Selection Principles on Manufacturing System for Part Family

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Abstract

In the mid-to-large volume manufacturing operations, a Single Part Manufacturing System (SPMS) is usually used to produce one part model. As the progress of manufacturing technologies, modern manufacturing systems such as reconfigurable manufacturing systems (RMS), are more capable of producing a family of part models, such a system is often referred to as a Multiple Parts Manufacturing System (MPMS). Therefore, given a number of part models within the same part family and their respective volumes, which system style is more economical will be a challenging question for system designers. To answer this question, this paper develops two sets of selection principles on manufacturing systems for part family. Firstly a cost model is constructed to account the investment on machine tools, material handling and transfer equipment as well as other devices utilized in a manufacturing system. Several selection principles are developed based on this model which captures the cost difference between SPMS and MPMS. Then a concept of utilization rate of a SPMS is initiated. Another set of selection principles based on the average utilization rate of the SPMSs are developed to assist the system designers in determining whether a MPMS should replace the SPMSs.

Keywords: manufacturing system, part family, cost model, utilization rate

1 Introduction

Traditionally most of mass production industries utilize a Single Part Manufacturing System that produces only one part model at a time with a large volume. With the growing trends towards high product variety and relatively low volume for each product, many enterprises have gradually shifted their philosophy from mass production to mass customization, which is devoted to delivering a wide range of products and services that meet specific needs of individual customers [1, 2]. For manufacturing companies, they face the challenges of building a manufacturing system with customized flexibility and reconfigurability for a part family that satisfies customers' requirements. The Reconfigurable Manufacturing System (RMS) initiated by Koren [3] is one of the options to handle a part mix with different volumes. When a RMS maintains the functionality and capacity to produce a range of part models, it is referred to as a Multiple Parts Manufacturing System (MPMS).

However, it does not mean that MPMS is more favored than SPMS. Either SPMS or MPMS has its own advantages and disadvantages, which are described from the following aspects.

1) System design task

It is easier for designers to identify the SPMS configuration and allocate the tasks since only one part model needs to be dealt with. Instead, MPMS design is much more complex since it has to handle several models simultaneously.

2) Material handling system

A MPMS requires more complex material handling and transferring devices, while those in a SPMS are relatively simpler.

3) Ramp up

Shorter ramp up time is needed by a SPMS than a MPMS. Furthermore, the quality control is a challenging issue for MPMS.

4) Flexibility

A SPMS only produces a single part model, lacking the flexibility to produce other models. Therefore it is difficult to offset the redundant capacity of a SPMS to the production of other part models within the same part family. On the contrary, this is the advantage of a MPMS, which is capable of adjusting production volumes of the part mix currently produced.

For a given production demand that consists of a number of part models in the same part family, how to select a system style between MPMS and SPMS is a challenging question for a system designer at the initial system planning stage. The system cost is usually a critical factor if other requirements such as capacity demand and process constraints are satisfied. Some design methodologies [4-6] for each system style can be utilized to identify the exact system configuration and further choose the better one by comparing their costs. But this is a time and resource consuming procedure which should be used cautiously. Instead, before performing the detail system design, one can resort to some simple principles to first decide which style is more appropriate for the given part mix. For this purpose, two sets of selection principles are developed on the basis of a cost model and utilization rate, respectively.

The paper is organized as follows. Section 2 presents selection principles based on a cost model that takes machine tools, material handling and transfer equipment as well as other facilities being used into consideration. It is concluded that the total number of machine tools needed to build the manufacturing system is the primary factor that impacts the overall system cost. In the next section, the concept of utilization rate is initiated to act as a critical decision factor of the selection principles that determine which system style should be employed. Section 4 concludes the paper.

2 Cost Model Based Selection Principles

A number of factors have been considered as the evaluation criteria for a manufacturing system, such as system cost, production capacity and product quality. When a manufacturing system is designed to satisfy the predefined throughput demand (production capacity) and subject to the constraints of process planning, system cost becomes the primary criterion. The less expensive system will be chosen because all systems are commeasurable in terms of capacity and quality criteria.

