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Multi plant cellular manufacturing design within a supply chain[*]

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Abstract

In this paper, we consider the problem of integrating multi plant cellular manufacturing design simultaneously with supply chain design. The supply chain consists of a number of plant facilities to manufacture a variety of parts with deterministic demands. Raw material can be procured from alternative suppliers. Traditionally, cellular manufacturing systems are designed on a single manufacturing facility. Also, design of supply chains are analysed without considering the suitable manufacturing plant design. A one period non linear model is proposed to design a supply chain where the multi plant manufacturing system is configured as a cellular manufacturing system subject to supplying process selection. Aiming to demonstrate the potential benefits of such design, illustrative examples are shown using a proposed linearized form of the problem. Cplex software is thus used to solve three sets of small sized problems demonstrating the potential benefits gained through increasing routing flexibility over plants on investment costs and the effect of integrating supply process in a multi plant cellular manufacturing configuration.

Keywords: Multi plant Cellular manufacturing, Supply chain management, flexibility, mathematical modeling

1. Introduction

Supply chain (SC) analysis involves the integration of different functions (e.g. purchasing, production, distribution), through where the products flow to satisfy effectively the customers. The main objective of a supply chain design is to determine its structure namely the location decision of the manufacturing plants, the assignment of products to plants, the distribution channel options and supplying process decisions. It has been realized that separated analysis of the different processes is not sufficient. Thought, to achieve efficient supply chain management, an effective design and integration of the supply chain is critical to reduce costs. Nowadays, parts or components for products may be produced in different networked manufacturing plants.

The performance of the manufacturing plants is tightly dependant with configuration decisions. In batch manufacturing, cellular design has known a broad implementation in industry. Cellular Manufacturing System (CMS) design is an application of group technology s recognised to offer performance in shorter delivery time, wider range of manufactured parts, shorter set up times, reduced throughput times, reduced work- in-process inventory and material handling, and of course lower production costs [3] , [18]. CMS design is realized at first

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with the identification of part families and independent machines cells. Each part family should be manufactured entirely in a machine cell. However, in real manufacturing world, parts may be processed in more than one cell. In fact**,** if the cells are to be located in a single manufacturing plant, the steps of the process of design of the corresponding supply chain may be conducted independently: identification of part families and machines cells, raw material supplying process decisions and distribution channels choices. The cells will behave as small manufacturing plants. This integrated SC design will contributes evidently to fasten delivery time and reduce inventory, with regard to the outbound part flows and reduce the global design cost in its corresponding supply chain. However, constraints on supply process may affect the operation and the performance of the CMS and in turn the entire supply chain.

Though, if the cells can be located in at least two different manufacturing plants, to preserve CMS advantages, especially levelling inventories and delivery time, the cellular manufacturing design should not be addressed independently with supplying process and distribution decisions; supply costs and constraints on supply process may affect the operation and the performance of the CMS and in turn the entire supply chain. The whole design process must create a balance between the cellular design cost in the different plants, supplying cost and distribution cost

Additionally, this balance may be created in managing inventory levels for product items (reducing inventory levels and stockout) through all the plants considered as an integrated cellular manufacturing system. Such design questions arise in both situations of investing in a new supply chain of known manufacturing plants or upgrading existing supply chain with cellular design of manufacturing plants.

Based on the above analysis, in this paper our objective is to demonstrate the utility of the integration of manufacturing configuration in the supply chain design process. We develop a cost based mathematical model to design a supply chain where the multi plant manufacturing system is configured as a cellular manufacturing system subject to supplying process selection. The manufacturing design parameters cope with real–life production as processing operation time, routing flexibility, quality issues at the manufacturing phase, capacity resource limits and also machine availability.

This paper is organised as follows: Section 2 gives a literature review on cellular manufacturing design, supply chain design and the integration of t , section 3 presents the developed model for a multiplant CMS design integrated with supplying process. In section 4, three set problems of illustrative examples are shown through experimentation based on a proposed linearized form of the model. Finally, a conclusion is given in section 5.

2. Literature review

2.1 Cellular manufacturing design

In the literature, various approaches are proposed and attempted to consider practical design parameters. Berardi et *al* [4] evaluated alternative cluster formulations based on Shafer et *al* mathematical model. Three strategies were used to eliminate exceptional elements, namely duplicating machine, intercellular moves and subcontracting. Taboun et *al* [18] proposed methods for developing part family and machine cell configuration to handle manufacturing system configuration or new system design. Their procedures take into account machine and intercell handling cost as well as subcontracting costs to obtain better utilized cells. First, a developed heuristic is used to form the machines cells and part families, the result of the heuristic is then integrated in a mathematical model to optimize the various design costs. Beaulieu et *al* [3] considered machine capacity, alternative routing and constraints on cell size. The authors proposed a two phased approach : formation of independent cells then introduction of intercell flow to optimize machine investment cost. To solve the same problem, Jayaswal and Adil [10] proposed a methodology comprised of simulated annealing and local search heuristics.

