach similar to the second item in the equation above, $\frac{op_{pm}^{2}}{(1+ri)^{2}}$, to calculate the present value of an income or expense amount occurring at the end of the second period.

In this case, if the planning period is taken into account as pl years, that is, more than one year, the objective function equation of the developed mathematical programming model for the problem handled in this study 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 given by Equations (2)–(12).

RESULTS AND DISCUSSION

In this section, the application of the developed mathematical programming model, which also includes the present value method, to a developed sample problem is discussed. In this 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 the demands for parts, alternative routes of parts, and the unit processing times of parts on five different machines according to these alternative routes of parts. Table 2 lists the unit operation costs of each part on the machines in terms of the currency unit, and the time capacity information of each machine. 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 tools 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 assigning employees 1, 2, and 3 to cell 1 are 3000, 3500, and 3250, respectively, in terms of currency units. The unit costs of assigning employees 1, 2, and 3 to cell 2 are 2900, 3600, and 3100 currency units, 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, less than 1 second, using a branch and bound algorithm under LINGO 19.0 optimization software on a personal laptop with an Intel® Core™ i5 4-core CPU @ 2.40GHz and 8GB RAM. The optimum total design cost is determined to be 50864 currency units. The cost elements that form the optimum total design cost are listed in Table 4 in terms of currency units.

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 selected as the optimum routes. 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 thus Equations (13)-(16), the 3-year present values of the operational costs listed in Table 2 are calculated. Then, using the calculated 3-year 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, less than 1 second, using a branch and bound algorithm under LINGO 19.0 optimization software on same personal laptop stated previously. The optimum total design cost and related cost elements for this problem are listed in Table 5 in terms of currency units.

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, as well as 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, including the present value method, to demonstrate the effect of alternative routes of parts on the optimum total design cost. Table 6 shows that when the alternative routings obtained according to the optimum solution are not available, 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 study, a mathematical programming model is presented for the optimum design of flexible cellular manufacturing systems. This model aims to minimize the total design cost, which includes the costs of operating parts on machines, using tools on machines, and assigning employees to cells. In addition, this developed model incorporates the present value method; that is, based on a certain planning horizon, the model optimizes 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, that is routing flexibility. The importance of alternative routings for the optimum total design cost of flexible cellular manufacturing systems is observed in the sensitivity analysis. When alternative routings are not available, the increases in the optimum total design cost occur.

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

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