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RELIABILITY CONSIDERATION IN THE DESIGN AND ANALYSIS OF CELLULAR MANUFACTURING SYSTEMS

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ABSTRACT

A multi-objective mixed integer programming model of cellular manufacturing system (CMS) design is presented which minimizes the total system costs and maximizes the machine reliabilities along the selected processing routes. A part may be processed under different process plans, each prescribing a sequence of operations to be performed at various machines in a serial configuration. Thus, each process plan is associated with a level of reliability corresponding to the machines in the selected process plan. The CMS design problem consists of assigning the machines to cells, and selecting, for each part type, the process route with the highest overall system reliability while minimizing the total costs of manufacturing operations, machine under-utilization, and inter-cell material handling. The proposed approach provides a flexible routing which ensures high overall performance of the CMS by minimizing the impact of machine failure through the provision of alternative process routes in case of any machine failure. The paper also proposes a performance evaluation criterion in terms of system availability for the parts and process plan assignments. A numerical example is provided to demonstrate the applicability of the model.

1 INTRODUCTION

Batch manufacturing accounts for a significant share of the total manufacturing activities. Due to the present competitive market, batch manufacturing needs to produce a large variety of products in small lot sizes at a competitive price in response to customer needs. Conventional manufacturing systems (job shops and flow shops) have found it difficult to comply with these requirements, and have resorted to Group Technology (GT) as a viable alternative to overcome these difficulties (Sofianopoulou, 1999) and to gain economic advantages similar to mass production while retaining the flexibility of job shops. Cellular manufacturing, a practical application of GT in which functionally dissimilar machines are grouped together to produce a family of parts, is widely accepted as an effective configuration for batch type manufacturing systems (Seifoddini and Djassemi, 2001). Many researches have discussed the advantages of CMS such as: reduction of set up times, reduction of material handling costs, reduction of in-process inventory, reduction of cycle times, improvement of shop floor control and improvement of production efficiency (Wemmerlov & Hyer, 1989; Askin & Estrada, 1999).

While the benefits of CMS are well documented by many researchers and practitioners, other studies have pointed out the disadvantages of CMS (Suresh & Meredith, 1994; Flynn & Jacobs, 1986; Morris & Tersine, 1990; Boughton & Arokiam, 2000, Agarwal & Sarkis, 1998). Their findings indicate that in cellular manufacturing:

1. flexibility is reduced;
2. machine utilizations are lower due to the dedication of machines to cells;
3. machine breaks down impact the due date performance adversely;
4. inventory levels are generally higher due to the dedication of machines to cells.

Among the factors influencing the performance of CMS are the structure of the machine–part matrix, the stability of the product mix and the reliability of the machines in manufacturing cells (Seifoddini & Djassemi, 2001). Reliability plays an important role in the overall performance of CMS. Traditionally, cell formation and work allocation are performed assuming all the machines to be 100% reliable, which is never the case. Machine failures cause the greatest impact on due date and other performance criteria even if there is the option of rerouting the parts to alternative workstations. Machines are a major component of CMS and often it is not possible to handle machine breakdowns as quickly as the production requirements dictate. In addition, the disturbances caused by these breakdowns lead to scheduling problems, which decrease the productivity of the entire manufacturing operations. This issue establishes an important need for the consideration of machine reliability in the design process of CMS, especially in light of the increasing complexity of such systems in recent years.

Any attempt at improving the reliability of a system invariably results in higher costs. Thus, an optimization approach that integrates cost and reliability considerations is the most appropriate strategy to achieve an optimum balance. This paper proposes a model of cell formation and operation allocation that incorporates machine reliability and cost considerations to develop an effective CMS design process. The model, which follows the approach of Atmani et al. (1995), is based on the selection of a process plan for each part which maximizes the overall system reliability, while minimizing the overall costs. In the process of allocating operations to machines, the machine availabilities are taken into account to determine effective machine capacities. The approach attempts to keep the intercellular movements of parts as small as possible, while utilizing the concept of alternative process plan assignments in order to cope with machine breakdowns. Finally, the model evaluates the system availability for each part and process plan as a performance measure.

The remainder of the paper is organized as follows. In section 2 the relevant literature is reviewed. Section 3 describes the reliability considerations in the design of CMS. Section 4 presents the mathematical model. In section 5 a numerical example is presented to demonstrate the methodology. Some concluding remarks are presented in section.

2 RELEVANT LITERATURE

The literature on cellular manufacturing is quite extensive. Comprehensive reviews and taxonomies of cellular manufacturing techniques and classifications can be found in Wemmerlov & Hyer (1986), Joines et al. (1996), Selim et al. (1998) and Mansouri et al.(2000).