The cost of a manufacturing system depends on numerous cost components, including machine cost C_M, material handling device cost (Conveyor cost C_V and Gantry cost C_G), tooling cost C_T, pallet and fixture cost C_F, and other operation/labor cost C_O. Essentially, all of these cost components are related to the total number of machines – M, and buffer spaces – B. Let C be the total cost of a manufacturing system, C will be the function of M and B,

$$C = f(M, B).$$

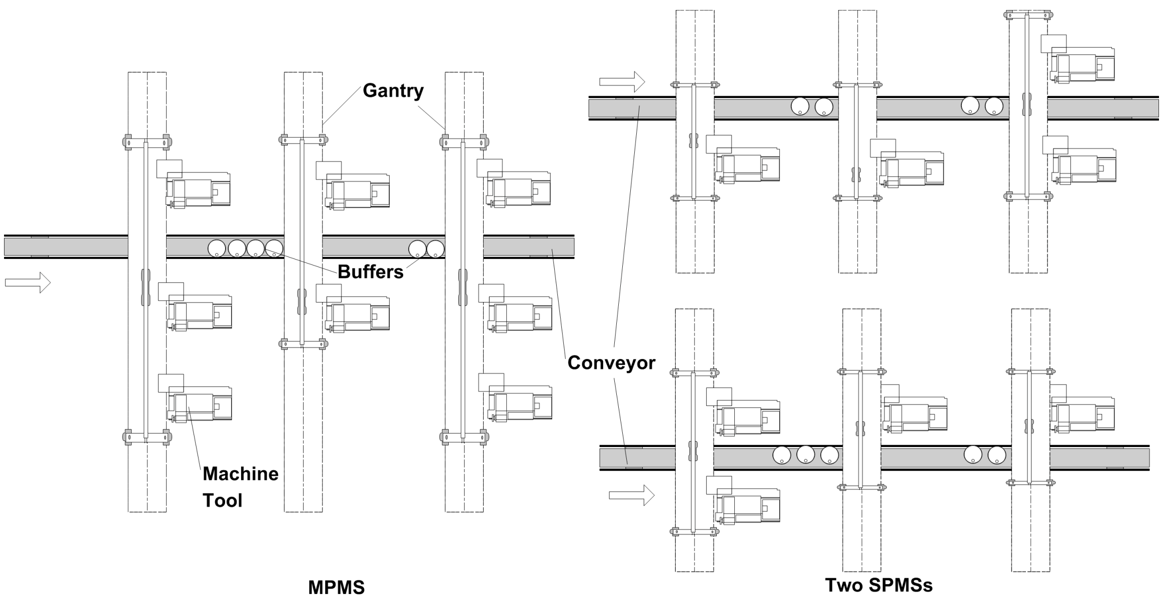


Figure 1 MPMS and SPMS Configuration

Figure 1 shows two system configurations; to the left is a MPMS that produces two part models and to the right are two SPMSs each of which produces one part model. Both MPMS and SPMS comprise three stages each of which contains a number of identical machines in parallel. Based on the shown configuration style, a system cost model is developed to analyze the cost difference between the SPMSs and a MPMS by examining each cost component mentioned above.

In each system an asynchronous conveyor system (power and free) [7] is used to connect all stages. The work-in-process parts are stored in buffer spaces on the conveyor between every two consecutive stages. Inside a stage, a gantry system is used to load parts to each machine or unload parts from each machine tool. Each gantry system has one basic cable control unit regardless of the number of machine tools. To access all the machines in a stage, an operating section corresponding to each machine tool in this stage will be built up[8, 9].

The cost difference between MPMS and SPMS will be analyzed in the context of each cost component.

1) Machine tool cost C_M

$$C_M = U_M * M,$$

where U_M is the unit price of a machine tool.

If both styles utilize the equal number of machine tools, then this cost is identical.

2) Conveyor cost C_V

The conveyor cost includes the fixed cost which depends on the number of stages N_S and the variable cost which is proportional to the buffer size N_B. The more buffer spaces, the longer conveyor is needed and thus incurs the more cost.

$$C_V = U_V * N_S + U_B * B,$$

where U_V is the average fixed cost per stage and U_B is the average cost per buffer space.

