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Virtual cellular manufacturing cell formation multi-objective problem by weighted sum goal programming method

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ABSTRACT

There are some reasons why a functional layout is still dominant in manufacturing industry and why some firms have even shifted from a cellular layout back to functional layout. Reorganizing in cellular layout to meet the changes required is time consuming and costly. If the change occur frequently, reconfiguration may become impractical or not a feasible. A relatively new alternative has been considered in recent years, known as virtual cellular manufacturing systems (VCMS). The few explanations for this arrangement are as follows. Firstly, the cellular layout reorganizes to cells to accommodate the necessary adjustments is expensive and time consuming. Secondly, reconfiguring could become unfeasible or impractical, costly if the changes happen often. VCMS are a relatively a new alternative that has been into consideration. A temporary grouping of equipment, jobs and personnel to achieve the advantages typical considered. A logical collection of workstations that are not necessarily arranged in close proximity to one another is called a virtual cell. For effective implementation, workers issue is important in VCMS. Therefore, in this paper, jobs, machinery and workers are logically grouped according to predetermined logic. It only exists in the imaginations of the employees and in the production control system. Though machines are not physically moved into cells, their functional arrangement is maintained. Depending on shifts, and as per the production quantities and product mix, virtual manufacturing cells are generated on a weekly, fortnightly or monthly basis. This paper also discusses a few of the key features of VCMS i.e. virtual cellular manufacturing system. A multiple objectives mathematical problem is formed for VCMS is discussed. Maximize total productive hours and minimize the set up time thereby reduce intercellular dependencies are the objectives considered. The weighted sum goal programming method is used to obtain the solutions of the mathematical formulation. Factors such as capacity constraints, cell size restrictions, load imbalance minimization, minimization of intercellular movements and labor flexibility are considered. Solving in Lingo v20 platform, results are obtained of the two hypothetical problems for getting cells. As the number of cells increases, more number of jobs is accommodated and demand for more number of machines increases. Job priority is incorporated in the second problem. It facilitates the formation of cells with change in parameters. Different cell formations are obtained with job priority. Therefore, implementation of VCMS is an important issue.

KEYWORDS

Virtual cellular manufacturing system, Cell formation, Multi-objective problem, Weighted sum goal programming method

1. INTRODUCTION

Implementing Cellular Manufacturing Systems (CMS) has major advantages. However, there also exist some important reasons why many firms still prefer the 'traditional' functional layout. In contrast to the cellular layout, the functional layout is more robust to the change in the product mix. In some cases functional layout offers a routing flexibility which improves the shop performance significantly. The functional layout preserves the functional specialization of workers and tends to foster functional synergies and expertise. At times, it also provides the economies of scale required for justifying new investments in manufacturing technology. In functional layout, machine utilization is moderate and routing flexibility is more. Conventional CMS possesses certain disadvantages due to the loss of routing flexibility, and inflexibility arising from machine dedication. These are important reasons why a functional layout is still dominant in manufacturing industry and why some firms have even shifted from a cellular layout back to functional layout. Reorganizing in the cellular layout to meet the changes required is time-consuming and costly. If the changes occur frequently, reconfiguration may become impractical or even infeasible. VCMS have been defined as a temporary grouping of machines, jobs and workers to realize the benefits normally associated with CMS. The machines in each virtual cell are assigned to the product families. A virtual cell is a logical grouping of workstations that are not necessarily transposed into physical proximity. The logical grouping of jobs, machines and workers is based on predefined logic, and it is only resident in the production control system and in the minds of the workers. Machines are not physically relocated into cells but those retain the functional layout. One of the most significant advantages of this method is the efficient utilization of machines. Another advantage of VCMS is enhancing the efficiency of tasks and increasing the responsiveness to tackle the changes in the manufacturing conditions and preventing reconfiguration requirements. Virtual manufacturing cells are created periodically, for instance every week or every month, depending on changes in production volumes and product mix. Literature review and some of the characteristics of virtual cells are discussed in section 2. In section 3, mathematical problem formulation for VCMS is discussed. This problem formulation for VCMS is presented and solved with a weighted sum goal programming method using Lingo platform. Two numerical examples are solved and results presented for different cell formations in section 4. Section 5 concludes the paper with future scope.