In the context of the research reported here, the number of research works dealing with the reliability aspects of CMS design is fairly small. Jeon et al. (1998) and Diallo et al. (2001) proposed CMS design approaches which consider alternative routings to handle machine breakdowns. A number of research works included alternative routings in the design of CMS, not to handle machine breakdowns, but to find the best process plans and the best cell configuration which minimize inter-cell movement of the parts, as well as the costs (e.g., Askin & Zhou, 1998). In practice, the consideration of routing flexibility makes it possible to accommodate demand changes, but it falls short of effectively addressing the uncertainty due to machine failures. Machine failures should be taken into account during designing of CMS to improve overall performance of the system (Jeon et al.,1998).

Jeon et al. (1998) developed a MIP model to simultaneously consider scheduling and operational aspects of grouping the machines into cells, assuming there are alternative process plans the parts. Alternative routing provides the option of maintaining the cell performance by allocating a part to an alternative route in case of a machine failure.

Diallo et al. (2001) proposed an approach to the design of a manufacturing cell which can change process plans to handle machine breakdowns. The study carried out reliability analysis of the individual machines and manufacturing system states in the presence of unreliable machines. To develop cell configuration the model allocates the demand of a part type to each of the available process plans. While the model selects the best process plans to satisfy the demand for parts and to reduce intercellular interaction, the cell configuration addresses the problem of manufacturing the parts in alternative process plans when the best plan is not available.

Utilizing buffers to handle machine breakdowns is an established practice in manufacturing systems. Gupta & Kavusturucu (1998) proposed a methodology for the analysis of finite buffer cellular manufacturing systems with unreliable machines. An open stochastic queuing network has been used to model the system, and to develop an approach for designing the buffer size and for the evaluation of the CMS throughput.

A number of studies dealing with CMS performance evaluation have focused on reliability as a measure of performance. Seifoddini & Djassemi (2001) studied the effect of machine reliability on the application of quality index (QI) as a screening process for deciding the suitability of machine part incidence matrix while converting manufacturing operations to CMS. The study suggested the use of QI and machine reliability together to achieve the best performance for CMS. Logendran & Talkington (1997) compared CMS and functional manufacturing systems in the presence of machine breakdowns. The study results indicated that, in the absence of any preventive maintenance or of any machine reliability considerations, the functional layout out-performs the CMS. Zakarain & Kusiak (1997) developed an analytical approach to evaluate system availability as a measure of performance for CMS by considering the probabilities of subsets of machines in working condition in each cell.

This paper proposes a novel approach to CMS design which identifies the alternative process plans for each part type, computes the resulting reliability along each process plan, and makes process plan-part type assignments which result in the highest overall system reliability. This process takes place within a cost optimization framework in order to achieve a balance between performance and economics. The objective is to determine the cell structures that result in the highest overall system reliability while minimizing the total costs of manufacturing operations, machine under-utilization, and inter-cell material handling.

3 MACHINE RELIABILITY ONSIDERATIONS

3.1 Availability consideration

The following assumptions are made in relation to the model development:

1. Updated machine reliability data in the form of mean time between failures (MTBF) and mean time to repair (MTTR) are available.
2. Machine failure and repair times follow an exponential distribution
3. Machine breakdowns occur independently.
4. MTBF and MTTR remain unchanged for the duration of the planning period under consideration.

Considering the machine states as either "operating" or " failed /under repair," a Markovian approach may be used to obtain point availability and interval availability expressions as follows:

$$A_j(t) = \frac{r_j}{r_j + \lambda_j} + \frac{\lambda_j}{r_j + \lambda_j} e^{-(r_j + \lambda_j)t} \tag{1}$$

$$A_{j(t_2 - t_1)} = \frac{r_j}{r_j + \lambda_j} + \frac{\lambda_j}{(r_j + \lambda_j)^2 (t_2 - t_1)} \left[e^{-(r_j + \lambda_j)t_1} - e^{-(r_j + \lambda_j)t_2} \right] \tag{2}$$

$$r_j = \frac{1}{MTTR_j}, \ \lambda_j = \frac{1}{MTBF_j} \tag{3}$$

where $A_j(t)$ is the point availability for machine *j* at time *t*, $A_j(t_2 - t_1)$ is the interval availability for machine *j* during the interval (t_1 to t_2), and r_j and λ_j are the repair and failure rates for machine *j*, respectively. In this paper we consider interval availability to estimate the effective machine capacity.

3.2 Machine Reliability Along a Process Plan

The concept of machine reliability corresponding to a part type-process plan assignment is considered in Table 1 which represents a typical routing table for a part type used in a manufacturing cell. It is evident from Table 1 that, for instance, part 1 may be processed using any of the four process plans depicted in Figure 1.

