A Method for the Configuration of Hybrid Cellular Manufacturing System

Minjie Chen, Tomohiro Murata

***Abstract*—A multi-phase comprehensive method for the design of hybrid cellular manufacturing (HCM) system is presented in this paper. The initial phase aims at categorizing parts to be produced on the cellular or the functional layout facilities of the system. Second and third phases show a mathematical approach with two inter-related models, where the first is to determine the formation of cells and the second is to eliminate the exceptional elements. Lastly the capability of the approach was demonstrated by applying it to an industrial example.**

***Keywords:* Group technology; Hybrid cellular manufacturing; Functional layout; Cell formation**

I. Introduction

The trend towards globalization and the recent world financial crisis have resulted in an increasingly competitive environment at manufacturing sector. Consequently, there have been major shifts in the design of manufacturing system using innovative concepts. Group technology (GT) is a manufacturing philosophy conceived during the 1940s in the USSR for improving productivity in batch production system [1]. Cellular manufacturing (CM) system is an application of GT in which machines of different types are grouped into cells so that each cell is dedicated to the manufacture of some specific part families [2]. CM system is known to offer several major advantages such as reduction of work-in-process (WIP), reduction of lead times, simplified flow of parts and centralization of responsibility. Therefore, the adoption of CM system has consistently formed a central element of many manufacturing systems and has received considerable interest from both practitioners and academicians [3].

However, a pure CM system is not always appropriated in practice. Several simulation studies have shown that, sometimes the use of 'traditional functional layout' can achieve better performance than a pure CM system because a functional layout is associated with high machine utilization and routing flexibility, hence more robust to changes in product mix than a pure CM system [3],[4]. It is also noticed that in practice, it is almost impossible to divide all parts and machines into independent cells, and reconfiguration of an existing facility from functional arrangement to a cellular system will involve several cost factors and inherent constraints

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[5], [6]. In addition, some special machine types those are hard to move around; make huge noises or need special working environment (e.g. furnace equipment) are better off being allocated in the functional layout. To overcome these problems, a hybrid cellular manufacturing (HCM) system is proposed to combine the benefits of cellular manufacturing systems with the flexibility of functional layouts.

Despite its widespread usage in practice, there has been very little research to date on design of HCM system, especially the analysis of categorizing parts by demand distribution pattern and stability of parts, which forms the theme of this paper. The objective of this paper is to propose a multi-phase procedure for designing HCM system in order to efficiently allocate production resources over a relatively long production planning span (one year or above). A three-phase approach is proposed for design of HCM systems: The initial phase is a classification phase for identifying which set of parts are favoured in GT-cells rather than functional layout; the second phase is a cell formation phase in which a mathematical model is developed to obtain the optimal performance of GT-cells in HCM system with consideration of minimizing both inter-cell and intra-cell material flow. The third phase tries to eliminate the exceptional elements (EE) by machine duplication or part subcontracting. An application in aircraft machine centre is provided to demonstrate the utility and possible limitations of the design.

II. Features of HCM system

The main difference between the traditional functional layout and CM system is the grouping and layout of machines. In a functional layout environment, machines are typically grouped based on their functional similarities whereas in a cellular manufacturing environment, a group of dissimilar machines that dedicated to the production of a set of parts with similar processing requirements are put together, defining that the given set of parts can be completed or nearly completed within this group of machines. HCM system can be essentially considered as a manufacturing machine centre with GT cells and a residual functional layout. The concept of HCM system is to regroup parts with high and stable demand in designed GT cells and the parts with low and unstable demand in functional layout. The very first step of HCM system design is to categorize parts. We will first review a few past research work which is dealing with the assignment of parts.

V. Figuier and H. Pierreval (2004) proposed an evolutionary programming approach for HCM system design where assignment of parts having stable demand

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is assigned in GT-cells. They defined a discrete stability index for each part type and set three levels of stability (stable, average stable and non-stable), and a penalty cost function is then applied to find the optimum solution [4].
S.I. Satoglu and N.C. Suresh (2008) conducted Pareto analysis of part demand volumes, using the idea of Pareto principle, to determine the type of parts with significant and repetitive demand. Pareto principle states that large majority of problems (80%) are produced by a few key causes (20%), therefore those high demand parts that constitute around 80% of total demand may be the potential candidates for GT-cells [5]. In the paper the part classification phase is mainly based on the Pareto analysis method considering various patterns of part demand distribution.