2. LITERATURE REVIEW AND SOME CHARACTERISTICS OF VIRTUAL CELLS

The literature on VCMS is reviewed. A virtual cell is defined as a logical grouping of products and resources within a controller. It allows time sharing of workstations with other cells by virtue of overlapping resource requirements. In a job shop environment, when the machines are under the control of either a particular virtual cell or a pool of idle machines. Then the shop floor control system schedules cell activation and allocate machines and other resources to these cells. Physically reconfigurable virtual cells for dynamic environment are constructed. It has been addressed in literature that CMS limits flexibility of production system and therefore fails to cope with the changes in market. Virtual cellular manufacturing system (VCMS) is a kind of CMS in which there is no physical separation of factory into distinct cells. In VCMS machine are yet to dedicated to the manufacture of particular group of parts without laying them in separate cells. Irani et al. [1] proposed method of forming virtual cells in layout design. Model is developed based on combination of graph theoretic and mathematical programming. Machine groups are formed. Kannan and Ghosh [2] used a simulation to compare the performance of different virtual cellular manufacturing systems (VCMS). They considered five VCMS configurations coupled with two setup times (major setup and minor setup) and two part-mix variability levels. Measures such as mean flow time, mean tardiness, mean standard deviation in WIP, average shop utilization etc are used to evaluate the performance of the production systems. The results reveal that the implementation of cellular systems need not adversely affect shop performance if the processing and layout properties of cellular manufacturing are separated. Kannan and Ghosh [3] reported that the prioritization of individual jobs within the cells is not an important decision in a VCMS environment. Kannan and Ghosh [4] reported the benefits of virtual cells over cellular manufacturing in context of batch production systems. Experimental design methodology was adopted and simulation environment was adopted. Marcoux et al. [5] have studied the performance of dynamic cellular manufacturing (DCM) and compared with classical cellular manufacturing system. The study shows that the DCM concept is effective in terms of both performance and flexibility. Kannan et al [6] addressed VCMS as a specific CMS configuration, which is able to exploit the setup efficiencies of CMS and routing flexibility of job-shop manufacturing. The VCMS is reported to be robust to the changes in the number and size of the families. Vakharia et al. [7] proposed an analytical approach to evaluate virtual cells and multistage flow shops. Many key factors are that are to be considered for virtual cells are identified. Babu et al. [8] surveyed Indian industries in general and small or medium enterprises (SMEs) in particular. The outline of identified difficulties such as investment in new facilities, re-layout, disturbances in normal operations, restructuring the organization, risk of losing flexibility, risk due to uncertain market, resistance of workers, coordination difficulties in implementation, inability to foresee benefits which discourage managers to adopt CMS. Virtual cellular manufacturing system (VCMS) is suggested as a solution that brings some advantages of CMS without partitioning factory into separate cells. A modular system consisting of Enterprise Modeler (EM), Cell Design Manager (CDM), Cell Operation Manager (COM), Simulator (SIM), Performance Evaluator (PE) and Report Generator (REP) modules are developed. Sarker and Li [9] developed a double-sweep algorithm to schedule virtual cells for multiple job orders. Results generated from this method include the optimal candidates of the virtual cell with the shortest throughput time with sub-optimal alternative routes and throughput time as the alternative candidates in case some resources are restricted. Ratchev [10] considered the design of virtual cellular manufacturing under dynamic production mix. The "Resource Element" concept is used to map the processing requirements of the production mix and match these to the processing capabilities of the manufacturing system. The virtual cell formation is done in four steps, namely manufacturing requirement analysis and generation of processing alternatives, definition of virtual cell capability boundaries, machine tool selection, and system evaluation. Ko and Egbelu [11] presented two algorithms. The first algorithm is used to analyze routing data and create set of machines that appear frequently in routings. The second algorithm specifies virtual configuration based on machine sharing. Suresh and Slomp [12] compared the performances of virtual cellular manufacturing with functional and cellular layouts in a dual resource constrained system context. The advantages of forming virtual cells are highlighted taking into consideration various resources. Slomp et al. [13] considered a multi-objective design procedure for forming virtual cells as temporary groupings of machines, jobs and workers, while retaining functional layout setup. Two phase methodology is developed based on interactive goal programming. In the first phase, maximizing set up savings and minimizing intercellular movements are the goals. In second stage, workers groupings are obtained by maximizing the skill levels of workers. Mak et al. [14] proposed a mathematical model to schedule manufacturing of parts in a job shop environment. Age based genetic algorithm is adopted. The performance of the algorithm is compared with conventional genetic algorithm by solving industrial case study. Nomden et al. [15] reviewed the virtual manufacturing cells. Based on comprehensive review, future issues and areas are identified. Khilwani et al. [16] proposed a methodology to design virtual cells that maximizes similarity index and minimizes lead time. A mathematical and a solution are proposed. According to the significance of workers dimension, Mahdavi et al. [17] has developed a mathematical model and solved with Lingo platform. Alternate process routing in VCMS which increases more independent cells and machine utilization is considered Fargoni et al [18]. Forboodi et al. [19] considered workers skills, interest and workload balancing among cells. A multi-objective mathematical model is developed for VCMS and solved a practical case multi choice goal programming. From the literature review it is evident that VCMS have advantages over CMS setup.

Some of the characteristics of virtual cellular manufacturing systems are identified. In virtual cells, machines, workers and jobs are the three important resources. Among these, machines are fixed as per the existing layout and jobs will be processed on machines or alternate machines. Job priority can be given for some of the jobs. The workers will be allotted to machines in the cells. Workers' skill to perform some of the jobs can be considered. Some workers may have more skills to do the jobs. VCMS provides more flexibility and better utilizations of the resources. Similarly, utilization of material handling equipment is more in virtual cell, as those can be best utilized. The formation of virtual cells helps to minimize the load balancing problems. The changes in demand can be easily incorporated. Unfinished jobs can be given preference to reduce the work-in-process inventory. Some jobs can be given priority to compensate for rush orders. VCMS outperforms cellular and process layout under a wide range of conditions. Thus, the virtual cells offer important advantages of: (1) avoiding a layout change (2) being more robust to turbulence demand (3) enabling GT/CMS benefits to firms without significant organizational time and investment. The advantages of virtual cells also include improved flow performance, higher efficiency, simplified production control, and better quality. Therefore, implementation of VCMS is an important issue. In the next section, formation of virtual cells is elaborated.