In the last ten years, another practical parameter design in cellular manufacturing design has gained attention shown in the design dynamics. Thus, dynamic CMS was addressed in a number of research papers [20] and [2]. Among these, Tavakkoli et *al* [20] proposed metaheuristics. to solve cell formation problem considering routing flexibility, machine flexibility and machine relocation cost. Balakrishnan et *al* [2] addressed the problem of CMS in a multi period horizon, dynamic programming is used to select the best cell configuration minimizing the sum of the shifting and material handling cost within the plan horizon. Recently, Jeon et al [11] developed a new methodology based on a new similarity coefficient which integrate routing flexibility during machine failure, and demand changes for multiple periods. The methodology is implemented in two sequential phases: identification of part families and machine assignment to part families using sequential and simultaneous cost based mixed integer programming models and considering the scheduling and operational aspects in cell design under demand changes.

All the researches on cellular manufacturing design are conducted on a single plant facility. However, in supply chain environment, multiple plants may interwork to manufacture parts and in turn different cells in different plant locations may contribute to satisfy a part demand.

2.2 Supply chain design

The manufacturing system acts as a major component with regard to suppliers and distributors. The integrated components form a supply chain. As a strategic issue, supply chain design aims to provide an optimal platform for efficient and effective management of these integrated components. The key issues considered in a supply chain design (SCD) are: the manufacturing strategy, the supply base design and the distribution strategy. Effective design and management of supply chains aims to deliver product at a low cost and short lead time. The challenge is to determine the number, location, capacity of production and distribution facilities. Over the last ten years, different researches has been conducted in supply chain design [8], [9],[19]. Originally, Arntzen et *al* [1] addressed the problem of worldwide supply chain management in Digital Equipment Corporation. The authors proposed a model which integrates production costs, inventory charges and distribution expenses. Their model determines alternative supply chain structures to meet estimated demand for multiple parts.

Goetschalckx et *al* [8] considered the production distribution design problem a*nd* proposed a mixed integer linear program methodology which integrates strategic and tactical decisions rather than in a hierarchical fashion. Especially, for the production stage, alternative manufacturing lines are considered which differ by their technology and capacity. The resource requirement and the marginal cost for manufacturing a particular product on a particular production line are known. Paquet et *al.* [12] introduced technology selection in the design of a manufacturing network. The proposed methodology aim to define the optimal structure with selected technology and capacity for each facility using Bender`s decomposition. Talluri and Baker [19] developed a multi-phase mathematical programming approach for effective supply chain design based on a combination of multi-criteria efficiency models and linear and integer programming methods.

Recently, a research of Park [13] proposed an integrated approach for production and distribution planning regarding production details as processing and set up time of manufactured items. Chauhan and Proth [5] addressed the problem of supply chain design when production/distribution of a new market opportunity is considered. The authors proposed a large-scale mixed integer linear programming model to address the strategic capacity planning in a three staged supply chain for a new market opportunity. To meet the deterministic customer demand at a minimal cost, production capacity and transportation limits are considered through the three stages.

Graves and Whilem [9] addressed how to configure the supply chain for a new product with multiple options of raw material suppliers, various choices of manufacturing and different transportation modes to the customer. A cost based dynamic model was proposed to select a supply chain configuration with a minimal total cost.

Some research has stressed the relationship between cellular manufacturing and supply chain. Samatova et *al* [17] proposed a generalized approach to group parts based on the similarity of their operation sequence from a broad set of part manufacturers rather than grouping parts based on a single manufacturing floor, to optimize the efficiency of the entire supply chain. Poornachandra Rao and Mohanty [15] investigated the impact of CSM design on SCD decisions and described the interrelationship between the two approaches through an illustrative example. However, no framework model was proposed to integrate cellular manufacturing design and supply chain issue. More recently, the inter factory linkage flexibility was investigated by Ferdows and Carabetta [7]. The authors examined the nature of the relationship between inter-factory linkage flexibility and the levels on inventories and backlogs in integrated process industries. A simulation approach was used to demonstrate that increased flexibility reduces inventory levels for parts through increasing the inter-factory linkage flexibility than investing in extra capacity

All the supply chain design models currently available consider that the alternative plants have known configurations. Additionally, the classical design process of a CMS is conducted in a single facility. In practice, a dominant partner in a supply chain may own a number of plants and desire to optimize their configuration simultaneously to respond to a market demand. Considering basically alternative routing plans for parts into only a plant, the value added by inter plant flexibility will contribute to minimize under utilized machines. So, the integration of multiple production systems in a simultaneous CMS design will promote savings in global design cost, give planning flexibility and allow improvement in throughput rates. Such problem has never be met in literature.

