XVII International Scientific Conference on Industrial Systems (IS'17)
Novi Sad, Serbia, October 4. – 6. 2017.
University of Novi Sad, Faculty of Technical Sciences,
Department for Industrial Engineering and Management
Available online at http://www.iim.ftn.uns.ac.rs/is17

Machine Duplication and Technology Considerations in Layered Cellular Manufacturing Systems

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Abstract
*This research focuses on comparing alternative manufacturing system designs for a global blood sugar strip manufacturer. A probabilistic method is used to design the manufacturing system. Two alternative designs are considered by considering machine duplication issues as well machines with different speeds as **fast** and **slow** systems. The results show that total number of machines needed is reduced when the faster system is used. However, the analysis can accurately be completed after only costs are taken into account.*

Key words: Cellular Manufacturing, Layered Cellular Design, Machine Duplication

1. INTRODUCTION

This research focuses on comparing alternative manufacturing system designs for a global blood sugar strip manufacturer. It is assumed that the facility located in Puerto Rico will meet only North American Market. Using cellular manufacturing concepts, number and type of manufacturing cells are determined for the plant by considering stochastic demand data. A probabilistic method is used to design the manufacturing system. Two alternative designs are considered by considering machine duplication issues as well machines with different speeds as fast and slow.

Typically, manufacturing systems are classified into four categories based on their layout as shown in Figure 1 as process layout, fixed layout, cellular layout and product layout. In fixed layouts, products stay in the same position and workers, machines and equipment are brought to the product [10]. In product layouts, each line is dedicated to a product. Product layout is an efficient but inflexible system due to its being dedicated to a product. Process Layout is used for low product volume systems with a high product variety. These systems are very flexible but not very efficient. Cellular Layout is more flexible than Product Layout. It suits for high product variety with low to moderate demand.

Cellular Manufacturing is based on the grouping of similar products with respect to common machines and assign them into one cell (or more if needed). However, in the real world, many uncertainties such as demand uncertainty, supply uncertainty and processing time uncertainty exist. These uncertainties have been discussed in various related research works.

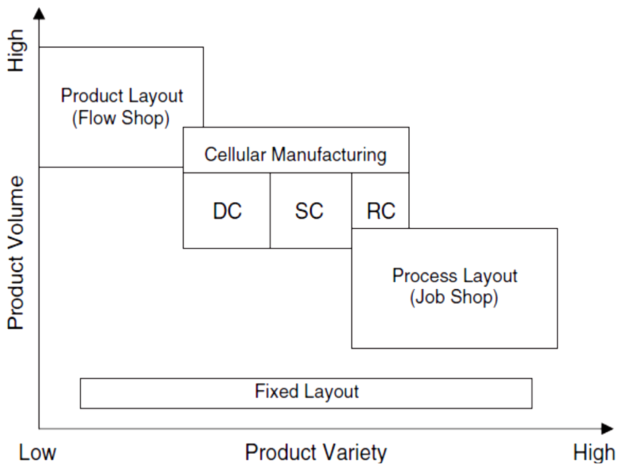

Figure 1. Four types of manufacturing layout [10]

2. LITERATURE REVIEW

Different cellular manufacturing systems have been proposed in the literature. Some of these works include dynamic cellular manufacturing [8], virtual cellular manufacturing, holonic manufacturing [7], fractal cellular manufacturing [6], layered cellular manufacturing with dedicated, shared and remainder cells [10]. A hierarchical classification is made in [10] of manufacturing cells as dedicated, shared and remainder cells. Dedicated cells are aimed to process only one part family, whereas shared cells have the ability to process two part families and remainder cells can process more than two part families.

Uncertainty in cellular manufacturing system design has not been widely studied. A mathematical model has been developed to design a cell formation with the objective of minimizing inter-cell material handling cost where product mix is probabilistic [9]. Uncertain demand has been considered to find out number of machines for cells for the current and future periods where three mixed integer programming models were utilized [4]. A stochastic mathematical model has been provided in [2] based on generalized p-median model in [5]. They considered probabilistic capacity requirements and demand for the products. In another study, a genetic algorithm model is developed to solve a dynamic multi-objective cell formation problem with the objectives of minimizing cost and cell loads [3]. Both stochastic and deterministic systems are simulated to make comparisons in terms of cell utilization, WIP, etc. Stochasticity for both design and control aspects of cellular manufacturing system design has been considered [1]. hey designed cells and scheduled operations under uncertain demand and processing times. A stochastic mathematical model is proposed and run for various design and control risk scenarios. It is found that taking high risks at design phase allows to take lower risks at the scheduling phase, and vice versa.

3. PROBLEM STATEMENT

In this research, a blood glucose test strip manufacturing system is considered to study the alternative design approaches, namely ***fast*** system and ***slow*** system.