3. PROBLEM DEFINITION

Consider a set of jobs which has to be produced on a set of machines in a job shop environment. A limited time period is considered. When the user needs any change in the system, it can be incorporated by giving job priority to unfinished jobs. Each job requires processing on various machine types. The required processing time for job i on machine type m is given by T_{im}. Each job belongs to a family of part types. The set of jobs belonging to a family of part types is given by S_f. The setup time needed for family S_f on machine m is given by S_{fm}. Only one setup is needed if two or more jobs of the same family are manufactured sequentially on the same machine. The available numbers of machines of type m in the shop are denoted by θ_m. A sufficient numbers of workers are available to operate the machines and to handle the setups. The mathematical formulation is described below.

The overall formulation attempts to maximize the total productive hours added in the predefined planning period and to minimize the extent of inter cell dependencies relating to machine and labor resources. Maximizing total productive machining hours induces part family orientation scheduling resulting in savings in setup time. The model is derived from the model of Slomp et al. [13], which is considered for this application [6]. Similarly, weighted sum goal programming method for solving the model formulation is stated as follows:

The following notation is used for the development of mathematical model.

$i = 1,2,\ldots,I$	Jobs;	$S_f =$	Set of jobs belonging to family f;
$m = 1,2,\ldots,M$	Machines;	$S_{fm} =$	Major setup time required for family f over machine type m;
$f = 1,2,\ldots,F$	Families;	$T_{im} =$	Processing time of job i on machine type m;
$c = 1,2,\ldots,C$	Cells;	$\theta_m =$	Number of machine type m available;

$R =$ Length of planning period; $\alpha =$ Setup factor indicating the ineffectiveness to reduce the setups;
$L =$ Number of available workers; $T_i =$ Available time on machine i in the given period of time;
$\beta_1, \beta_2, \beta_3 =$ weight factors; $\Omega =$ a large number;
MAXW = Maximum size of a virtual cell in terms of number of workers;
MINW= Minimum size of a virtual cell in terms of the number of workers;

Variables

$w_c =$ number of full time workers to perform in cell c;
$v_m^+ =$ Number of machines of type m needed in more than one cell;
$v_m^- =$ Number of machines of type m not needed in any cell;

$$x_{ic} = \begin{cases} 1; \text{ if job } i \text{ selected for cell } c; \\ 0; \text{otherwise} \end{cases}$$

$$y_{icm} = \begin{cases} 1; \text{ if job } i \text{ is selected for cell } c \text{ and needs machine } m \\ 0; \text{ otherwise} \end{cases}$$

$$z_{fcm} = \begin{cases} 1; \text{if family } f \text{ is processed in cell } c \text{ on machine } m \\ 0; \text{otherwise} \end{cases}$$

$n_{mc} =$ number of type m machine alloted to cell c (real);
$nn_{mc} =$ number of type m machines needed for cell c (integer);

Objective function

The objective function consists of three terms. The first term is maximizing productive output in terms of machining hours processed in virtual cells in the release period R. The machine setups are reduced. The parameter β_1 indicates the importance of this objective. The second term minimizes the total number of additional machines *m* needed for creating virtual cells. It reflects the extent to which intercellular movements are to be minimized without increasing additional machines that may be required. The third term maximizes number of machines that are not required in any cell. The parameters β_2 and β_3 reflects the importance of minimizing the variable v_m^+ and maximizing v_m^-, which reflects the extent to which intercellular movements are to be minimized without increasing additional machines that may be required. Weights for β_1, β_2 and β_3 are 100, 10 and 1 respectively.

$$Maximize \;\; Z = \beta_1 \times \sum_i \sum_c \sum_m (T_{im} \times x_{ic}) - \sum_m (\beta_2 \times v_m^+) + \sum_m (\beta_3 \times v_m^-) \tag{1}$$

Constraints

(1) Each job is assigned to one virtual cell at maximum in time *R*.

$$\sum_c x_{ic} \le 1, \quad \forall i \tag{2}$$

(2) Number of full-time-equivalent workers needed to perform the operation in cell *c*

$$\sum_c w_c \le L \tag{3}$$

(3) Integer number of type *m* machines needed in cell *c* which exceeds the real (fractional) number of required type *m* machines in cell *c*.

$$n_{mc} \le nn_{mc}, \; \forall m,c \tag{4}$$

(4) Calculate the number of machines of type *m* which are needed in more than one virtual cell

$$\sum_c nn_{mc} \le \theta_m + v_m^+ - v_m^-, \quad \forall m \tag{5}$$

(5) Whether or not a worker is needed in cell *c* to process job *i* on machine type *m*.