In summary, the literature on cellular manufacturing design is focused essentially on single production plan, none of the existing methodologies considered the implication of cellular design of manufacturing system over multiple plant locations and moreover if integrated with raw material supplying process. Therefore, there is a need to analyse a supply chain, in terms of multiple manufacturing plants to be connected to suppliers.

Since cell design is part of designing a manufacturing system and the system is expected to stay for a long duration of time, even a small improvement in overall investment design cost can be valuable over the life of the manufacturing system. Thus, there is a need to demonstrate the potential benefits of multi facility cellular manufacturing design on the supply chain structure. However, such features exist in real world manufacturing. Based on the above analysis, in this paper, our objective is to develop a cost based mathematical model to design a supply chain where the multi plant manufacturing system is configured as a cellular manufacturing system subject to supplying process selection. The design parameters cope with real–life production as processing operation time, routing flexibility, quality issues at the manufacturing phase, capacity resource limits, machine availability and supply process costs and constraints.

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3. Problem description

The challenge is to develop a framework which allows the simultaneous optimization of production facilities and supplier selection process. It is clear that such a model and solution methodology can yield significant savings for a corporation seen as the dominant partner in a supply chain, likely to be linked to alternative suppliers to satisfy market demand in several customer zones. Figure 1 illustrates the structure of this supply chain with a manufacturing system split in multiple plants.

The production system consists of a number of plants which will produce multiple parts. Each part requires one raw material. Annual part demand is assumed deterministic. Thus, machine capacity is limited yearly. Routing flexibility is considered namely each part operation can be completed on alternative machines with different processing times and different reject rates. For each operation on a part, a variable cost is incurred. There is no storage capacity at the plants. The splitting of demand between machines is not allowed.

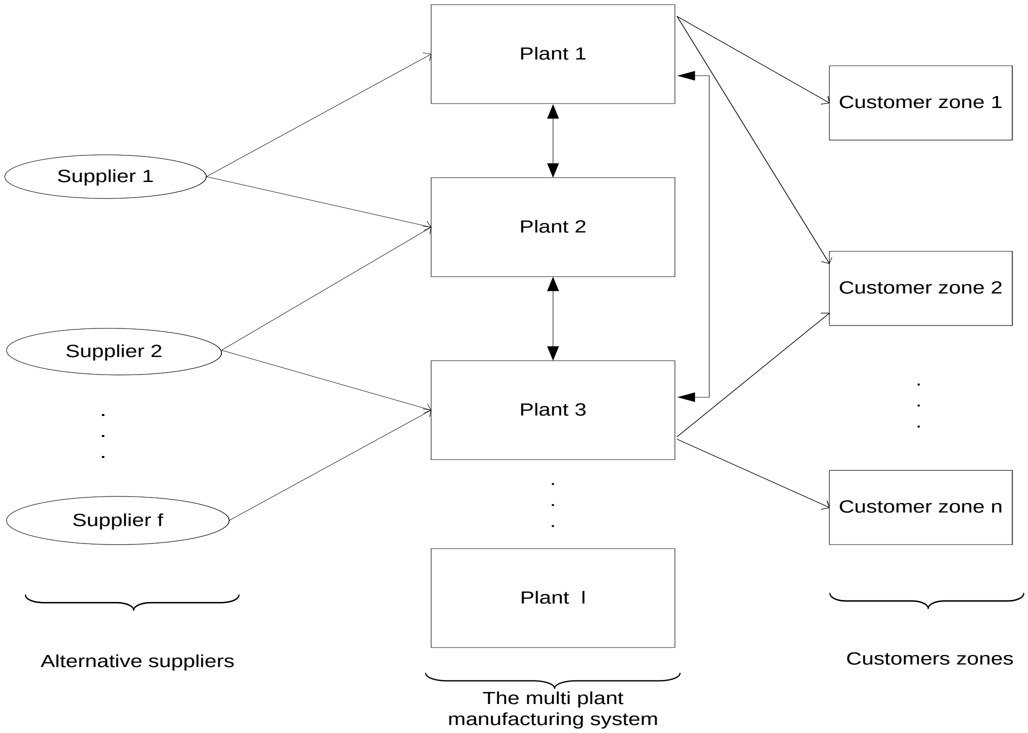

Fig. 1 Supply chain structure

The developed mathematical model aims to define simultaneously the cellular manufacturing structure at each plant, the flows between plants and optimize the flows between suppliers and production plants. The model identifies:

- Part families and machines cells for each plant ,
- Flows between plants

- Selection of suppliers from a set of raw material suppliers
- Flows between suppliers and production plants.