From this perspective, a MPMS is more economical than two SPMSs since two systems require two conveyors which double the cost. It is derivable that more SPMSs would incur more conveyor cost.

3) Gantry cost C_G

The gantry cost comprises two portions as well: the base cost U_{GC} that provides the base control unit with necessary cable/rail connections and the operating section cost U_{GS} for each machine tool.

$$C_G = U_{GC} * N_S + U_{GS} * M,$$

where N_s is the number of stages and M is the total number of machine tools being used.

Again, MPMS is more economical than two SPMSs in this aspect because two SPMSs have more stages.

4) Tooling cost C_T

The tooling cost depends on the total cutting time to fulfill the production demands of the part family, which is identical for both configurations. Thus C_T is equal in MPMS and SPMSs.

5) Pallet and fixture cost C_F

The number of required pallets and fixtures is related to the total number of machine tools and buffer spaces. It is quite conservative to assume that it equals to two times of the sum of the total number of machine tools M and the total number of buffer spaces B, $2*(M+B)$.

Since a MPMS produces multiple part models and in the worst scenario each part model may need distinctive fixtures and even pallets, the SMPSs may cost less than the MPMS in this aspect.

$$C_F = 2*N_P*U_F*(M+ B),$$

where U_F stands for the unit cost for pallets and fixtures, N_P is the number of part models in the part family.

6) Operation and Labor cost C_O

The operation and labor cost is usually assumed linear proportional to the number of machine tools M.

$$C_O = U_O * M,$$

where U_O represents the average operation/labor cost by each machine.

Applying the above equations to the two configurations in Figure 1, the cost expressions for SPMS and MPMS can be derived. Let M_1, B_1, M_2, B_2 be the total number of machine tools and buffer spaces of MPMS and SPMS, respectively.

Cost of MPMS (C_{MP})

$$C_{MP} = C_M + C_V + C_G + C_T + C_F + C_O$$
$$= U_M*M_1 +U_V*N_S +U_B*B_1 +U_{GC}*N_S +U_{GS}*M_1 +C_T +2*N_P*U_F*(M_1+B_1) +U_O*M_1 \quad \text{……………………}(1)$$

Cost of two SPMS (C_{SP})

$$C_{SP} = C_M + C_V + C_G + C_T + C_F + C_O$$
$$= U_M*M_2 +N_P*U_V*N_S +U_B*B_2 +N_P*U_{GC}*N_S +U_{GS}*M_2 +C_T +2*U_F*(M_2+B_2) + U_O*M_2 \quad \text{……………………}(2)$$

Assuming that $M_1 = M_2 = M$, $B_1 = B_2 = B$, the cost difference between a MPMS and two SPMSs is:

$$\_ = C_{MP} - C_{SP}$$
$$= 2*(N_P-1)*U_F*(M+B) - (N_P-1)*U_V*N_S - (N_P-1)*U_{GC}*N_S$$
$$= (N_P-1)*[2*U_F*(M+B) - U_V*N_S - U_{GC}*N_S] \quad \text{……………………………………………}(3)$$

Given the configuration data of $N_P = 2$, $M = 8$, $B = 6$, $N_S = 3$, and the cost coefficients from industry practitioners: U_F = \$5K-10K, U_V = \$150K-200K, U_{GC} = \$35K-50K, the cost difference is depicted in Figure 2. The three coordinate axes stand for U_F, U_V and U_{GC} value respectively, and triangles of different colors correspond to different _ values. The best case occurs when U_F takes the lowest value while U_V and U_{GC} have the highest cost. Shown as the solid triangle of the figure, the maximum cost difference is -\$610K. On the other hand, the minimum cost difference (-\$275K) occurs when U_F takes the upper bound while U_V and U_{GC} take the lower bound, as indicated by the dash-double-dot triangle. The cost difference ranges from -\$610K to -\$275K, which means MPMS can save this amount of investment compared to two SPMSs. This example demonstrates that MPMS is more cost-efficient than MPMS even though they utilize the same number of machines and buffers.