$$T_{im} x_{ic} \le \Omega \times y_{icm}, \quad \forall i,c,m \tag{6}$$

(6) At least one worker is assigned to family *f* in cell *c* on machine *m*

$$\sum_{i \in jf} y_{icm} \le \Omega \times z_{fcm}, \quad \forall f,c,m \tag{7}$$

(7) Total worker time is more than the total machining time. All the jobs assigned to workers are performed within the planning period *R*.

$$\sum_{m} T_{cm} \le w_c \times R, \qquad \forall c \tag{8}$$

(8) Machining time in each cell is less than the total available machining time in each cell for number of machines (n_{mc}) in each cell and planning period *R*.

$$T_{cm} \le n_{mc} \times R, \quad \forall c, m \tag{9}$$

(9) Time that an operator needs for machine setups

$$T_{cm} = \left[\sum_{i} T_{im} y_{icm} + \sum_{f} (\mathrm{LB}_{fcm} + \alpha \times (\mathrm{UB}_{fcm} - \mathrm{LB}_{fcm})) S_{fm} \right], \qquad \forall c, m \tag{10}$$

(10) Lower bound equals all the jobs of family *f* assigned to machine type *m* in cell c

$$\mathrm{LB}_{fcm} = z_{fcm}, \quad \forall f, c, m \tag{11}$$

(11) Upper bound equals all the jobs of family *f* assigned to machine type *m* in cell *c*.

$$\mathrm{UB}_{fcm} = \sum_{i \in S_f} y_{icm}, \quad \forall f, c, m \tag{12}$$

(12) Number of workers is less than upper number of full-time-equivalent workers

$$w_c \le \mathrm{MAXW}, \quad \forall c \tag{13}$$

(13) Number of workers is greater than lower number of full-time-equivalent workers

$$w_c \ge \mathrm{MINW}, \quad \forall c \tag{14}$$

(14) Numbers of machines needed in each cell are less than or equal to available ones

$$\sum_{c} n_{mc} \le \theta_m, \qquad \forall m \tag{15}$$

$$x_{ic}, y_{icm} \text{ and } z_{fcm} \text{ are binary variables } \forall i, c, f, m \tag{16}$$

$$nn_{mc}, w_c, v_m^{+}, v_m^{-}, \mathrm{LB}_{fcm} \text{ and } \mathrm{UB}_{fcm} \text{ are integer variables } \forall c, m, f \tag{17}$$

$$n_{mc} \text{ is a real variable}, \quad \forall m, c \tag{18}$$

4. COMPUTATIONAL RESULTS

In this formulation, the machines and jobs are allocated to virtual cells to maximize output of the whole system. Because of the limited capacity in time period *R,* it may happen that some jobs will not be assigned to a virtual cell [6]. Equation (10) consists of time an operator needs for machine setups; and is calculated by the term $\sum_{c}\sum_{m}\sum_{f}(\mathrm{LB}_{fcm} + \alpha_c(\mathrm{UB}_{fcm} - \mathrm{LB}_{fcm}))S_{fm}$.

The real number of machine setups to be performed for family *f* at machine *m* in cell *c* is between the lower and the upper bound and is controlled by the parameter $\alpha_c\,(0 \le \alpha_c \le 1)$. This parameter depends on the size of the virtual cells and the ability to schedule operations of jobs of the same family sequentially at a machine within a cell. The minimum number of setups to be performed by operator on machine type *m* at cell *c* for family *f* equals 1 if all the jobs of family *f* are performed at machine type *m*. Hence, Equation (11) gives the lower bound which is at least 1. The limits to the size of virtual cells are set by means of the lower and upper number of full-time-equivalent workers which are controlled by Equations (13) and (14). Thus, the total set up time T_{cm} is calculated for all machines and for all cells. The results are obtained through a goal programming approach in which sequential priority is given to the three terms in the objective function. Lingo platform is used for solving the goal programming model [6] [7]. Computational results are given in different tables with allocation in this section.

Table 1: Workstation-Job load matrix for Problem 1

Jobs	Machine Type (Number of machines)							Job Priority
	Family of jobs	M1 (2)	M2 (2)	M3 (2)	M4 (2)	M5 (2)	Total work load	
J1	1	3	5	4	0	0	12	0

J2	1	0	5	3	0	4	12	0
J3	1	0	0	0	4	0	4	0
J4	1	3	6	4	0	0	13	0
J5	2	0	0	4	8	6	18	0
J6	2	0	4	0	0	3	7	0
J7	2	5	0	6	4	0	15	0
J8	2	0	0	6	8	6	20	0
J9	3	0	8	0	0	0	8	0
J10	3	0	8	8	0	6	22	0
J11	3	5	0	4	4	0	13	0
J12	3	0	8	0	8	0	16	0

Table 2: Setup time load matrix for Problem 1

Set up time						
Family of jobs	M1	M2	M3	M4	M5	Total set up time
1	5.0	3.0	5.0	3.0	2.0	18.0
2	5.0	6.0	3.0	3.0	5.0	22.0
3	4.0	5.0	2.0	5.0	3.0	19.0
Total	14.0	14.0	10.0	11.0	10.0	59.0