Now, the system reliability corresponding to the machines in process plan 1 is:

$$R_{11}(t) = R_{M1}(t) R_{M3}(t) R_{M5}(t) \tag{4}$$

where $R_{Mj}(t)$ is the reliability of machine M_j at time *t*. Assuming that machine failures are exponentially and independently distributed, the reliability expression for a machine is:

$$R_{Mj}(t) = EXP(-\lambda_j t) \tag{5}$$

and the system reliability along the selected process plan:

$$R_S(t) = EXP\left(-\sum_j \lambda_j t\right) \tag{6}$$

which may be written as:

$$\frac{1}{\ln R_s(t)} = \sum_j \lambda_j t \tag{7}$$

Since *t* is a planned time period, it may be considered the same for all the machines under consideration. Therefore, the above equation can be expressed as:

$$\frac{1}{\ln R_s(t)} * \frac{1}{t} = \sum_j \lambda_j = LIR \tag{8}$$

Table 1: A Typical Routing Table for a Cell with 5 Machines

Part type	Operations		
	1	2	3
1	MC1,MC2	MC3	MC5, MC4

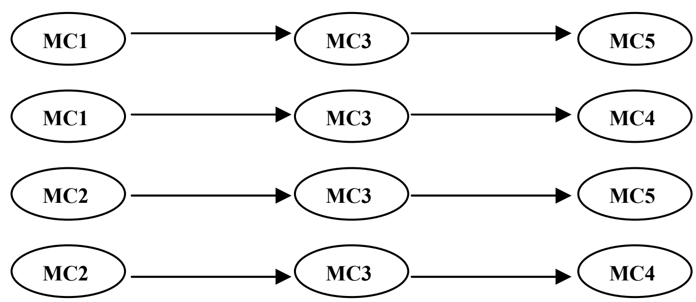

Figure 1: Alternative Process Plans for Part Type 1

where *LIR* is the system failure rate corresponding to a specific process plan. One of the objectives in this work is to minimize *LIR* in order to ensure the selection of machines and process plans would lead to an optimum level of reliability for CMS.

3.3 Performance Evaluation

A major consideration in CMS design is the evaluation of the system performance (Zakarian & Kusiak, 1997). As has been pointed out already, unscheduled machine down times have a major influence on system performance. Typically, the failure of one machine in a CMS does not result in a complete system failure, but it affects the system performance for the following reasons:

- All the parts which are planned to be processed on the failed machine are needed to be rerouted if alternative routes are available.
- If alternative routes do not exist, the parts have to wait for the machine until it is repaired. The subsequent operations will have to be halted while the repair process is underway. Often, this causes a chain reaction, reducing the utilization of subsequent machines and causing due date delays.

The Markovian approach is extensively used for performance evaluation modeling of manufacturing systems, and the most common performance measures in use are availability, throughput and lead times (Zakarian & Kusiak, 1997). Here we employ the Markov modeling approach for the evaluation of system availability as the performance index of the CMS.

The system availability corresponding to a part type-process plan combination is the total steady state probability of the machines required for that combination to be in operating condition. These steady state probabilities will be computed using a Markovian approach explained below**.**

In a manufacturing cell with m machines, the state of an individual machine j may be represented by the set $S_j = \{0,1\}$, $j = 1,2.....m$**,** where *1* indicates that the machine is *"up"*, and *0* indicates that the machine is *"down."* Therefore, the cell states may be defined by the set:

$$W = \{w_1, w_2, .., w_N\},$$

where each $w_k=\{s_1,s_2,..,s_m\}$, $k = 1,2,..,N$, $N=2^m$.

To explain further, consider a cell with five machines where $N = 2^5 = 32$ states. As time goes on, the state of the cell changes, depending on whether a machine fails, or a repaired machine returns to operations. We may represent such state changes using transition probabilities, $P_{w_k w_l}$, of going from state w_k to state w_l. Assuming that the transition probabilities are stationary, and that the individual machine states are independent, we compute all the $P_{w_k w_l}$ terms, then describe the transition probability matrix, *TM*, and finally the steady-state probability vector $V = [\pi_1, \pi_2, \ldots, \pi_N]$, whose components can be calculated from the relation $V=V*TM$, and the normality equation, providing us with the steady state probabilities of the various cell states. Suppose states 1 and 5 are defined by:

$$w_1 = \{1,1,1,1,1\} \text{ and } w_5 = \{1,1,0,1,1\}$$

Thus, a transition from w_1 to w_5 implies that machine 3 has failed, and the corresponding transition probability is:

$$P_{w_1 w_5} = P^{u,u}_{j=1} \times P^{u,u}_{j=2} \times P^{u,d}_{j=3} \times P^{u,u}_{j=4} \times P^{u,u}_{j=5}$$