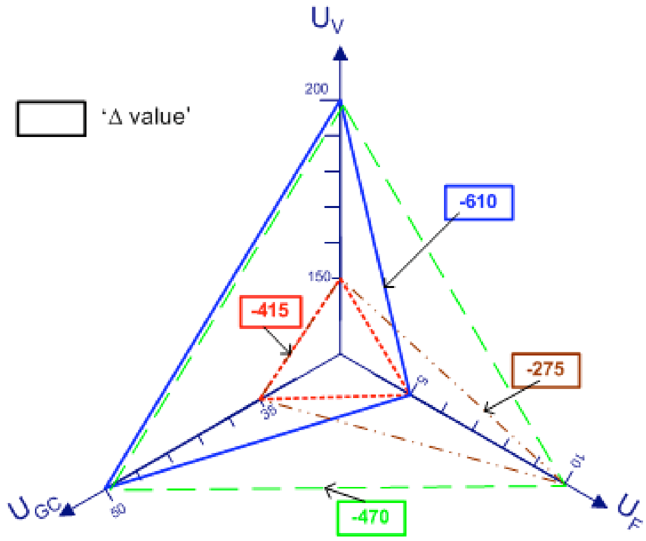


Figure 2 Cost Difference between MPMS and SPMSs

If different configuration data (N_P, M, B, N_S), other than the values specified in the preceding paragraph, are applied, it is still more likely that MPMS is preferred than SPMSs with equal machines and buffers. Considering Formula (3), the number of part models N_P is identical for both configuration styles and it will not influence the cost difference. Whereas, increasing the number of stages N_S will lead to more conveyor and gantry cost for SPMSs. The only factor that increases MPMS cost is the number of pallets and fixtures. Considering the worst scenario (maximal U_F = \$10K, and minimal U_V = \$150K, U_{GC} = \$35K), the sum of M and B must be greater than 27 in order to make _ = $C_{MP} - C_{SP}$ >0. This value for a three-stage manufacturing system is big enough. In addition, it is just the result in the worst scenario so it is very likely that MPMS is more economical than SPMSs with equal machines.

The above analysis is based upon the assumption that both configuration styles contain the equal number of machine tools. What if the MPMS uses fewer machines than the SPMSs? Manifestly, it can be claimed that the MPMS configuration is highly preferred according to equation (1) and (2). The reasons are as follows:

a) Considering that the unit cost of machine tool is a significant value (\$100K-200K) compared to other equipment costs, fewer machines in MPMS will incur huge amount of saving in machine tool cost C_M.

b) Meanwhile, fewer machines will result in savings on pallet and fixture cost C_F as well as operating and labor cost C_O.

In a summary, the following selection principles are developed based on the aforementioned cost model:

Principle A-1

If a MPMS and its corresponding SPMSs require the equal number of machine tools, the MPMS is highly probably more economical considering other equipment costs, like material handling and transferring devices, fixtures, pallets, etc.

Principle A-2

If a MPMS require fewer machine tools than the SPMSs, the MPMS is definitely better in terms of cost.

3 Utilization Rate Based Selection Principles

The previous section concludes that the number of machines is the primary factor to determine the total cost of a manufacturing system with consideration of other equipment costs. MPMS configuration is highly probably preferred than SPMS when they utilize the equal number of machines. Obviously, a MPMS is more cost-efficient if it uses fewer machines than the SPMSs. So the number of machines being used is an important criterion for the system designers to make a decision.

However, the total number of machines of a system is unknown before the exact system configuration is identified. Is it possible that one can estimate a quantity of one style (say MPMS) with knowing the information of other one (SPMS)? The answer is positive. The research finds that the average utilization rates of the SPMSs are closely correlated to the total number of machines in a MPMS that undertakes the same production demands. The utilization rate of a SPMS can be calculated if the configuration is known. This situation is quite common especially for the current industrial practitioners who have experiences in designing a SPMS but not for a MPMS. Once the total number of machines of the MPMS is estimated, from the conclusion of Section 2 the system designer can determine which type of system should be utilized.

This section proposes some selection principles based on the average utilization rate of SPMSs in order for the system designers to decide a MPMS should replace a number of SPMSs. The principles rely on the information of every SPMS configured for each part model, more specifically, the utilization rate of each SPMS.