The virtual cells formed are also shown in the respective tables. It is observed that the value of α predominantly influences the cell formation. For $\alpha = 0$, only two cells are formed, and the output is highest. The three values of α considered are 0, 0.5 and 1.0. As the number of cells increases, more numbers of jobs are accommodated. The demand considered for number of machines increases. The distribution of workers to the cells is more even. For three numbers of cells, in first two cases, the output is maximum. In the third case, output is less for α = 1.0. This indicates that for large number of setups i.e. larger value of α , it is more difficult to limit the number of setups. Sharing of machines require undesirable coordination problems between the workers. Thus different cell formations provide some insight [6].

Table 3: Worker-job-machine assignment to cells for Problem 1(3 workers)

`	α	Cell range	Workers			STI	Jobs assigned to			Machines assigned to			v_m^+	v_m^-
			C1	C2	C3		C1	C2	C3	C1	C2	C3		
1	0.0	2-3	3	0	0	79	3,4	2,3	1	1,2	1,2	1	-	1,2, 3,4,5
	0.5	2-3	3	0	0	72	4	2,3	1,2	2	1,2	1	-	1,2,3,4,5
	1.0	2-3	3	0	0	68	4	2,3	3	2	1,2	1	-	1,1,2,3,4,5
2	0.0	2-3	3	0	0	153	4,6,7	1,2,3, 5,6,8	1,7	1,2, 3,4	1,2, 3	1,1, 2,3	2	-
	0.5	2-3	3	0	0	136	1,5, 6,8	6,7	1,3, 8	1,2, 3,4	1,2, 3	1,2, 3	-	-
	1.0	2-3	3	0	0	129	8	3,5, 7,8	1,3, 5	2,3, 4	1,2, 3	1,2, 3	-	1
3	0.0	2-3	2.2	2.6	2.2	160	1,3, 4,9,12	5,7,8, 11	2,6, 10	1,2, 3,4	1,3, 4,5	2,3, 5	3	-
	0.5	2-3	2.6	2.2	2.2	160	3,9,10, 11, 12	5,7,8	1,2, 4,6	1,2, 3,4, 5	1,3, 4,5	1,2, 3,5	1,3, 5	-
	1.0	2-3	2.6	2.2	2.2	160	3,9,10, 11,12	5,7,8	1,2, 4,6	1,2,3, 4,5	1,3,4, 5	1,2,3, 5	1,3, 5	-

Table 4: Worker-job-machine assignment to cells for Problem 1(5 workers)

No. of cells	α	Cell range	Workers			STI	Jobs assigned to			Machines assigned to			v_m^+	v_m^-
			C1	C2	C3		C1	C2	C3	C1	C2	C3		
1	0.0	2-5	5	0	0	134	1,2,4	1,2, 3,4	3,4	1,2	1,1,2	1,1	-	1,4, 5
	0.5	2-5	5	0	0	119	3, 4	2,3,4	2,3,4	1,2,2	1,2,2	1,1	-	1,5
	1.0	2-5	5	0	0	111	3,4	1,2,3	3,4	1,2,2	1,1,2,2	1,1	-	1
2	0.0	2-5	3.4	3.2	0	160	1,2,3,	2,6,	4,7	1,2,	2, 3	1,2	-	1,5

							4,5,6	7,8		3,4				
	0.5	2-5	3.3	3.6	0	160	2,4,6,7	1,2, 3,6,8	4,7	1,2,3,4	1,2,3	1,2,3	-	-
	1.0	2-5	3.4	3.5	0	145	7,8	1,2,3,5	1,3, 5,8	2,3	1,2,3	1,2,3,3	-	-
3	0.0	2-5	2.2	2.6	2.2	160	1,3, 4,9,12	5,7,8, 11	2,6, 10	1,2, 3,4	1,3, 4,5	2,3, 5	3	-
	0.5	2-5	2.6	2.2	2.2	160	3,9,10, 11,12	5,7,8	1,2, 4,6	1,2, 3,4,5	1,2, 3,4,5	1,2,3,5	1,3,5	-
	1.0	2-5	2.6	2.2	2.2	160	3,9,10, 11, 12	5,7,8	1,2, 4,6	1,2,3, 4,5	1,2,3, 4, 5	1,2,3,5	1,3,5	-

Table 5: Worker-job-machine assignment to cells for Problem 1(7 workers)