III. Development of the Methodology

1. Part Classification Phase

A pre-condition analysis is required to be done in part classification phase before applying the Pareto analysis method. The prediction of demand pattern of each part type, including the monthly average quantity and monthly standard deviation, based on the previous data, is essential for deciding the stability of the parts.
There are three main criteria for dividing parts into cellular and functional layouts: Demand quantity, demand distribution and variability (stability) of parts.
Demand distribution can be determined by the coefficient of variation (CV). CV measures the dispersion of part demand quantity around the mean and it is defined as the ratio of standard deviation to the mean. Distribution of a data set with CV < 0.5 is considered low-variance (evenly distributed), while the one with CV > 1.5 is considered high-variance. Different approaches will be adopted for different distribution patterns.

The variability of each part type is defined using coefficient of variation in demand (CVD), which is equal to the monthly standard deviation divided by monthly average quantity for each type of parts. Generally, a CVD threshold value of 1.2 (a CVD value of 1.2 or above depicts a rather erratic demand, therefore not efficient in GT-cells) is used to check whether those types of parts are suitable for GT-cells [7].
Three sets of data with different distribution patterns are provided in order to demonstrate the idea. All the parts are listed in order of decreasing demand and numbered from part 1 to part 20.

In case A parts are reasonably equally distributed with a CV value of 0.33. Since the distribution of 20 parts is considered low variance, it is suggested that the variability of parts should be the main factor for determining the 80% of total demand. We relist all the parts in case A in order of increasing CVD values in Fig. 1, and the demand cumulative percentage data shows that the first 15 parts with the lowest CVD values were considered to be the stable-parts.

In case B there is a smooth drop from high demand to low demand for parts considered, as shown in Fig. 2. The CV value of this data set is 1.18, which is between 0.5 and 1.5. Therefore, parts with CVD value of 1.2 or above are firstly discarded from the GT-cell group, and then the cumulative 80% of the remaining parts with highest demand, according to the Pareto analysis, are selected to be processed in GT-cell.

In case C, (Fig. 3) the CV value of this data set is 1.62 and it is noticed that only 3 out of 20 parts have extremely high annual demand and the rest are low demand products. For this kind of high variance cases, only high demand parts (Part 1,2,3) are suggested to be assigned to GT-cell, regardless of 80% cumulative demand, and low demand parts are for the functional layout. However, if the products in high demand area involve seasonal products (CVD value is greater than 1.2) then a further analysis will be conducted to check if the benefit of reconfigurating an existing facility seasonally is greater than the total machine relocation costs.

After all parts are separated into two groups, a capacity planning is then conducted to determine the total production capacity required for both cellular and functional layouts and check if the machines on hand can meet the total workload requirement.