where $P^{u,d}_{j=3}$ is the probability that machine 3 is changing states from "up" to "down" in a short time period, Δt**.** Now, the system availability may be calculated as the total probability of the relevant cell states where the machines required for a part type-process plan combination are in working condition. In the above example, if part type 1 under process plan 1 needs machine 2, 3 and 5 to perform the required operations, the relevant cell states are: *11111, 01101, 01111*, and *11101***,** and the system availability corresponding to this part type- process plan combination, therefore, is:

$$\pi_{(11111)} + \pi_{(01101)} + \pi_{(01111)} + \pi_{(11101)}$$

4 MATHEMATICAL MODEL

The multi-objective mathematical model of the manufacturing cell design is explained below.

4.1 Objective Functions

The first objective function:

$$F_1 = VCM+MHC+MNC \qquad (9)$$

minimizes the sum of the variable cost of machining (*VCM*), the inter-cell material handling cost (*MHC*), and the penalty cost of machine non-utilization (*MNC*), where:

$$VCM = \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \{C_{oj}(ip) + R_{oj}(ip)\} \sum_{c=1}^{C} X_{ojc}(ip)$$

$$MHC = \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \sum_{1 \le c, \hat{c} \le C} H_{ijc\hat{j}\hat{c}} X_{ojc}(ip) X_{(o+1)\hat{j}\hat{c}}(ip)$$

$$MNC = \sum_{j=1}^{m} cp_j \Big(1 - \Big[\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \frac{TO_{oj}(ip) + TF_{oj}(ip)}{A_{jt} b_j}\Big] \Big) \sum_{c=1}^{C} X_{ojc}(ip)$$

The second objective function:

$$F_2 = \sum_{i=1}^{n} \sum_{p=1}^{P(i)} LIR_{ip} \tag{10}$$

maximizes the system availability over all the part-process plan combinations, where

$$LIR_{ip} = \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \sum_{c=1}^{C} \lambda_j X_{ojc}(ip) \qquad \forall i, p \tag{10a}$$

4.2 Constraints

$$\sum_{p=1}^{P(i)} Z(ip) = 1 \qquad \forall i \tag{11}$$

$$\sum_{j \in Jipo} \sum_{c=1}^{C} X_{ojc}(ip) = Z(ip) \qquad \forall i, p, o \tag{12}$$

$$\sum_{c=1}^{C} M_{jc} \le 1 \qquad \forall j \tag{13}$$

$$\sum_{j=1}^{m} M_{jc} \le UM \qquad \forall c \tag{14}$$

$$\sum_{i=1}^{n} \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} X_{ojc}(ip) \ge M_{jc} \qquad \forall j, c \tag{15}$$

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} [\ TO_{oj}(ip) + TF_{oj}(ip)\ ] X_{ojc}(ip) \le b_j M_{jc} A_{jt} \qquad \forall j, c \tag{16}$$

$$X_{ojc}(ip) + X_{(o+1)\hat{j}\hat{c}}(ip) - 2Y_{ojc\hat{j}\hat{c}}(ip) \ge 0$$
$$\forall i, p, o \in \{1, O(ip) - 1\}, j \in J_{ipo}, \hat{j} \in \hat{J}_{ip(o+1)}, c, \hat{c} \tag{17}$$

$$X_{ojc}(ip) + X_{(o+1)\hat{j}\hat{c}}(ip) - Y_{ojc\hat{j}\hat{c}}(ip) \le 1$$
$$\forall i, p, o \in \{1, O(ip) - 1\}, j \in J_{ipo}, \hat{j} \in \hat{J}_{ip(o+1)}, c, \hat{c} \tag{18}$$

$$SA(ip) = \sum_{w_k=1}^{W_N} \pi_{w_k} TH_{w_k}(ip) \qquad \forall i, p \tag{19}$$

$$\sum_{c=1}^{C} X_{ojc}(ip) MS_{w_k j} - SI_{w_k}^{ipoj} = 0 \qquad \forall w_k, i, p, o, j \tag{20}$$

$$\left(\sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \sum_{c=1}^{C} X_{ojc}(ip) - \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} SI_{w_k}^{ipoj} \right) \le K(1 - TH_{w_k}(ip) \qquad \forall w_k, i, p \tag{21}$$

$$(\ 1 - TH_{w_k}(ip)\ ) - \left(\sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \sum_{c=1}^{C} X_{ojc}(ip) - \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} SI_{w_k}^{ipoj} \right) \le 0 \qquad \forall w_k, i, p \tag{22}$$

$$X_{ojc}(ip), Y_{ojc\hat{j}\hat{c}}(ip), Z(ip), M_{jc}, SI_{w_k}^{ipoj}, TH_{w_k}(ip) \in \{0,1\} \ldots \forall i, p, o, j, c, \hat{j}, \hat{c}, w_k \tag{23}$$