In most manufacturing systems, different products require to be processed on different machines. Due to high product variety, products are grouped into several families based on their similarity. Table 1 shows an example of product-machine incidence matrix. In this table, “1” in row i and column j indicates that product i needs to be produced on machine j. For example, Product 1 (P1) is processed on Machine 1 (M1), and Machine 2. One can observe that products with similar manufacturing processes are grouped together. Table 2 shows families and cells they are assigned to in cellular manufacturing.

Table 1. An example product-machine incidence matrix

	M1	M2	M3	M4	M5
P1	1	1			
P2		1	1		
P3	1	1	1		
P4				1	1
P5				1	1
P6	1			1	
P7	1			1	

Table 2. Product families and cells

Family	Products	Cell	Machines in the Cell
F1	P1, P2, P3	Cell1	M1, M2, M3
F2	P4,P5	Cell2	M4, M5
F3	P6,P7	Cell3	M1, M4

When a product family has very high demand, they may need to be produced in more than once cell as shown in Table 3. For example, due to high demand, product families 1, 2 and 3 may need 3, 2 and 2 cells, respectively.

Yet another possibility is that demand values for product families follow a probabilistic distribution. In some cases, expected utilization for some cells of families may be low. As a result, several product families may be expected to share one cell. A Dedicated Cell (DC) deals with one product family. A Shared Cell (SC) operates two product families, which have relatively similar operations. A Remainder Cell (RC) handles more than two product families. Both Shared Cells and Remainder Cells usually handle product families that have medium or low expected utilization values for some of its cells. Table 4 shows the cell sharing between three product families. For example, Cell 1 (C1) is Dedicated Cell for Product Family 1 (F1). C2 is also Dedicated Cell for F2. C3 is a Shared Cell between F1 and F3. Finally, C4 is a Remainder Cell to be shared by F1, F2 and F3.

Table 3. Family vs. Multiple cells due to high demand

	C1	C2	C3	C4	C5	C6	C7
F1	1	1	1				
F2				1	1		
F3						1	1

Table 4. Layered cellular design due to stochastic demand

	C1	C2	C3	C4
F1	1		1	1
F2		1		1
F3			1	1
	(DC)	(DC)	(SC)	(RC)

4. CASE STUDY

The problem considered in this paper is discussed in detail in this section. Table 5 shows the demand information for the blood sugar strip manufacturer plant located in Puerto Rico. It is assumed that this plant will cover the demand in North America along with their standard deviation values.

Table 5. Demand for Puerto Rico facility

Fam	Mean	%	STDEV
1	1,337,087	25	334,271
2	6,672,986	24	1,601,51
3	6,309,389	24	1,514,25
4	22,856,82	21	4,799,93
5	2,949,511	25	737,377

There are a total of nine operations performed. There are a total of three operations are in the fabrication cell and the remaining of the 6 operations are performed in the packaging cell. These two cells are connected with a conveyor system, thus connected cells.

The information about ***fast*** fabrication cell operations are given in Table 6. There is one machine performing operation 1. There are two types of of machines performing operation 2. T1 machine is slow and T2 is fast. In the fast system, there are two of each. Finally there are two types of machines performing operation 3, T3 is slow and T4 is fast. In the fast system, there is only one fast machine. These operation characteristic remain the same for all families.

Table 6. Fast Fabrication Cell

	Op-1	Op-2		Op-3	
		T1	T2	T3	T4
Production Rate	120	17	40	60	123
# Machines	1	0	2	0	1
Production	120	80		123	

Fast packaging cell operations are summarized in Table 7. The last column indicates the bottleneck operation output rate.

Table 7. Fast Packaging Cell

	Op4	Op5	Op6	Op7	Op8	Op9	B
F1	160	135	***80***	150	150	NA	***80***
F2	160	135	***80***	150	150	NA	***80***
F3	160	135	80	150	150	***60***	***60***
F4	160	135	***80***	150	150	NA	***80***
F5	160	135	***80***	150	150	120	***80***

The similar information for slow fabrication and packaging cells are summarized in Tables 8 and 9, respectively. As one can notice, there is one machine of each type for operation 2 and also slower machine is chosen for operation 3. Similarly the operational characteristics given in Table 8 remain the same for all five families. As to packaging cells, the speed varies for machines used for operations 6 and 9.