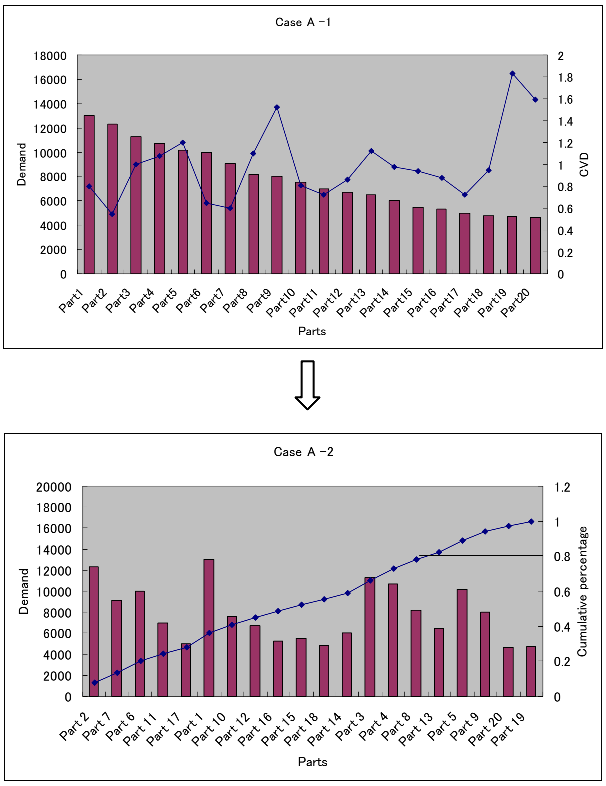

Fig. 1. Case A

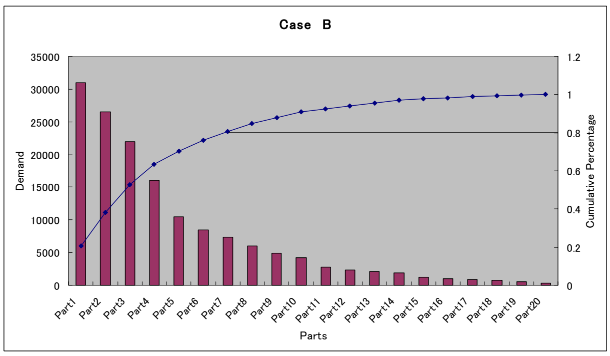

Fig. 2. Case B

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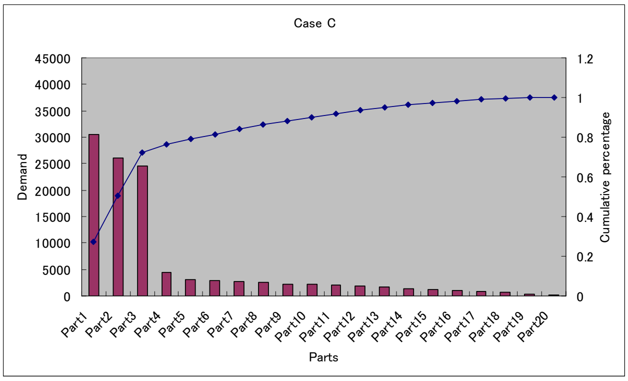

Fig. 3. Case C

2. CELL FORMATION PHASE

The next step is to group machines into cells to form the cellular part of the HCM system. The rank order clustering (ROC) technique is a traditional and easy-to-use algorithm for grouping machines into cells [8]. It works by reducing the part-machine incidence matrix to a set of diagonalized blocks that represent part families and associated machine groups, which can be called as clusters or cells. However, the ROC technique does not include part quantities; hence it is not very efficient when the demand of parts has relatively high variance.

This section presents a generalized mathematical programming approach for cell creation, machine allocation and parts assignments. This model deals with minimization of both inter-cell and intra-cell material flow as the main objective. It is considered that the intercellular movement cost $Inter_i$ only occurs when a part is going out of the cell, including finished parts being moved out to the shipping place at final step. It is also assumed that material handling costs are only related to the property of the part-i (e.g. weight of the part) but not the distance travelled. The intracellular movement cost is set to be much smaller than the intercellular movement cost. The integer nonlinear programming model for cell formation is presented below.

- **Indices**
  - i — parts
  - m — machine
  - c — cell
- **Parameters**
  - D_i — Annual forecasted demand for type-i part
  - O_{im} — Type-i part being operated on type-m machine
  - Oc_m — Operation cost needed for type-m machine (unit: hour)
  - $Maxsize_c$ — Maximum machine number constraint in each cell
  - $Mcurrent_m$ — Current number of type-m machine that is available
  - Lt_{im} — Lead time of type-i part operated on type-m machine (unit: minute)
  - Mc_m — The annual capacity of type-m machine
  - $Intrac_i$ — Intracellular movement cost of type-i part
  - $Interc_i$ — Intercellular movement cost of type-i part
- **Decision variables**
  - $Routed_{ic}$ — Type-i part routed through type-c cell
  - $Allo_{mc}$ — Allocate type-m machines to type-c cell
  - Ass_{imc} — Assign type-i part to type-m machine in type-c cell
  - $Intra_{ic}$ — Intracellular movements of type-i part in type-c cell
  - $Inter_i$ — Intercellular movements of type-i part