The first constraint, equation (11), ensures that each part is processed under a single process plan. The second constraint, equation (12), ensures that once a process plan is selected, each operation in that process plan is processed on only one of the available machines in one of the cells. Constraint (13) ensures that a machine *j* may be assigned to only one cell. Constraint set (14) specifies upper bounds for the number of machines in a cell. Constraint (15) ensures that once a machine is assigned to a cell, then some operations of the part types must be assigned to it. Constraint (16) ensures that the allocated operations do not overload the effective capacity of the machines. Constraint equations (17) and (18) are the linearization constraints (see Appendix B). Constraint (19) calculates the performance of the cell in terms of system availability *SA(ip)* for part type *i* and process plan *p* depending on steady state probabilities of the cell state space w_k. Constraint (20) selects a machine *j*, which is in operating condition, for part type- process plan combination (*ip)* to perform operation *o* when the cell is in state w_k. Constraints (21) and (22) select only those probable states of the cell where the machines necessary to process the required operations of the part type-process plan combination (*ip)* are in operating condition. The last constraint, (23), describes the integrality of the variables.

5 NUMERICAL EXAMPLE

Input data. We consider a cell in which 12 part types are to be processed on 7 machines. There are alternative process plans for each part type, each plan specifying the sequence of operations to be performed on different machines. For each machine, the capacity and the reliability information (MTBF and MTTR) are available.

Due to space limitation, we present a portion of the data for part type 1 only. Table 2 shows the relevant processing data, and Table 3 displays the machine-related information. Based on these data, the availability and the effective capacity of the machines are computed.

To evaluate the performance measure, we follow the steps outlined in section 3.3 With seven machine, there are $2^7 = 128$ possible cell states, designated as: 1111111, 1111110, 0000001,….., 0000000. To develop the transition probability matrix *TM*, we need to compute the probability of individual machines changing states during the short pe

Table 2: Processing times and cost of the parts

i and d_i	*p*	Data type	Operations 1	Operations 2	Operations 3
1	1	M/C	M1 M4	M1 M5	M4 M6
		Time	0.91 1.34	0.83 2.42	2.25 2.02
		Cost	0.28 0.78	0..76 0.54	0.55 0.4
100	2	M/C	M1 M5	M4 M6	
		Time	1.78 2.39	2.76 1.78	
		Cost	0.96 0.83	0.93 0.68	

Table 3: Machine Information

Data types	M1	M2	M3	M4	M5	M6	M7
Capacity (Hrs)	1500	1400	1200	1100	130 0	1000	1400
MTBF (Hrs)	90	82	126	76	98	50	144
MTTR (Hrs)	14	3	4	10	12	8	2
Avail-ability	0.87	0.96	0.97	0.88	0.89	0.86	0.99

riod (t, $t+\Delta t$). For example, for machine *2,* we need to compute $P_2^{1,1}, P_2^{1,0}, P_2^{0,1}$, $P_2^{0,0}$. $P_2^{1,1}$ is taken to be the interval availability of machine 2 during the planning horizon under consideration. As such, $P_2^{1,0}$ = (1-availability of machine 2).

When a machine is failed at time t (state 0), the probability for the machine to be in operating condition at time $t+\Delta t$, is decided depending on the reparability and maintainability of the machine. For exponential distribution, probability of completing the repair work within t time units is $=H(t) = 1 - e^{-t/MTTR}$ where t is the total down time, which is considered to be higher than *MTTR*. Depending on the average length of the downtime, $P_j^{0,1}$ may be computed, and then P_j^{00} can be estimated from P_j^{00} = 1-$P_j^{0,1}$. The other transition probability terms may be computed in a similar manner, and the transition probability matrix can be completed.

As an example, consider the computation of the term *TM (3,5)* in the transition matrix, that is, the transition probability of the cell state changing from w_3 = (1111101) to w_5 = (1111011). The computation is as follows:

$$TM(3,5) = P_{w_3,w_5} =$$

$$P_1^{1,1} * P_2^{1,1} * P_3^{1,1} * P_4^{1,1} * P_5^{1,0} * P_6^{0,1} * P_7^{1,1}$$

Finally, the procedure of section 3.3 is followed to compute the steady state probabilities (π_{wk}).

Solution and analysis. The model was solved using LINGO 7 on a Pentium 4 CPU (2.26GHz, 512 MB RAM) machine. The number of continuous variables, integer variables and the constraints are 52228, 49088, and 18948, respectively.