3.1 Notations

Before formulating the model, we define the problem parameters and decision variables as follows

$i \in I$, a set of parts

$j \in J$, a set of manufacturing plants

f Index of suppliers

m Index of machine type

l Index of manufacturing plant

c Index of production cells

NP Number of parts

NO_i Number of operations of part i

NL Number of manufacturing plants

NC Number of manufacturing cells

NF Number of suppliers

NM Number of machine types

D_i Annual demand for part i

DO_{ij} Annual demand for operation j on part i

$$DO_{ij} = \frac{D_i}{\prod_{k=1}^{NO_i}(1-R_{ik})}$$

t_{ijm} Process time to complete operation j on part i on a candidate machine m

R_{ij} Reject rate of operation j on part i

B Batch size for inter plant and inter cellular flow

MNB_{mcl} Number of machine of type m in cell c of plant l

MFC_m Annual fixed cost of machine type m

MVC_m Annual variable cost of machine type m

fc_f Operation fixed cost of supplier f

vc_{ilf} Variable cost integrating purchasing and transportation of raw material for part i from a candidate supplier f to a plant l

ISC Transportation cost of a batch between two production plants

ICC Material handling cost for a batch transferred between two cells.

CF_{if} Supplier f capacity for raw material needed for product i

a_{ijm} =1 if a machine of type m can be used to process operation j on part i , = 0 otherwise.

3.2 Decision variables

MNB_{mcl} number of machine type m to purchase for cell c in production plant l

OP_{ij}^{mcl} a 0-1 variable indicating whether operation j on product i is performed on machine m of cell c of the production plant l or not

YF_f a 0-1 variable indicating whether supplier f is selected or not

Y_{if} a 0-1 variable indicating whether material of product i is supplied from supplier f or not

WF_{ilf} total units of material for product i supplied from supplier f to production plant l

3.3 The objective function

The objective function (1) is a nonlinear integer equation. The objective function expresses the total cost of the multi plant cellular manufacturing within a supply chain. It consists of two types of cost which are interrelated and could be conflicting. First, the total production cost in all production plants is split on fixed machine costs, variable machine costs, intercellular flow costs and total cost of flow between plants when machine resources are shared. The inter plant flow state that manufacturing operations is also enabled if machine capacity is available in other plants. A fixed transportation cost per batch is assumed. This inter plant linkage increases operation routing flexibility and tends to minimise under utilized machines. A linear cost is assumed to inter plant or intra plant flow and therefore optimise the total cost of supply chain design

Second, total supply costs including fixed ordering cost and flow cost between selected suppliers and all production plants.

3.4 The constraints

Constraint set (2) ensures that each operation on a part is completed on only one machine type, in one cell and in one plant. Constraint sets (3) and (4) limit the lower and the upper number of machines in a cell. Constraint set (5) allows to design cells with realistic availability machine percentage. For flows between suppliers and plants, supplier selection, constraint set (6) is specified. Binary and integer restrictions on the decision variables are enforced through constraint sets (7).

Specific constraints may be added such as space floor, budget at each plant, overall budget, the balance of the number of machines in each plant, or a constraint avoiding backtracking flow between plants.

For a supply chain with a single facility and alternative suppliers, the problem can be decomposed in two independent problems. The first aims to design the cellular manufacturing system for the facility plant, the second aims to select raw material suppliers with a minimum purchasing and transportation cost.

For a supply chain with multiple plants allowing sharing production capacity, the problem of determining parts families, machine cells and supplier selection must be regarded simultaneously.

In the particular case of no cross flows between plants, the problem still not analysed in literature, however, it will analyse the best location of cells with regard to the integration of the supplier echelon in the supply chain design.