Define:

M = Minimal number (can be a fraction) of machines in a SPMS needed to satisfy the throughput demand in ideal conditions such as absolutely balanced task allocation and error-free operations.

A = Actual number of machines of the SPMS to satisfy the throughput demand. It is derived by a common design method using in industrial practice where the stages are well balanced in order to achieve the maximal throughput.

T = Total processing times of the part model (in seconds).

TH = The throughput demand for the part model (parts/shift)

SH = The duration of a shift (in hours).

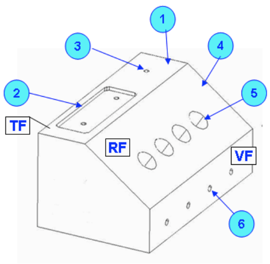
Thus,

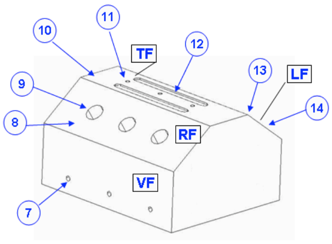
$\boldsymbol{M} = \boldsymbol{TH} * \boldsymbol{T} / (\boldsymbol{SH}*3600)$

The utilization rate of the SPMS is defined as

$$\boldsymbol{\mu} = \boldsymbol{M} / \boldsymbol{A}.$$

Because the SPMS usually utilizes multiple stages and the imbalance between stages is hardly eliminated, the actual machine quantity ***A*** is greater than ***M***. In other words, the value of $\boldsymbol{\mu}$ is between 0 and 1 ($0<\boldsymbol{\mu}<1$).





Part 1				
ID	Description	Time(min)	Time(sec)	Direction
1	Face mill the top face.	2	120	TF
2	End mill the pocket on the top face.	2	120	TF
3	Drill 3 holes on the top face.	1	60	TF
4	Face mill the right incline face.	2. 5	150	RF
5	Bore 4 holes on the right incline face.	4	240	RF
6	Drill 4 holes on the vertical face.	2	120	VF
	SUM=	13. 5	810	
Part 2				
7	Drill 3 holes on the vertical face.	1. 5	90	VF
8	Face mill the right incline face.	2. 5	150	RF
9	Bore 3 holes on the right incline face.	3	180	RF
10	Face mill the top face.	2	120	TF
11	Drill 3 holes on the top face.	1	60	TF
12	End mill the 2 pockets on the top face.	2. 5	150	TF
13	Bore 3 holes on the left incline face.	3	180	LF
14	Face mill the left incline face.	2. 5	150	LF
	SUM=	18	1080	

Figure 3 Example Part Familsy

A number of case studies are conducted to examine the relationship between the utilization rates of the SPMSs and the total number of machines of the equivalent MPMS. Figure 3 shows an example family being used. The task descriptions and process times are listed in the table on the right. It is assumed that all tasks can be performed in the same type of machine.

The following tables list the values of ***M***, ***A*** and $\boldsymbol{\mu}$ of the SPMS for each part model with different throughput demands.

Table 1 Utilization Rate of SPMS for Part 1

TH (Parts/Shift)	250	260	270	280	290	300	310	320	330	340	350	360	370	380
M	3.56	3.7	3.84	3.98	4.12	4.27	4.41	4.55	4.69	4.83	4.98	5.12	5.26	5.4
A	5	5	5	5	5	5	5	5	6	6	6	6	6	6
μ	0.7120	0.7400	0.7680	0.7960	0.8240	0.8540	0.8820	0.9100	0.7817	0.8050	0.8300	0.8534	0.8767	0.9000

Table 2 Utilization Rate of SPMS for Part 2

TH (Parts/Shift)	300	310	320	330	340	350	360	370	380	390	400
M	4.74	4.93	5.12	5.31	5.5	5.69	5.88	6.07	6.25	6.44	6.63
A	6	7	7	7	7	7	7	8	8	8	8
μ	0.7900	0.7043	0.7314	0.7586	0.7857	0.8129	0.8400	0.7588	0.7813	0.8050	0.8288

To compare with a MPMS producing both part models, the MPMS optimal design algorithm developed by the author [4] is applied to calculate the number of machines required, which are shown in Table 3.