Mathematical model:

Minimize $$\sum_c \sum_i Intra_{ic} Intrac_i + \sum_i Inter_i Interc_i + \sum_m \sum_c Allo_{mc} Oc_m \quad (1)$$

Subject to:

$$\sum_c Ass_{imc} = O_{im} \qquad \forall i \in I, \forall m \in M \quad (2)$$

$$\sum_m Allo_{mc} \le Maxsize_c \qquad \forall c \in C \quad (3)$$

$$\sum_c Allo_{mc} \le Mcurrent_m \qquad \forall m \in M \quad (4)$$

$$\sum_i Ass_{imc} D_i Lt_{im} / 60 \le Allo_{mc} Mc_m \qquad \forall m \in M, \forall c \in C \quad (5)$$

$$Intra_{ic} = \sum_m Ass_{imc} D_i \qquad \forall i \in I, \quad \forall c \in C \quad (6)$$

$$Routed_{ic} \begin{cases} 1 & if \ Intra_{ic} > 0 \\ 0 & otherwise, \end{cases} \qquad \forall i \in I, \quad \forall c \in C \quad (7)$$

$$Inter_i = \sum_c (Routed_{ic} D_i) \qquad \forall i \in I \quad (8)$$

$$Ass_{imc} \in \{0,1\}; \ Allo_{mc} \in \text{int} \quad (9)$$

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The objective function of this model minimizes the intracellular movement cost (material movement cost occurred within cells), intercellular movement cost (material movement cost occurred between cells), as well as the machine operating cost.

Constrain (2) allocates machines into a cell to satisfy an operation. Constraint (3) ensures that each cell satisfies maximum cell size constraint. Constraint (4) ensures that each machine type satisfies maximum current machine number constraint. The number of machines available is derived from the capacity planning. Constraint (5) indicates that demand work load should be less than or equal to the available total capacity. Equation (6) determines the amount of intracellular movements of each type of part in each cell. Constraint (7) determines if part-i is routed in a certain cell and set $Routed_{ic}$ to 1 if the part-i passes through cell-c. Equation (8) calculates the intercellular movements for each type of part.

If type-i part is a high-priority part and is required to be assigned to only one cell, the following additional constraints could be added:

$$Inter_i = D_i \qquad (10)$$

where its intercellular movement cost is the cost of moving all the type-i parts from the cell to the shipping place.

3. EXCEPTIONAL ELEMENTS ELIMINATION PHASE

After an initial cell formation solution has been derived, a further improvement of the model is proposed to deal with the Exceptional Elements (EE), providing that the number of cells remains fixed.

EE is defined as bottle neck machines and exceptional parts that span two or more manufacturing cells [9]. In Fig. 4, for example, part 7 is an exceptional part and machine D is called the bottleneck machine. Since it is not common to have part families and associated machine cells completely segregated, cell formation solutions often contain EE and minimizing EE is one of the fundamental objectives in HCM system design.

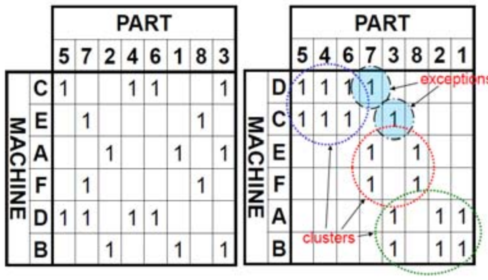

Fig. 4. Exceptional Elements in cell formation

Solutions suggested to deal with EE usually involve duplicating bottleneck machine and subcontracting the exceptional parts. Machine duplication is the most efficient way to eliminate EE, but the duplication cost, which includes the machine purchasing cost, machine maintenance cost and depreciation, is usually very high. The subcontracting is an alternative for EE elimination which is raised by Kamien and Li as an important aspect in capacity planning, and it implies that the producer can establish a long-term supplier-producer relationship for parts in long-term planning so that purchasing the exceptional parts from other suppliers is possible [10]. Shafer and Kern (1992) also mentioned that the organization may design a 'remainder cell' to which the subcontracted parts are assigned [11]. HCM system has a distinct functional layout that can accept those exceptional parts if total capacity of functional layout is not exceeded. The mathematical programming model for dealing with EE is shown as follows:

- **Parameters**
  - B_p Annual budget for purchase of new machines.
  - D_m Annual cost of duplicating a type-m machine
  - S_i Incremental cost for subcontracting/outsourcing a type-i part
  - I_i Incremental cost for moving type-i part outside of a cell as opposed to within a cell
  - C_m Annual capacity (in machine hours) of type-m machine
  - C_c Current number of machine in type-c cell
- **Decision variables**
  - X_i Units of type-i part to be subcontracted.
  - Y_{mc} Units of type-m machine to be purchased for cell c.
  - Z_{im} Units of intercellular movement needed by type-i part as type-m machine is not available.
  - M_{im} Number of type-m machines dedicated to production of type-i part.

Minimize $\sum_i X_i S_i + \sum_m Y_{mc} D_m + \sum_i Z_{im} I_i$ for all exceptional parts i in cell c (11)

Subject to:

$D_i = Z_{im} + X_i + [C_m M_{im} / (Lt_{im} / 60)]$ for all exceptional parts i and its corresponding bottleneck machine m (12)

$$\sum_i M_{im} \le Y_{mc} \quad \forall m \in M, \forall c \in C \qquad (13)$$

$$\sum_m \sum_c D_m Y_{mc} \le B_p \quad \forall m \in M, \forall c \in C \qquad (14)$$

$$\sum_m (Y_{mc}) + C_c \le Maxsize_c \quad \forall c \in C \qquad (15)$$

$$X_i, Y_{mc}, Z_{im} \in \text{int} \qquad (16)$$

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The objective function (11) accounts for the total costs associated with all exceptional parts. The constraint (12) states that total demand should equal to the sum of parts being intercellular transferred, parts being subcontracted and parts being produced in GT-cells due to duplication of the bottleneck machine. Constraint (13) ensures the number of machines purchased is greater than the number of machines assigned to the various EE found in constraint (12). The variable M_{im} in constraint (12) and (13) does not have to be an integer and this allows one machine to be shared by two or more exceptional parts in one cell. Constraint (14) states the total new machine purchasing cost is within the given annual budget. Constraint (15) ensures that adding new machines to a cell will not exceed its cell size restriction.

In this paper, two inter-related mathematical models are proposed rather than one big model, and the reasons for having two models are:

1. The second mathematical model provides a solution for resolving the inefficiency caused by EE, therefore it is better to get an initial cell formation solution that contains EE in a separated model first.
2. Less computational effort needed for solving two models rather than one big model.

IV. CASE STUDY

A hypothetical example using Boeing's Defense and Space Group (D&SG)'s machining centre as prototype is provided in order to demonstrate the utility of this methodology. The Machining Centre only supports commercial programs. Commercial customers place orders for parts up to two years in advance at a known rate, therefore there is little uncertainty in the demand. However, the center is also expected to produce parts for AOG's (Airplane On Ground) and replenishment spares, thus this kind of emergent production occurs from time to time [12].

Fig. 5 and 6 show the predicted annual demand, cumulative percentage of demand and CVD of 20 types of parts that are expected to be manufactured at this machine centre in the coming year. Since the CVD values for high demand part are not so large, the decision maker is suggested to conduct the Pareto analysis referring to Case B as discussed in phase 1. The first 6 parts with a cumulative percentage of demand of 78.51% are selected to be produced in GT-cells, as shown in Fig. 6.