3.5 The mathematical model

$$
\begin{aligned}
&Min \left(\sum_{\mathrm{l}=1}^{\mathrm{NL}} \left(\sum_{\mathrm{c_l}=1}^{NC} \left(\sum_{m=1}^{NM} \left(MNB_{mcl} * MFC_m + \sum_{i=1}^{NP} \sum_{j=1}^{NO} OP_{ij}^{mcl} * MVC_m \right) \right) \right) \right) \\
&+\frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO} ICC \cdot \left\lceil \frac{DO_{ij}}{B} \right\rceil \cdot \sum_{l=1}^{NL} \sum_{c=1}^{NC} \left| \sum_{m=1}^{NM} OP_{ij}^{mcl} - \sum_{m=1}^{NM} OP_{i,j+1}^{mcl} \right| \\
&-\frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO} ICC \cdot \left\lceil \frac{DO_{ij}}{B} \right\rceil \cdot \sum_{l=1}^{NL} \left| \sum_{m=1}^{NM} \sum_{c=1}^{NC} OP_{ij}^{mcl} - \sum_{m=1}^{NM} \sum_{c=1}^{NC} OP_{i,j+1}^{mcl} \right| \\
&+\frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO} ISC \cdot \left\lceil \frac{DO_{ij}}{B} \right\rceil \cdot \sum_{l=1}^{NL} \left| \sum_{m=1}^{NM} \sum_{c=1}^{NC} OP_{ij}^{mcl} - \sum_{m=1}^{NM} \sum_{c=1}^{NC} OP_{i,j+1}^{mcl} \right| \\
&+\sum_{f=1}^{NF} \left(fc_f \cdot YF_f + \sum_{i=1}^{NP} \sum_{l=1}^{NL} WF_{ifl} \cdot WW_{i1l} \cdot vc_{ifl} \right)
\end{aligned} \tag{1}
$$

Subject to

$$\sum_{l=1}^{NL} \sum_{c=1}^{NC} \sum_{m=1}^{NM} a_{ijn} * OP_{ij}^{mcl} = 1 \qquad \forall i, j \tag{2}$$

$$\sum_{m=1}^{NL} MNB_{mcl} \geq ll \qquad \forall c, l \tag{3}$$

$$\sum_{m=1}^{NL} MNB_{mcl} \leq uu \qquad \forall c, l \tag{4}$$

$$\sum_{i=1}^{NP} \sum_{j=1}^{NO} DO_{ij} \cdot t_{ijm} \cdot OP_{ij}^{mcl} \leq cap_m \cdot MNB_{mcl} \qquad \forall m, c, l \tag{5}$$

$$
\begin{aligned}
&\sum_{f=1}^{NF} Y_{if} = 1 && \forall\ i \\
&\left(NP \cdot YF_f - \sum_{i=1}^{NP} Y_{if} \right) \geq 0 && \forall\ f \\
&\sum_{l=1}^{NL} WF_{inl} \leq\ CF_{in} * Y_{in} && \forall i, f
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
&OP_{ij}^{mcl} \ \text{boolean} && \forall i, j, m, c, l \\
&Y_{if}, Y_f \ \text{boolean} && \forall i, f \\
&MNB_{mcl} \ \text{integer} && \forall m, c, l \\
&WF_{ifl} \ \text{integer} && \forall i, f, l
\end{aligned} \tag{7}
$$

4. Solution approach and illustrative problems

The objective function (1) has a nonlinear form because of absolute terms and polynomial terms. Using existing linearization techniques, additional variables and constraints are introduced to obtain a mixed integer linear problem, presented in appendix. The problem still NP-hard. To solve illustrative examples, CPLEX software (Cplex 9.0) is selected to allow an analysis of the results of the multi plant CMS design.

The following examples illustrate the developed model. The results are analysed through three set problems. In these examples, we assume the same number of operations for all parts to manufacture and a null reject rate when processing operation. The number of operation routing on a part is at most four. Alternatives routing for an operation is at most two. The model is also specified by a balance of the number of parts assigned to plants. We evaluate the potential benefits gained through linked CMS plants integrating raw material supplying process, achieved with routing flexibility inside and outside the first plant visited. Numerical data are based on extensions of data examples gathered from cell design literature.