Due to the multi-objective structure of the model, we used the ε-constraint method to develop the solution. In the first step, we optimize the first objective function, F_1, disregarding the second objective function. Table 4 shows the resulting optimum cell formation, operation allocation and the reliability related information (due to space limitation, the results are displayed for only part types 1 and 2). The value of the second objective function corresponding to this solution represents an upper bound on F_2.

In the second step, we optimize the second objective function, F_2, disregarding the first objective function. Table 5 shows the results for part types 1 and 2. The value of the first objective function corresponding to this solution represents an upper bound on F_1.

To generate the range of solutions between the two solutions obtained above (i.e., the efficient frontier of the multi-objective problem), we proceed by minimizing the first objective function subject to the original constraints as well as a new constraint on the second objective:

Minimize: Objective I
s. t. Objective II $\leq \varepsilon$, $LB_\varepsilon \leq \varepsilon \leq UB_\varepsilon$

Table 4: Model result when only objective function I is optimized

i	*p*	Cell 1				Cell 2		
		M 1	M 2	M 3	M 4	M 5	M 6	M7
1	2					O1	O2	
2	2		O2	O1 O3				
Machine utilization		0.83	0.69	0.89	0..95	0..97	0..99	0.48

Inter-cell movements: 1

Cost minimization : Objective function I only
Total cost : 1815.74
(VCM = 1410.33,MHC = 50,MNC = 355.41)
Total system failures = 0.3622013
SA(1,2)=0.681, SA(2,2)= 0.825

Table 5: Model result with only objective function II is optimized

i	*p*	Cell 1			Cell 2		Cell 3	
		M1	M 3	M5	M2	M7	M4	M6 not used
1	2			O1			O2	
2	2		O1, O3			O2		
Machine Utilization		0.67	0..97	0.94	0.54	0.99	0.78	

Inter-cell movements: 12

Reliability optimization: Objective function II only
Total cost : 2896
(VCM = 1616, MHC = 600, MNC = 680)
Optimum system failure = 0.2896087
SA(1,2)=0.799, SA(2,2)=0.772

Table 6: Optimizing Objective Function I with a Constraint on Objective Function II

i	*p*	Cell 1		Cell 2				
		M1	M 4	M2	M3	M5	M7	MC 6 not used
1	2		O2			O1		
2	2				O1 O3		O2	
9	1	O2			O3		O1	
Machine Utilization		0.67	0.78	0.54	0.97	0.93	0.99	
Inter-cell Movements: 6								
Objective function I, & Objective II ≤ 0.29 **Total Cost : 2595** (VCM = 1616, MHC = 300, MNC = 680) **Optimum system failure = 0.2896087** SA(1,2)= 0.799, SA(2,2)=0.772								

where UB_{ε} is the value of F_2 when only objective function I is considered, and LB_{ε} is the optimum value of objective function II when its optimized in the second step.

Table 6 shows the results of one such optimization. The table also displays the system availabilities, *SA(ip),* corresponding to part types 1 and 2 for the selected process plans. The efficient frontier diagram for the multi-objective problem is shown in Figure 2, and the data related to the diagram is presented in Table 7.

The model output represented in Table 7 shows the influence of machine reliability on the cell configuration cost components, and offers a range of solutions. Depending on the business priorities, the model will help the user to make an effective design decision considering the cell configuration, system availability, machine utilizations, etc.

6 CONCLUSIONS

In this paper, we presented a new approach to the CMS design by considering machine reliability and cost optimization simultaneously. By integrating machine reliability at the design stage of the cell, the selection of process plan assignments for each part type takes place with the objective of achieving a high system reliability. We are also keeping the provision of routing flexibility to handle the machine breakdown situations. To strike a balance between cost and reliability, the ε-constraint method is proposed as a solution approach to the multi-objective problem. A performance evaluation criteria in terms of system availability is also considered to guide the user is selecting a CMS design.

Table 7: Information for Efficient Frontier Diagram

Objective I	**Objective II**	∈	**Objective I components**		
			VCM	**MHC**	**MNC**
2595.762	0.2896087	0.29	1615.95	300	679.8121
2184.409	0.2977575	0.3	1578.27	0	606.1393
2079.044	0.3097848	0.31	1453.02	50	576.0237
2039.471	0.3176816	0.32	1377.275	150	512.1956
1945.102	0.3297744	0.33	1396.02	100	449.0819
1875.902	0.3337203	0.34	1417.07	50	408.8322
1820.187	0.3490434	0.35	1410.38	50	359.807
1815.000	0.3622000	0.37	1410.00	50	355.000