Table 8. Slow Fabrication Cell

	Op-1	Op-2		Op-3	
		1	2	1	2
Production Rate (vial/min)	120	17	40	60	123
# Machines	1	1	1	1	0
Production Rate	120	***57***		60	

Table 9. Slow Packaging Cell

	Op4	Op5	Op6	Op7	Op8	Op9	B
F1	160	135	***60***	150	150	NA	***57***
F2	160	135	***60***	150	150	NA	***57***
F3	160	135	60	150	150	***40***	***40***
F4	160	135	***60***	150	150	NA	***57***
F5	160	135	***60***	150	150	80	***57***

5. METHODOLOGY USED

The mean capacity requirement for a product family is calculated by using Equation 1. Bottleneck Processing Time (BPT) is defined by the bottleneck machine as the longest processing time in the cell.

$$MCR_F = Mean_{Demand} * \frac{BPT}{60}(hr) \quad (1)$$

The mean capacity requirements for Product Family 1 in fast system is calculated as 279 hours and STDEV as 70. BPT (Bottleneck Processing Time) is 1/80 = 0.0125 min. The results of Mean Capacity Requirements and standard deviation are shown in Table 10 for the same fast system.

$$MCR_{F1} = 1{,}337{,}087 * \frac{0.0125}{60} = 279$$

$$STDEV_{CapacityF1} = \sqrt{334{,}271^2 * \frac{0.0125^2}{3600}} = 70$$

Table 10. Mean capacity requirements and standard deviation for fast system

Family	MCR	STDEV
1	279	70
2	1390	334
3	1756	421
4	4762	1000
5	614	154

The demand coverage probability indicates the probability that a given number of cells will meet the demand. The demand is assumed to follow the normal distribution. The annual capacity per cell is 2000 hrs. Demand Coverage Probability (DCP) for a family and cell combination is calculated by Equation 2.

The demand coverage probability for the first cell for family 1 in fast system is 99.99%. In other words, only one cell is sufficient to cover demand almost fully for Family 1.

$$DCP_{FC} = Normsdist\left(\frac{2000 * CellNo. - MCR_F}{STDEV_{Capacity}}\right) \quad (2)$$

All of the results of Demand Coverage Probabilities are shown in Table 11. For family 3, one cell will cover demand 72% of the time. By adding a second cell, the Demand Coverage Probability jumps to 99.99%.

$$DCP_{F1C1} = Normsdist\left(\frac{2000 * 1. - 279}{70}\right) = 1$$

Table 11. Demand coverage probabilities for fast system

Cell / Family	1	2	3	4	5
1	1.00				
2	0.97	1.00			
3	0.72	1.00			
4	0.001	0.22	0.89	0.99	1.00
5	1.00				

Expected Cell Utilization is determined by using Demand Coverage Probability, Mean and Standard Deviation from Equation 3 to Equation 6.

$$E(C = X) = P(CR > X) * PU_1 + P(X - 1 \le CR \le X) * PU_2 + P(CR < X - 1) * PU_3 \quad (3)$$

Where

E(C=X) Expected cell utilization for the Xth cell in a product family

P(CR>X) Probability that the number of cells required (CR) > X

PU1 Percentage utilization of the Xth cell when CR > X, PU1 =1.0

P(X-1≤CR≤X) Probability that CR between X-1 and X

PU2 Percentage utilization of Xth cell when CR between X-1 and X

P(CR<X-1) Probability that CR < X-1

PU3 Percentage utilization of Xth cell when CR < X-1, PU3 = 0.0

PU2 is solved by Equation 4.

$$PU_2 = \int_{2000(X-1)}^{2000X} \frac{y * f(y)}{2000 * A} dy - (X - 1) \quad (4)$$

Where

y Variable represents CR

f(y) Probability density formation for CR

A Probability that CR between X-1 and X

f(y) and A are calculated by Equations 5 and 6, respectively.

$$f(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(y-\mu)^2 \frac{1}{2\sigma^2}} \quad (5)$$

$$A = P(X - 1 \le CR \le X) \quad (6)$$

For example, the expected cell utilization of the first cell for Product Family 1 is calculated by considering the probability that the number of cells required is greater than 1 (percentage utilization of the 1st cell when CR > 1) and probability that CR between 0 and 1 (percentage utilization of 1st cell when CR between 0 and 1).

$$E(C = 1) = P(CR > 2000) * PU_1 + P(0 \le CR \le 2000) * PU_2 + P(CR < 0) * PU_3 = 0 * 1 + 1 * PU_2 = PU_2$$
$$= \int_0^{2000} \frac{y}{2000 * 1} * \frac{1}{70 * \sqrt{2\pi}} e^{-(y-279)^2 * \frac{1}{2*70^2} dy} = 0.14$$

All of the results of expected cell utilizations for different regions are shown in Table 12.