In the first set problems, the supplying process is ignored, so the proposed model is solved for a manufacturing system composed of 2 plants. The multiplant manufacturing system should be designed to manufacture 8 parts using 10 machine types. A limit of two cells at each plant is considered. The lower and upper bound of the number of machine at each cell respectively are 2 and 10. Material handling cost is fixed to 20 for intercellular flows and 60 for interplant flows. Tables 1 and 2 present data for problem 1. Table 3 shows through the first problem a summary comparison between independent multi plant facility cell design and linked multi plant cell design, using different performance measures. In the first design, no inter plant flow is allowed, as shown in table 6, in other words, sharing capacities between plants is not allowed. In the second one, manufacturing operations on parts can be completed using more than one plant with an additional cost called inter plant transportation cost, which is revealed in table 7. The second multi plant CMS design gives a saving of 2 machines and an improvement in overall average machine utilisation rate (AMU) (49.1 %) compared with separated CMS plant design (41.66 %). Besides that, the two configurations have totally different configurations: the part families and the respective machine cells are dissimilar except for cell 2 in plant 2 which is preserved, as presented in tables 4 and 5.

Table1

Parts demand and operation requirements

Part, i	Part demand,	Operation, j	No of alternatives	Machine type m, t_{ijm} (h)
P1	3900	OP11	1	M10 (0.47)
		OP12	2	M5 (0.7),M8 (0.65)
		OP13	1	M2 (1)
		OP14	1	M7 (0.92)
P2	2980	OP11	1	M10 (0.33)
		OP12	1	M4 (0.75)
		OP13	1	M1 (0.5)
		OP14	1	M2 (0.78)
P3	2700	OP11	1	M3 (0.13)
		OP12	2	M2(1),M4(0.55)
		OP13	1	M1(0.5)
		OP14	1	M6(0.93)
P4	2990	OP11	1	M3(1.05)
		OP12	1	M3(0.62)
		OP13	1	M3(0.52
		OP14	1	M1(0.54)
P5	2000	OP11	2	M5(0.35),M8(0.2)
		OP12	1	M4(0.63)
		OP13	1	M5(0.89)
		OP14	1	M3(0.92)
P6	2400	OP11	1	M3(0.13)
		OP12	2	M2(1),M4(0.25)
		OP13	1	M1(0.5)
		OP14	1	M6(0.73)
P7	2500	OP11	1	M3(0.23)
		OP12	2	M2(1),M4(0.65)
		OP13	1	M1(0.7)
		OP14	1	M6(0.73)
P8	2450	OP11	1	M3(0.33)
		OP12	2	M2(1),M4(0.65)
		OP13	1	M1(0.7)
		OP14	1	M6(0.73)

Table 2
Resource data

Machine type	Annual fixed cost	Capacity
M1	52640	7000
M2	62800	7000
M3	42600	7000
M4	72600	7000
M5	52550	7000
M6	52640	7000
M7	62800	7000
M8	42600	7000
M9	72600	7000
M10	52550	7000

Table 3
Some performance measures of multi plant cell design (Independent plants, linked plants)

Performance measures	Independent plants	Linked plants	Improvement (%)
Overall cost	2904749.2000	2825829.2000	2.71
Fixed machine cost	842060.0000	756860.0000	10.1
Variable and fixed machine cost	2900989.2000	2815789.2000	2.9
Number of machines	16	14	12.5
Intercellular cost	3760	5900	
Number of intercellular flow	4	5	
Interplant cost	0	4140	
Number of interplant flow	0	2	
Overall AMU (%)	41.66	49.1	6.6

Table 4
Average machine utilisation per cell in multi plant cell design with independent plants

	Plant 1		Plant 2	
Cells	Cell 1	Cell 2	Cell 1	Cell 2
Parts	5,6	4,7	3,8	1,2
Machines	3,8	1,3,4,5,6	1,3,4,6	2,7,8,10
AMU (%)	3.65	56.9	54.7	51.4

AMU %: Average Machine Utilisation percentage

Table 5
Average machine utilisation per cell in multi plant cell design with linked plants

	Plant 1		Plant 2	
Cells	Cell 1	Cell 2	Cell 1	Cell 2
Parts	3,7	4,6	1,2	5,8
Machines	1,3,4,5,6	3,6	1,4,10	2,3,7,8
AMU (%)	64.4	37.4	46.9	47.7

Table 6
Multi plant cell design with independent plants (intercellular flows allowed)

Plant	Cell	Machine type /#	Parts							
			5	6	4	7	3	8	1	2
1	1	3	1							
		8		1						
	2	1		1	1	1				
		3(2)	1		1	1				
		4	1	1		1				
		5	1							
		6		1		1				
2	1	1					1	1		1
		3					1	1		
		4					1	1		1
		6					1	1		
	2	2							1	1
		7							1	
		8							1	
		10							1	1

Table 7
Multi plant cell design with linked plants

Plant	Cell	Machine type/ #	Parts							
			3	7	4	6	1	2	5	8
1	1	1	1	1	1	1				
		3	1	1	1				**1**	
		4	1	1		1			**1**	
		5							**1**	
		6	1	1						
	2	3			1	1				
		6				1				**1**
2	1	1						1		1
		4						1		1
		10					1	1		
	2	2					1	1		
		3					1			1
		7					1			
		8							1	

We further illustrate the model using nine other examples. The data of these examples are generated by an extension of data of problem 2. The common data are: two manufacturing plants, two cells for each plant. The variable data do not follow any particular pattern and concerns the features cited below.