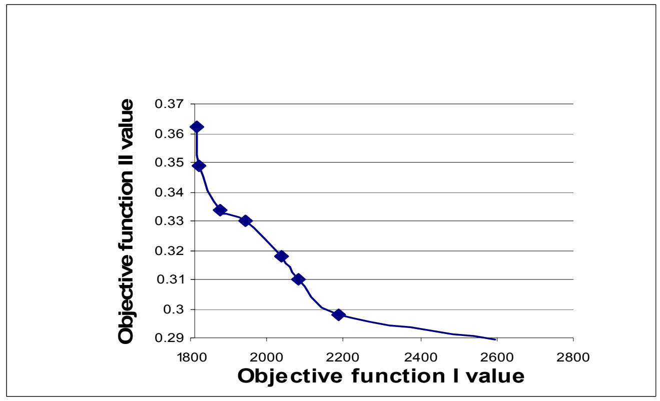

Figure 2: Efficient Frontier: Cost and Reliability Optimization

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APPENDIX A : NOTATION

Indices

$c \in \{1,..,C\}$	cells
$i \in \{1,..,n\}$	part types
$j \in \{1,..,m\}$	machines
$J_{ipo} \subset \{1,..,m\}$	set of machines *j* that can perform operation *o* of *(ip)*
$k \in \{1,..,N\}$	cell states
$o \in \{1,..,O(ip)\}$	operations on part type *i* under process plan *p*
$p \in \{1,..,P(i)\}$	process plans for part type *i*
(*ip*)	a part type *i*, process plan *p* combination
$s_j \in \{0,1\}$	machine states for machine *j*
$w_k \in \{s_1,..,s_m\}$	cell states with *m* machines

Parameters

$A_j(t)$	= availability of machine *j* at time *t*
b_j	= capacity of the machine *j*
$C_{oj}(ip)$	= cost of performing operation *o* of *(ip)* on machine *j* per unit time
cp_j	= penalty cost for under utilization of machine *j*
d_i	= number of units of part type *i* demanded

$H_{ijc\hat{j}\hat{c}}$ =cost of moving part type i from machine j in cell c to machine $\hat{j}$ in cell $\hat{c}$ to perform the next operation

$MTTF_j$ = mean time between failures for machine j

$MTTR_j$ =mean time to repair for machine j

$MS_{w_k j}$ = parameter indicating the state of the machine j in cell state w_k (0 or 1)

$R_{oj}(ip)$ = cost of refixturing when performing operation o of (ip) on machine j per unit time

r_j = repair rate for machine j

$TO_{oj}(ip)$ = time to perform operation o of (ip) on machine j

$TF_{oj}(ip)$ = time for refixturing when performing operation o of (ip) on machine j

λ_j = failure rate of the machine j

π_{w_k} = steady state probability of the cell state w_k

UM = maximum number of machines in a cell

K = a large positive number

Decision Variables

LIR_{ip} = system failure rate corresponding to the machines in process plan p, while performing operations of part type i

M_{jc} = 1 if machine j is assigned to cell c, 0 otherwise

$SA(ip)$ = system availability of the cell corresponding to $(i\,p)$

$SI_{w_k}^{ipoj}$ =1 if the cell state w_k has machines j in operating condition to perform operation o of (ip) on machine j, 0 otherwise

$TH_{w_k}(ip)$ =1 if cell state w_k is selected, which has all the required machines in operating condition to proess $(i\,p)$, 0 otherwise

$X_{ojc}(ip)$ =1 if operation o of (ip) is performed on machine j in cell c, 0 otherwise

$Y_{ojc\hat{j}\hat{c}}(ip)$ =1if (ip) moves to machine $\hat{j}$ in cell $\hat{c}$ to perform the next operation after performing operation o on machine j in cell c, 0 otherwise

$Z(ip)$ = 1 if part type i is processed under process plan p, 0 otherwise

APPENDIX B: LINEARIZATION

The MHC term in the first objective function is nonlinear:

$$MHC =$$

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \sum_{\hat{j} \in \hat{J}ipo} \sum_{1 \le c, \hat{c} \le C} H_{ijc\hat{j}\hat{c}} X_{ojc}(ip) X_{(o+1)\hat{j}\hat{c}}(ip)$$

To lineralize it, we introduce the zero-one lineralization variable:

$$Y_{ojc\hat{j}\hat{c}}(ip) = X_{ojc}(ip).X_{(o+1)\hat{j}\hat{c}}(ip) \text{ --------------- } (A1)$$

that satisfies equation (A1) and equations (16) and (17). $Y_{ojc\hat{j}\hat{c}}(ip)$ takes the value of 1 if and only if (ip) is moved from machine j in cell c after performing operation o to machine $\hat{j}$ in cell $\hat{c}$ to perform operation $o+1$. The final form of the equation for MHC is given below:

$$MHC =$$

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \sum_{\hat{j} \in \hat{J}ipo} \sum_{1 \le c, \hat{c} \le C} H_{ijc\hat{j}\hat{c}} Y_{ojc\hat{j}\hat{c}}(ip),$$