Table 3 Number of Machines Required by MPMS

TH1 \ TH2	300	310	320	330	340	350	360	370	380	390	400
250	10	11	11	11	11	11	11	12	12	12	12
260	10	11	11	11	11	11	12	12	12	12	12
270	11	11	11	11	11	12	12	12	12	12	13
280	11	11	11	11	12	12	12	12	12	13	13
290	11	11	11	12	12	12	12	12	12	13	13
300	11	11	11	12	12	12	12	12	13	13	13
310	11	11	12	12	12	12	12	13	13	13	13
320	11	12	12	12	12	12	13	13	13	13	13
330	12	12	12	12	12	13	13	13	13	13	13
340	12	12	12	12	12	13	13	13	13	13	14
350	12	12	12	12	13	13	13	13	13	14	14
360	12	12	12	13	13	13	13	13	14	14	14
370	12	12	13	13	13	13	13	13	14	14	14
380	12	13	13	13	13	13	14	14	14	14	14

It is difficult to discover any trend or pattern from the above matrix. However, if the difference of machine quantity between two configurations is plotted on the diagram in which two coordinate axes are the utilization rates of two SPMSs, as shown in Figure 4, it can be clearly seen that some relations exist between the average utilization rate of the SPMSs and the machine quantity of the MPMS.

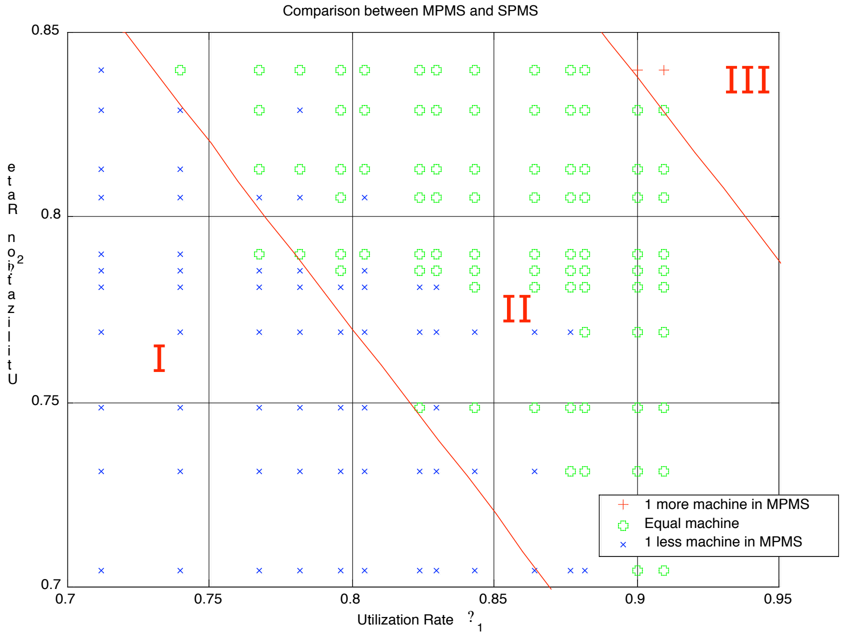


Figure 4 Utilization Rate Vs. Difference in Machine Quantity

Basically, these points are distributed in three areas I, II and III. The points of the area I refer to the MPMS that uses one fewer machine than two SPMSs do. In the area I the average utilization rate is less than 0.8. For most of points in the area II two types of systems use equal number of machines where the average utilization rate is between 0.8 and 0.85. When the average utilization rate becomes greater than 0.85 (the area III), which means both SPMSs have high utilization rates, the MPMS requires one more machine than both SPMSs (though it may be very rare).

From the pattern of the above figure, it can be derived that the higher the average utilization rate of all SPMSs, the lower possibility the MPMS will save machines (i.e. cost). And it is true conversely.

Another set of data is applied where the same part family is used (with the same part geometry and task precedence graph) except that tasks have different process times. Similar conclusions can be derived from the results of Figure 5. The only difference is that in some cases the MPMS will save up to 2 machines compared to the SPMSs.