- Intercellular cost and interplant cost;
- Number of parts;
- Number of machine types;
- Number of operations per part;
- Part demand.

A summary of the impact of sharing machine capacity between plants on the objective cost and the total number of machine obtained for these problems is given in table 8. The last column of this table shows the increments of the objective function varying from 0 % to 8.5%, demonstrating the potential benefit of allowing operation flexibility between plants. This benefit, if occurred, is also confirmed by decreasing the total number of required machines to satisfy the annual demand. Such manufacturing design system can be challenging to improve customer delivery time when variability of demand occurs.

Table 8
Impact of interplant flows on the objective function value and the machine requirements

			Independent plants		Linked plants		
Problem no	Number of parts	Number of machine types	Total design cost.	Machine requirements	Total design cost	Machine requirements	Improvement (%)
2	6	10	578521.5533	10	529481.5533	9	8.5
3	6	10	578521.5533	10	531881.5533	9	8.06
4	8	10	676966.6533	12	637106.6533	11	5.8
5	8	10	676966.6533	12	638306.65	11	5.7
6	8	10	956380.3533	17	956380.3533	17	0
7 *	12	10	1570587.6467	27	1538735.9800	26	2.03
8	12	5	513702.4000	14	508559.9500	12	1.0
9	13	5	608998.0833	14	606411.0667	12	0.4
10	13	5	608998.0833	14	601426.0833	12	1.24

* Results of a feasible solution

A second set of problems are run using the complete mathematical model detailed in section 3, namely the supply chain under study consists of two alternative raw material suppliers for a two plant manufacturing system which should satisfy a known demand.

Table 9 shows summarized results for eight problems. The fourth column shows simultaneously the objective function value and the supply cost. The last column gives the improvements occurred of the objective function value and the supply cost respectively. As can be seen from the table, the simultaneous integration of raw material supply process and the design of a cellular configuration over multiple manufacturing plants have resulted in significant overall improvement ranging from 2 % to 13.1%. Cost saving are generated by the economy of the supply cost coupled with a decreased machine investment cost explained by a balance cost of the capacity sharing between plants and suited selection of supplier.

A third set of experiments are conducted on manufacturing systems composed of three plants which will manufacture 12 parts requiring 5 machine types. Each part has a three operation routing. To complete an operation, at most two alternatives are allowed. The manufacturing system is integrated with the raw material supply process from 3 alternative suppliers. Each supplier is defined by a fixed ordering cost, a variable cost and capacity limit. Although, the size of the problem increases, experimentation show that the addition of supplying constraints decrease the resolution time compared with the same data problem resolved as in the first set problems.

As presented in tables 10 and 11, the comparison of independent CMS plants and networked plants give a pattern where the CMS structure of the different plants is partially altered with saving investment cost through completing operation in another cell of another plant.

Other experiments illustrate two other result patterns. One demonstrates that machine cells are partially or totally preserved however part families may change totally when allowing flow between plants. The other shows that the machine cells and part families are preserved however plants where cells are located changed.

Table 9

			SC with independent plants		SC with linked plants		
Problem no	Number of parts	Number of machine types	Total cost. (supply cost)	Machine requirements	Total cost (supply cost)	Machine requirements	Improvement (%)
1	8	10	799086.6533 (122120)	12	748006.6533 (105800)	11	6.4 (1.3)
2	8	10	1387190.3533 (330690)	17	1359409.9367 (289050)	17	2 (12.6)
3	9	10	2375287.75 (520990)	32	2325633.1700 (434050)	32	2 (17)
4	10	5	306359.7167 (189050)	13	299938.0500 (189050)	11	2.09 (0)
5	10	5	976802.7000 (212720)	11	848749.7167 (189050)	9	13.1 (11.12)
6	12	5	356856.2833 (226050)	15	345599.4167 (226050)	11	3.15 (0)
7	12	5	475661.7333 (251850)	12	450979.4167 (226050)	11	5.3 (10.2)
8	12	5	356856.2833 (226050)	15	350395.6667 (226050)	12	1.8 (0)

Impact of integration of supply process with multi plant cellular manufacturing system deign