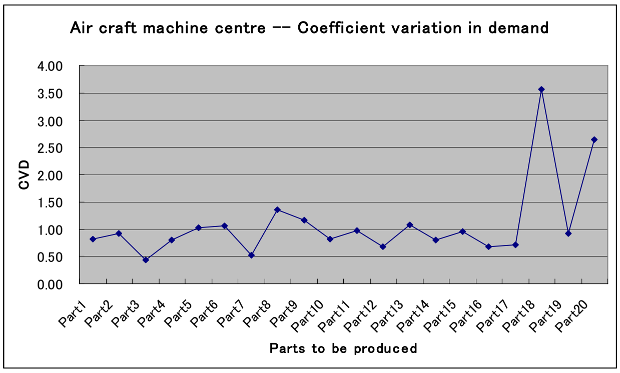

Fig. 5. Coefficient variation in demand for parts

There are six types of machines: 3 axis numerically controlled (NC) machine, 5 axis NC machine, manually operated sawing, drilling and milling machines and manual deburring system. The process routing sequence for each part is defined as: Parts should start their routing at a NC machine, then go through some conventional operations (saw, drill and mill) before reaching the deburring station [12]. A capacity planning is carried out to determine the total number of machines required and number of machines needed at functional layout side. The number of machines remained are the maximum machine number constraint (input parameter) for the cell formation model and the results are shown in Table 1.

Table 1: Proposed solution for machine allocation in capacity planning

Machine	Total required	Total on hand	Purch ased	Functional layout	Input for model
3-NC	5	5	0	1	4
5-NC	5	4	1	1	4
Saw	4	5	0	1	4
Drill	7	8	0	2	6
Mill	5	7	0	1	5
Deburr	6	6	0	1	5

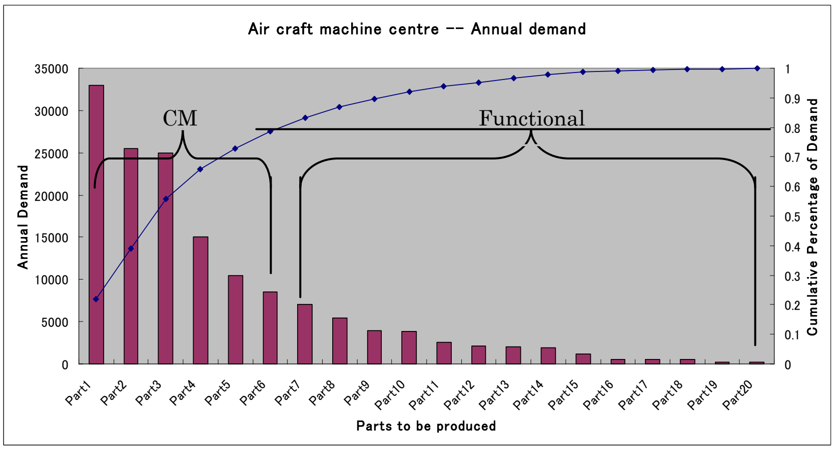

Fig. 6. Part classification result

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Table 2: Machine-part matrix for part 1 to part 6

Machine	Part1	Part2	Part3	Part4	Part5	Part6	Mc_m	Oc_m
3-NC	5		5				1500	3000
5-NC		8			8	8	1500	3000
Saw		6	6	6			2000	1500
Drill		7	7	7	7		2000	700
Mill	8				8		1800	700
Deburr	5		5	5	5	5	1800	1000
D_i	33000	25500	25000	15000	10500	8500		
$Intrac_i$	0.1	0.1	0.1	0.1	0.1	0.1		
$Interc_i$	0.6	0.65	0.55	0.9	0.6	0.6		

The next step is to allocate machines and assign parts. Table 2 corresponds to a machine-part matrix with lead time and other necessary data for the six selected GT-cell candidates. The maximum number of cells is set to four, with up to seven machines in each cell.

The mathematical model developed in phase 2 was solved by the LINGO 11 using global solver with respect to the presented parameter setting in Table 1 and 2. The solutions are shown in Table 3 and Table 4.

Table 3: Results for numbers of machines assigned

Machine	Cell 1	Cell 2	Cell 3	Cell 4	Functional
3-NC	2		2		1
5-NC				4	1
Saw		3	1		1
Drill		3	1	1	2
Mill	3			1	1
Deburr	2	1	1	1	1

Table 4: Proposed cell formation with exceptional elements

Machine	Part1	Part2	Part3	Part4	Part5	Part6	D_m
3-NC	●		○				10000
Mill	●				●		7000
Deburr	●		○	●	●	●	7000
Saw		●	●	●			6500
Drill		●	●	●	●		6000
5-NC		○			●	●	15000
S_i	0.9	1	0.6	1.2	0.9	0.85	
I_i	0.5	0.55	0.45	0.8	0.5	0.5	

In Table 4, all the parts have been grouped into four cells. The black dot represents a single operation in the cell and the hollow dot represents EE. Part 2 and part 3 are the exceptional parts and 5-NC, 3-NC and Deburr are the bottleneck machines. An attempt to minimize EE was done by using the model developed in phase 3, and the results are presented in table 5.