No. of cells	α	Cell range	Workers			STI	Jobs assigned to			Machines assigned to			v_m^+	v_m^-
			C1	C2	C3		C1	C2	C3	C1	C2	C3		
1	0.0	2-7	7	0	0	160	1,2,3,4	1,2,3,4	1,2,3,4	1,2,2	1,2,2	1,1	-	1,5
	0.5	2-7	7	0	0	160	1,2,3, 4	1,2,3,4	1,2,3,4	1,2,2	1,1,2,2	1,1	-	1
	1.0	2-7	7	0	0	145	1,2,3,4	1,2,3,4	1,4	1,2,2	1,1,2,2	1,1	-	1
2	0.0	2-7	3.4	3.2	0	160	1,2,3,4,5,6	1,6,7,8	4,7	1,2,3,4	2, 3	1,2	-	1,5
	0.5	2-7	3.3	3.7	0	160	2,4,6,7	1,2,3,6,8	4,7	1,2,3,4	1,2,3	1,2,3	-	-
	1.0	2-7	3.0	3.8	0	145	1,2,3,4,5,6	2, 7	7,8	1,2,3,4,4	2,3	1,2	-	1
3	0.0	2-7	2.2	2.6	2.2	160	1,2,3,9,12	5,7,8,11	2,6,10	1,2,3,4	1,3,4	2,3,5	3	-
	0.5	2-7	2.6	2.2	2.4	160	3,9,10,11,12	5,7,8	1,2,4,6	1,2,3,4,5	1,3,4,5	1,2,3,5	1,3,5	-
	1.0	2-7	2.3	2.4	2.2	145	1,3,4, 12	2,8,10	5,7,11	1,2,3,4	2,3,4, 5	1,3,4,5	3,4	-

In problem 2, five types of machines are considered. Twelve jobs are to be processed on machines. The machines are placed in three cells. The data for processing time of jobs and the family of each machine is provided in Table 6. Job priority is considered for job 4. The number of machines available of each type is shown in the Table 6. The assignment of jobs to the family and total work load is also shown in the Table 6.

Table 6: Workstation-job load matrix for Problem 2

Jobs	Machine Type (Number of machines)							Job Priority
	Family of jobs	M1 (2)	M2 (2)	M3 (3)	M4 (3)	M5 (2)	Total work load	
J1	1	9	6	4	0	0	19	0
J2	1	0	6	8	0	9	25	0
J3	1	0	0	8	4	0	12	0
J4	1	8	8	4	0	0	20	1
J5	2	0	0	4	8	8	20	0
J6	2	0	8	6	0	6	20	0
J7	2	9	0	6	8	0	23	0
J8	2	0	0	6	8	9	23	0
J9	3	0	8	4	8	0	20	0
J10	3	0	8	8	0	9	25	0
J11	3	9	0	4	8	0	21	0
J12	3	0	8	8	8	0	24	0

Table 7: Setup time load matrix for Problem 2

Set up time						
Family of jobs	M1	M2	M3	M4	M5	Total set up time
1	6	12	6	3	3	30
2	8	6	3	8	10	35
3	7	8	7	8	5	35
Total	21	26	16	19	18	100

Table 7 shows the setup times required for each machine in each family of jobs. Total of eight workers are considered for a total of three cells. Minimum two workers should be allotted to every cell. A week for the workers consists of 40 working hours per week. Maximum eight numbers of workers can be assigned to any cell. Three different assignments of workers are considered. Table 8 shows the assignment of jobs to the family and total work load for maximum three workers. Table 9 gives the allocation where a maximum of five workers assignment is considered. Table 10 gives the allocation where a maximum of eight workers is considered.

Table 8: Worker-job-machine assignment to cells for Problem 2 (3 workers)

No. of cells	α	Cell range	Workers			STI	Jobs assigned to			Machines assigned to			V_m^+	V_m^-
			C1	C2	C3		C1	C2	C3	C1	C2	C3		
1	0.0	2-3	3	0	0	74	3,4	2,3	1	1,2	1,2	1	-	1,2,3,4,5
	0.5	2-3	3	0	0	64	4	2,3	1,2	2	1,2	1	-	1,2,3,4,5
	1.0	2-3	3	0	0	57	4	2,3	3	2	1,2	1	-	1,1,2,3,4,5
2	0.0	2-3	3	3	0	147	4,6, 7	1,2,3,5, 6,8	1,7	1,2, 3,4	1,2, 3	1,1, 2,3	2	-
	0.5	2-3	3	3	0	133	1,5, 6,8	6,7	1,3, 8	1,2, 3,4	1,2, 3	1,2, 3	-	-
	1.0	2-3	3	3	0	104	8	3,5,7,8	1,3,5	2,3,4	1,2,3	1,2,3	-	1
3	0.0	2-3	2.43	2.6	3.0	210	1,3,4,9,12	5,7,8,11	2,6,10	1,2,3,4	1,3,4,5	2,3,5	3	-
	0.5	2-3	2.78	2.9	2.3	186	3,9,10,11, 12	5,7,8	1,2,4,6	1,2,3,4,5	1,3,4,5	1,2,3,5	1,3,5	-
	1.0	2-3	2.63	2.28	2.2	150	3,9,10, 11,12	5,7,8	1,2, 4,6	1,2,3, 4,5	1,3,4, 5	1,2,3, 5	1,3, 5	-

Table 9: Worker-job-machine assignment to cells for Problem 2 (5 workers)