Table 12. Expected cell utilization values-fast system

Cell / Family	1	2	3	4	5
1	0.14	0.00			
2	0.69	0.00			
3	0.84	0.04	0.00		
4	1.00	0.94	0.42	0.03	0.00
5	0.31	0.00			

6. RESULTS

Having determined Expected Cell Utilization values, Dedicated Cells (DC), Shared Cells (SC), and Remainder Cells (RC) are identified. The heuristic algorithm is used for identifying cells [10]. First, expected cell utilizations are sorted in decreasing order. High Utilization values (>50%) are assigned to cells. Then an attempt is made to assign low utilization segments (<50%) to existing cells such that cell utilization values get close to 100% by considering similarities among families. Shared cells (SC) process two families whereas remainder cells (RC) process three or more product families. The threshold value is the lowest acceptable similarity coefficient that allows two families to be grouped in a cell. The Similarity

Threshold is set to 77% in this research and similarity coefficient values are given in Table 13. If a cell runs products of a single family, then it is called dedicated cell (DC). The results are summarized in Table 14.

Table 13. Similarity coefficients between product families

Family	1	2	3	4	5
1		1.00	0.89	0.78	0.70
2	1.00		0.89	0.78	0.70
3	0.89	0.89		0.70	0.80
4	0.78	0.78	0.70		0.89
5	0.70	0.70	0.80	0.89	

Table 14. Layered Design – fast system

Cell / Family	1	2	3	4	5
1				0.14	
2				0.69	
3			0.84	0.04	
4	1.00	0.94		0.03	0.42
5					0.31
	DC	DC	DC	RC	SC

The results for expected cell utilization for slow system and corresponding layered design are given in Tables 15 and 16, respectively.

Table 15. Expected cell utilization values-slow system

	PR					
Cell / Family	1	2	3	4	5	6
1	0.20	0.00				
2	0.89	0.08	0.00			
3	0.97	0.34	0.00			
4	1.00	0.99	0.87	0.41	0.05	0.00
5	0.43	0.00				

Table 16. Layered Design – slow system

	PR						
Cell / Family	1	2	3	4	5	6	7
1							0.20
2				0.89			0.08
3			0.97				0.34
4	1.00	0.99			0.87	0.41	0.05
5						0.43	
	DC	DC	DC	DC	DC	SC	RC

The details of the layered design for the fast system are presented in Table 17. The last column shows the total number of machines for the system. The cells with two numbers (X,Y) indicates that X is slower machine and Y is the faster machine. A similar design is performed for slow system and its details are shown in Table 18.

Table 17. Final Design – fast system

	C1	C2	C3	C4	C5	Total
	F4	F4	F3	F1-F4	F4,F5	
M1	1	1	1	1	1	5
M2S/F	0/2	0/2	0/2	0/2	0/2	0/10
M3S/F	0/1	0/1	0/1	0/1	0/1	0/5
M4	1	1	1	1	1	5
M5	1	1	1	1	1	5
M6F	0/1	0/1	0/1	0/1	0/1	0/5
M7	1	1	1	1	1	5
M8	1	1	1	1	1	5
M9S/F	NA	NA	0/1	0/1	0/1	0/3

7. CONCLUSION

The difference in terms of number and type of machines are summarized in Table 19. In fast design, number of cells are reduced (5 cells vs 7 cells in slow design). On other hand, number of machines vary based on the type of machines used. By duplicating the fast machines for operation 2 (3 more fast machines), and choosing the faster machines for operation 3 (2 less machines but faster machines), for operation 6 (2 less machines but faster machines) and for operation 9 (same number of machines but faster), the total number machines are reduced. One can also note that slow machines for slow system are all eliminated if fast system is implemented. More accurate analysis would be possible If machine costs were available. A sensitivity analysis will be carried out in the future to discuss different possibilities.

Table 18. Final Design – slow system

	C1	C2	C3	C4	C5	C6	C7	T
	F4	F4	F3	F2	F4	F4,F5	F1-F4	
M1	1	1	1	1	1	1	1	7
M2S/F	1/1	1/1	1/1	1/1	1/1	1/1	1/1	7/7
M3S/F	1/0	1/0	1/0	1/0	1/0	1/0	1/0	7/0
M4	1	1	1	1	1	1	1	7
M5	1	1	1	1	1	1	1	7
M6S/F	1/0	1/0	1/0	1/0	1/0	1/0	1/0	7/0
M7	1	1	1	1	1	1	1	7
M8	1	1	1	1	1	1	1	7
M9S/F	NA	NA	1/0	NA	NA	1/0	1/0	3/0

Table 19. Comparison of Designs

	Fast	Slow	Slow-Fast
M1	5	7	2
M2	0/10	7/7	7/-3
M3	0/5	7/0	2S
M4	5	7	2
M5	5	7	2
M6	0/5	7/0	2S
M7	5	7	2
M8	5	7	2
M9	0/3	3/0	F

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