Table 5 shows that the exceptional element part 2 remains unchanged. And for exceptional element part 3, 3400 parts are subcontracted and the rest remains intercellular moves. It is noticed that the subcontracted cost is usually greater than the intercellular movement cost, therefore subcontracting only occurs when multiple bottleneck machines are corresponding to a single part type. No intercellular moves are eliminated by machine duplication because the cell size constraint prevents the cell from accepting new machines. The total cost saved by EE elimination is 1020.

In the example, the total number of cells and the cell size constraint were pre-determined by the decision maker. A further investigation has revealed that increase $Maxsize_c$ (cell size) of one or multiple cells will result in a decrease in total cost. However, there is a tradeoff between maximum cell size and intracellular movement distance, that is, if the maximum number of machines in each cell increases, the intra-cell material movement cost should increase accordingly. Otherwise all machines would just be allocated in one large cell and the whole system would become a functional layout system. We could add a penalty cost to intracellular movement cost when relaxing the cell size constraint and the penalty cost should be somehow proportional to the cell size. Alternatively, a goal programming can be adopted with the cell number and cell size set as soft constraints, which gives decision makers more flexibility.

Table 5: Results for EE elimination

Exceptional Parts (Bottleneck Machine)	Intercellular moves	Intercellular moves eliminated due to subcontracting	Intercellular moves eliminated due to machine duplication	Intercellular moves remained
Part 2 (5-NC)	25500	0	0	25500
Part 3 (3-NC)	25000	0	0	21600
Part 3 (Deburr)	3400	3400	0	0

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V. Discussion and Future Work

By adopting HCM system, total costs could be decreased for this aircraft machine centre because the part travel distance and queuing time are greatly reduced in GT-cells. The majority of the quality problems caused during the manufacturing could also be identified and corrected much faster due to the close proximity of the working environment in GT-cells. In addition, by being responsible for several operations in the production of a part, cell operators are not only more aware of the root causes of defects, but also develop a sense of ownership facilitating quality improvements, self-discipline and trust in the process. On the other hand, the existence of functional layout can increase the flexibility of the system by absorbing unexpected events or responding to emergencies like AOG's. The complexity of job shop scheduling is also being considerably reduced and thus overall system efficiency can be improved.

In future studies, a sensitivity analysis with respect to changes of cell size will be conducted to observe the effect of changing cell size on overall system performance. A method for transforming the current system into a hybrid system, which involves substantial machine relocation costs, should also be considered for HCM system implementation.

LINGO software is efficient to deal with the medium-sized cell formation problems. With the use of global solver, LINGO will give us an optimal solution that a heuristic procedure cannot guarantee. However, for some large-scale problems (more than 20 parts), the global variable limitation and running time will cause some difficulties for LINGO. For those big models, a heuristic approach appears to be a promising alternative.

VI. Conclusions

Converting a traditional functional layout system or a pure cellular manufacturing system into a hybrid cellular manufacturing system may be more viable and cost-efficient for many types of manufacturers. This paper presented a three-phase comprehensive approach for the configuration of HCM system. In part classification phase, three factors (demand quantity, demand distribution and stability of parts) were considered for dividing parts into cellular and functional layouts. It is followed by a mathematical programming approach, which targets the minimization of both intracellular and intercellular material handling costs and EE elimination for the cellular part of the HCM system. The result obtained in EE elimination phase was not very satisfactory due to the cell size constraint. In future studies, a constraint relaxation method for the further elimination of EE could be pursued (e.g. changing the maximum cell size), a method for transforming the current job shop into a HCM system could be developed and a heuristic method for large-sized problems using the current mathematical models could be explored.

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