No. of cells	α	Cell range	Workers			STI	Jobs assigned to			Machines assigned to			V_m^+	V_m^-
			C1	C2	C3		C1	C2	C3	C1	C2	C3		
1	0.0	2-5	5	0	0	140	1,2,3	1,2,3	1	1,2	1,2	1,1	-	1,3,3, 4,4,5
	0.5	2-5	5	0	0	115	1, 2	2,3	1,2	1,2	1,1,2,2	1,1	-	1,3, 4,4
	1.0	2-5	5	0	0	104	2, 3,4	--	1,4	1,2	1,1,2	1,1	-	1,3,4,4,5
2	0.0	2-5	3.1	4.9	0	227	2,4,6,7	1,3,6,8	2,4,7	1,2,2,3,4	1,2, 3	1,2,2,3	2,5	4
	0.5	2-5	4.4	3.6	0	185	1,3,4,4,7	1,3,6,8	2,4,7	1,2,2,4,4	1,2,2,3	1,2,2,3,3	5	1,4
	1.0	2-5	4.2	3.8	0	166	-	3,4,5,8	1,2,3,5	2,3,4	1,2,3	1,2,2,3,3	5	1,4
3	0.0	2-5	2.3	3.1	2.6	227	5,6,8	9,10,11,12	1,2,3,4	2,3,4,5	1,2,3,4,5	1,2,3,4,5	2,5	-
	0.5	2-5	2.3	2.9	2.9	186	1,3,4	5,7,8	9,10,12	1,2,3,4,	1,3, 4,5	2,3,4,5	-	-
	1.0	2-5	3.3	2.7	2.0	166	4,7,8	3,5,8	2, 6	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	5	1,4

Table 10: Worker-job-machine assignment to cells for Problem 2(8 workers)

No. of cells	α	Cell range	Workers			STI	Jobs assigned to			Machines assigned to			V_m^+	V_m^-
			C1	C2	C3		C1	C2	C3	C1	C2	C3		
1	0.0	2-8	8	0	0	227	1,2,3	1,2,3,4	1,2,3,4	1,2,2	1,1,2,2	1,1	-	1,3,4
	0.5	2-8	8	0	0	186	1,2,3, 4	2,3	1,3,4	1,1,2,2	1,1,2,2	1,1,1	-	4
	1.0	2-8	8	0	0	166	2,3,4	1,2,3	1,2	1,2,2	1,1,2,2	1,1,1	-	1,4
2	0.0	2-8	5.7	2.3	0	227	1,3,4,6,7	2,6	1,4,7	1,2,3,4	2,2, 3	1,1,2,3	2	1,4
	0.5	2-8	5.3	2.7	0	186	1.3,4,6,7	2, 6	1,4,7	1,2,3,4	2,2,3	1,1,2,3	-	4
	1.0	2-8	3.8	4.2	0	166	3,4,5,6	2, 7	1,4	1,2,3,4,4	2,3,3	1,2,3	5	1,4
3	0.0	2-8	2.3	3.2	2.6	227	2,3,4,5	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5	2,3,4,5	1,2,3,4,5	2,5	-
	0.5	2-8	2.3	2.8	2.9	186	1,3,4	9,10,12	5,7,8	1,2,3,4,5	1,2,3,4	1,3,4,5	-	-
	1.0	2-8	3.3	2.1	2.7	166	2,4, 7	6,10	3,5,8	1,2,3,4,5	2,3,5	3,4,5	5	1,4

The virtual cells formed are also shown in the respective tables. It is observed that the value of α predominantly influences the cell formation. For $\alpha = 0$, only two cells are formed, and the output is highest. Three values of α considered are 0, 0.5 and 1.0. As the number of cells increases, more numbers of jobs are accommodated. The demand considered for number of machines increases. Distribution of workers to the cells is more even. For three numbers of cells, in first two cases, the output is maximum. In the third case, however, output is less for $\alpha = 1.0$. This indicates that for large number of setups i.e. larger value of α, it is more difficult to limit number of setups. In this example, job priority is considered. Only job 4 is assigned a priority. As observed from the output, job J4 is given priority for processing. Thus, different cell formations are also formed with job priority.

5. CONCLUSIONS

A virtual manufacturing system is a temporary grouping of machines, jobs and workers. The grouping is meant to focus on machines and the minds of workers to families of jobs. This supports the minimization of setup time losses. The application of mathematical programming models is done to create virtual manufacturing cells. The LINGO version 20 platform is used for applying weighted sum goal programming method. Maximize productive hours in a predefined period and minimize inter cell dependencies relating to machine and labor resources are the goals defined in the mathematical model. The model is based on weighted sum goal programming. Two problems are solved for getting cells. Job priority is incorporated in the second problem. It facilitates the formation of cells with change in some parameters. Different cell formations are obtained.