and the final form of the first objective function is:

$$Minimize \quad F_1 = \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \{C_{oj}(ip)$$

$$+ R_{oj}(ip)\} \sum_{c=1}^{C} X_{ojc}(ip) +$$

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \sum_{j \in Jipo} \sum_{\hat{j} \in \hat{J}ipo} \sum_{1 \le c, \hat{c} \le C} H_{ijc\hat{j}\hat{c}} Y_{ojc\hat{j}\hat{c}}(ip) +$$

$$\sum_{j=1}^{m} cp_j \Big(1 -$$

$$\Big[\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{o=1}^{O(ip)} \frac{TO_{oj}(ip) + TF_{oj}(ip)}{A_j(t) b_j}\Big] \Big) \sum_{c=1}^{C} X_{ojc}(ip)$$

REFERENCES

Agarwal, A., and J.A. Sarkis. 1998. Review and analysis of comparative performance studies of functional and cellular manufacturing layouts. *Computers and Industrial Engineering* 34(1):77-89.

Askin, R. G., and S. Estrada. 1999. Investigation of cellular manufacturing practices. In *Handbook of Cellular manufacturing Systems,* ed. S.A. Irani, New York: Wiley.

Askin, R. G., and M. Zhou. 1998. Formation of independent flow line cells based on the operation requirements and machine capabilities. *IIE Transactions* 30(4):319-329

Atmani, A., R.S. Lashkari, and R.J. Caron. 1995. A mathematical programming approach to joint cell formation and operation allocation in cellular manufacturing. *International Journal of Production Research.* 33(1):1- 15 .

Boughton, N. J., and I.C. Arokiam. 2000. The application of the cellular manufacturing: a regional small to medium enterprise perspective. In *Proceedings of the In-*

stitution of the Mechanical Engineers, *Journal of Engineering Manufacture* 214(Part B):751-754.

Diallo, M., H. Perreval, and A. Quillot. 2001. Manufacturing cell design with flexible routing capability in presence of unreliable machines. *International Journal of Production Economics* 74(1-3):175-182.

Flynn, B. B., and F.R. Jacobs. 1986. A simulation comparison of group technology with traditional job shop manufacturing. *International Journal of Production Research* 24(5):1171-1192

Gupta, S. M., and A. Kavusturucu. 1998. Modeling of finite buffer cellular manufacturing systems with unreliable machines. *International Journal of Industrial Engineering* 5(4) :265-277.

Jeon, G., H.R. Leep, and H. R. Parsaei. 1998. A cellular manufacturing system based on new similarity coefficient which considers alternative routes during machine failure. *Computers and Industrial Engineering* 34(1):21-36.

Joines , J. A., R.E. King, and C.T. Culbreth. 1996. A comprehensive review of production–oriented manufacturing cell formation techniques. *International Journal of Flexible Automation and Intelligent Manufacturing* 3(3/4):161-120.

Logendran, R., and D. Talkington. 1997. Analysis of cellular and functional manufacturing systems in the presence of machine breakdown. *International Journal of Production Economics* 53(3):239-256.

Mansouri, S.A, S.M.M. Husseini, and S.T. Newman. 2000. A review of modern approaches to multi-criteria cell design. *International Journal of Production Research* 38(5):1201-1218.

Morris, S. J., and R.J. Tersine. 1990. A simulation analysis of factors influencing the attractiveness of group technology cellular layouts. *Management Science* 36(12): 1567-1578.

Seifoddini, S., and M. Djassemi. 2001. The effect of reliability consideration on the application of quality index. *Computers and Industrial Engineering* 40(1-2) :65-77.

Selim, H. M, R.G. Askin, and A. Vakharia. 1998. Cell formation in group technology: review, evaluation and directions for future research. *Computers and Industrial Engineering* 34(1):3-20.

Sofianopoulou, S.1999. Manufacturing cells design with alternative process plans and or replicate machines. *International Journal of Production Research* 37(3): 707-720.

Suresh, N. C., and J.R. Meredith. 1994. Coping with the Loss of pooling synergy in cellular manufacturing Systems. *Management Science* 40(4):466-483

Wemmerlov, U., and N. L. Hyer. 1986. Procedures for the part family machine group identification problem in cellular manufacturing. *Journal of Operations Management* 6(2):12-147

Wemmerlov, U., and N. L. Hyer. 1989. Cellular manufacturing in the U S industry: a survey of users. *International Journal of Production Research* 27(9):1511-1530.

Zakarian, A., and A. Kusiak. 1997. Modeling manufacturing dependability. I*EEE Transactions on Robotics and Automation* 13(2):161-168.

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