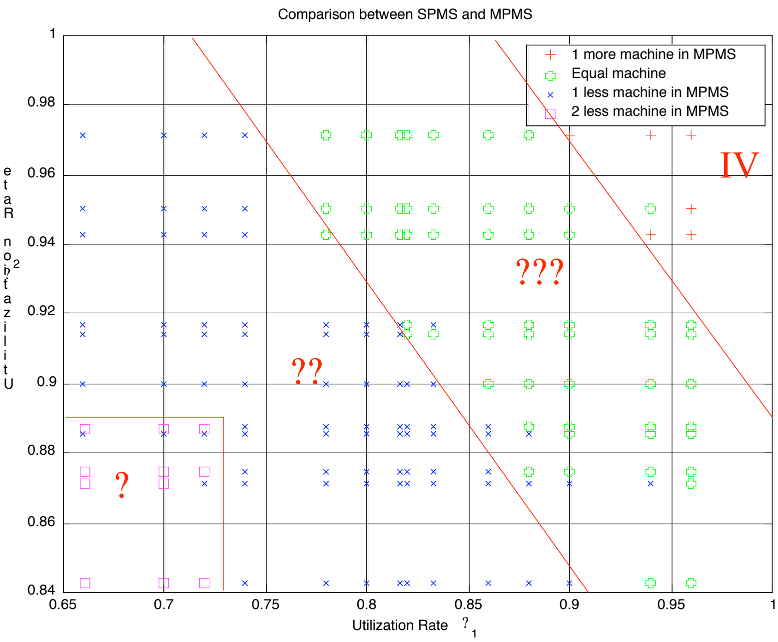


Figure 5 Utilization Rate Vs. Difference in Machine Quantity

Some selection principles are derived to justify whether or not numerous SPMSs should be replaced b a MPMS based on the value of the average utilization rate $\_a$ of the SPMSs.

Principle B-1

If $\_a$ > 0.85, the MPMS requires more machines than the SPMSs. Thus the SPMSs are more favorable.

Principle B-2

If 0.75< $\_a$ < 0.85, the two system configuration may use equal number of machines. In this situation, MPMS is a little bit beneficial than the SPMSs according to the principles in Section 2. However, further comparisons are needed.

Principle B-3

If $\_a$ < 0.75, the MPMS is preferred since most probably it save one or two machines which will cost a huge amount of investment.

The underlying rationale is intuitively straightforward. If the SPMS for a single part model has a low utilization rate, it either has a higher-than-throughput demand or has to utilize very unbalanced task allocation. The latter situation is a little more complex. Two causes may result in unbalanced task allocation: one is that the constraints of task precedence make it impossible to absolutely balance the task allocation; the other is that the aggregation of discrete task processing times can not be adjusted continuously.

If any of the situations occurs, there is potential resource redundancy (machines) in the SPMS. This resource redundancy could be reduced by combining multiple SPMSs into a MPMS to produce all part models by the same system. Then the MPMS will be more beneficial than the SPMSs. When every SPMS exploits resources fully enough by way of balancing the system with respect to its configuration, there is no more superfluous resource left for other part models. In this case combining SPMSs into a MPMS may not save any machines.

The above principles are kind of approximation but they provide the system designers a straight-forward index for justification. It is noticeable that the utilization rate of a SPMS is dependent on the task processing times and the volume demand of the part model. Given the fluctuated volume demands for a part model, the system designer has to figure out all the corresponding utilization rates and then evaluate which configuration style is better based on the average utilization rate of all the scenarios.

4 Conclusions

This paper presents a number of selection principles of manufacturing system for part family, specifically, choice between a MPMS and several SPMSs for a given part family. Although each configuration style has its own characteristic, the ultimate decision is dependant upon the monetary investment on the system to fulfill specific part mix and demands. A cost model taking into account various factors ranging from machine and material handling system cost to operating and labor cost, has been proposed to capture the cost difference between two configuration styles and derive the selection principles. Based on this model, it is concluded that with equal number of machines and buffers, the MPMS is highly probably better than the SPMSs in terms of system cost.

When the configuration of the SPMSs for the part models is known, the system designers can resort to the average utilization rate of all SPMSs to determine if a MPMS should replace the SPMSs. The utilization rate based selection principles are developed based on the results of some case studies.

Acknowledgments

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