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REFERENCES

[1] S. A. Irani, T. M. Cavalier, and P. H. Cohen, "Virtual manufacturing cells: exploiting layout design and intercell flows for the machine sharing problem", The International Journal of Production Research, Vol. 31(4), pp. 791–810, https://doi.org/10.1080/00207549308956757, (1993)

[2] V. R. Kannan and S. Ghosh, "Using dynamic cellular manufacturing to simplify scheduling in cell based production systems", Omega, Vol. 23(4), pp. 443–452, https://doi.org/10.1016/0305-0483(95)00010-L, (1995)

[3] V. R. Kannan and S. Ghosh, "Cellular manufacturing using virtual cells", International Journal of Operations & Production Management, Vol. 16(5), pp. 99–112, https://doi.org/10.1108/01443579610113979, (1996)

[4] V. R. Kannan and S. Ghosh, "A virtual cellular manufacturing approach to batch production", Decision Sciences, Vol. 27(3), pp. 519–539, https://doi.org/10.1111/j.1540-5915.1996.tb00862.x, (1996)

[5] Y. Marcoux, J. Drolet, and G. Abdulnour, "Studying the performance of a dynamic cellular manufacturing system", Computers & Industrial Engineering, Vol. 33(1–2), pp. 239–242, https://doi.org/10.1016/S0360-8352(97)00083-1, (1997)

[6] V. R. Kannan and S. W. Palocsay, "Cellular vs process layouts: an analytic investigation of the impact of learning on shop performance", Omega, Vol. 27(5), pp. 583–592, https://doi.org/10.1016/S0305-0483(99)00020-1, (1999)

[7] A. J. Vakharia, J. P. Moily, and Y. Huang, "Evaluating virtual cells and multistage flow shops: An analytical approach", International Journal of Flexible Manufacturing Systems, Vol. 11, pp. 291–314, https://doi.org/10.1023/A:1008117329327, (1999)

[8] A. Subash Babu, K. N. Nandurkar, and A. Thomas, "Development of virtual cellular manufacturing systems for SMEs", Logistics Information Management, Vol. 13(4), pp. 228–242, https://doi.org/10.1108/09576050010340866, (2000)

[9] B. R. Sarker and Z. Li, "Job routing and operations scheduling: a network-based virtual cell formation approach", Journal of the Operational Research Society, Vol. 52(6), pp. 673–681, https://doi.org/10.1057/palgrave.jors.2601137, (2001)

[10] S. M. Ratchev, "Concurrent process and facility prototyping for formation of virtual manufacturing cells", Integrated Manufacturing System, Vol. 12(4), pp. 306–315, https://doi.org/10.1108/09576060110393406, (2001)

[11] K. C. Ko and P. J. Egbelu, "Virtual cell formation", International Journal of Production Research, Vol. 41(11), pp. 2365–2389, https://doi.org/10.1080/0020754031000087193, (2003)

[12] N. C. Suresh and J. Slomp, "Performance comparison of virtual cellular manufacturing with functional and cellular layouts in DRC settings", International Journal of Production Research, Vol. 43(5), pp. 945–979, https://doi.org/10.1080/00207540412331320508, (2005)

[13] J. Slomp, B. V. Chowdary, and N. C. Suresh, “Design of virtual manufacturing cells: a mathematical programming approach”, Robotics and Computer-Integrated Manufacturing, Vol. 21(3), pp. 273–288, https://doi.org/10.1016/j.rcim.2004.11.001, (2005)

[14] K. L. Mak, J. S. K. Lau, and X. X. Wang, “A genetic scheduling methodology for virtual cellular manufacturing systems: an industrial application”, International Journal of Production Research, Vol. 43(12), pp. 2423–2450, https://doi.org/10.1080/00207540500046020, (2005)

[15] G. Nomden, J. Slomp, and N. C. Suresh, “Virtual manufacturing cells: A taxonomy of past research and identification of future research issues”, International Journal of Flexible Manufacturing Systems, Vol. 17, pp. 71–92, https://doi.org/10.1007/s10696-006-8122-1, (2005)

[16] N. Khilwani, B. H. Ulutas, A. A. Islier, and M. K. Tiwari, “A methodology to design virtual cellular manufacturing systems”, Journal of Intelligent Manufacturing, Vol. 22(4), pp. 533–544, https://doi.org/10.1007/s10845-009-0314-6, (2011)

[17] I. Mahdavi, A. Aalaei, M. M. Paydar, and M. Solimanpur, “Multi-objective cell formation and production planning in dynamic virtual cellular manufacturing systems”, International Journal of Production Research, Vol. 49(21), pp. 6517–6537, https://doi.org/10.1080/00207543.2010.524902, (2011)

[18] K. Forghani, S. M. T. Fatemi Ghomi, and R. Kia, “Concurrent scheduling and layout of virtual manufacturing cells considering assembly aspects”, Proceedings of the Institution of Mechanical Engineers, Part B, Vol. 235(6–7), pp. 1036–1049, https://doi.org/10.1177/0954405420980685, (2020)

[19] S. Farboodi, M. M. Paydar, and A. Nemati, “Designing a virtual cellular manufacturing system with route selection and workers’ considerations: A multi-objective robust possibilistic model”, Expert Systems with Applications, Vol. 238(part F), p. 122263, https://doi.org/10.1016/j.eswa.2023.122263, (2024)

[20] LINGOversion20, LINDOSYSTEMSINC, (2024)