Table 10

Multiplant cell design with three independent plants

	Plant 1		Plant 2		Plant 3	
	Cell 1	Cell 2	Cell 1	Cell 2	Cell 1	Cell 2
Parts	1,4	3,7	2,8	5,9	10,12	6,11
Machines	1(2)	1,4	4,5	2,3	2,3	1,4

Table 11

Multiplant cell design with three linked plants

	Plant 1		Plant 2		Plant 3	
	Cell 1	Cell 2	Cell 1	Cell 2	Cell 1	Cell 2
Parts	1,3	5,9	10,12	7,11	2,8	4,6
Machines	1,5	2,3	2,3	1,4	4,5	1(2)

5. Conclusion

This paper considers the problem of integrating CMS design in SC design. Therefore, multi plant cellular manufacturing design is aimed considering cross linkage between plants and supplier selection. Operation routing is enabled through alternatives paths in a sole plant or in the remaining plants. Although, intercellular flows are allowed, this novel feature will contribute to minimize equipment investment and gives a background to cope with dynamic demand. A non linear model is constructed to consider these factors. To demonstrate the potential benefits, a linearized model is proposed. Three set problems of small sized problems are solved using Cplex 9.0. The analysis of the results show the usefulness of networked multi CMS plant and the effect of integrating supply process in the cell location within a multi plant manufacturing system. The savings generated with this integration are demonstrated with comparing linked multi plant CMS and independent multi plant CMS. The potential benefits are identified by the decreased total supply chain cost and the improvement of machine utilisation rate. Such supply design approach is challenging to help design capacity in face of demand variability; this question is currently in investigation. Also, since, the proposed model is NP hard, heuristic approaches are presently in construction which allows solving industrial problem instances and demonstrates realistic supply chain issues.

Appendix:

The linearized problem

$$Min \left(\sum_{\mathrm{l}=1}^{\mathrm{NL}} \left(\sum_{\mathrm{c_1}=1}^{NC} \left(\sum_{m=1}^{NM} \left(MNB_{mcl} * MFC_m + \sum_{i=1}^{NP} \sum_{j=1}^{NO} OP_{ij}^{mcl} * MVC_m \right) \right) \right) \right)$$

$$+\frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO-1} ICC \cdot \left| \frac{DO_{ij}}{B} \right| \cdot \sum_{l=1}^{NL} \sum_{c=1}^{NC} \left(MOP_{ijcl} + NOP_{ijcl} \right)$$

$$-\frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO-1} ICC \cdot \left| \frac{DO_{ij}}{B} \right| \cdot \sum_{l=1}^{NL} \left(QOP_{ijl} + ROP_{ijl} \right)$$

$$+\frac{1}{2} \sum_{i=1}^{NP} \sum_{j=1}^{NO-1} ISC \cdot \left| \frac{DO_{ij}}{B} \right| \cdot \sum_{l=1}^{NL} \left(QOP_{ijl} + ROP_{ijl} \right)$$

$$+\sum_{f=1}^{NF} \left(fc_f \cdot YF_f + \sum_{i=1}^{NP} \sum_{l=1}^{NL} Z_{ifl} \cdot vc_{ifl} \right)$$

Subject to

(2), (3), (4), (5), (6) and (7)

Additional constraints (linearization of absolute terms)

$$ZZ_{i,j+1,cl} - ZZ_{ijcl} = MOP_{ijcl} + NOP_{ijcl} \qquad \forall \text{ i,j,c,l}$$

$$WW_{i,j+1,l} - WW_{ijl} = QOP_{ijl} + ROP_{ijl} \qquad \forall \text{ i,j,l}$$

$$ZZ_{ijcl} = \sum_{m=1}^{NM} OP_{ij}^{mcl} \qquad \forall \text{ i,j,c,l}$$

$$WW_{ijl} = \sum_{c=1}^{NC} \sum_{m=1}^{NL} OP_{ij}^{mcl} \qquad \forall \text{ i,j,l}$$

$$ZZ, WW, MOP, NOP, QOP, ROP \quad boolean$$

Additional constraints (linearization of polynomial terms)

$$\mathrm{Z_{ifl}} \le D_i \square WW_{i1l} \qquad \forall \mathrm{i,f,l}$$

$$\mathrm{Z_{ifl}} \le WF_{ifl} \qquad \forall \mathrm{i,f,l}$$

$$\mathrm{Z}_{ifl} \ge WF_{ifl} - D_i \square (1\text{-}\mathrm{WW}_{i1l}\ ) \qquad \forall \mathrm{i,f,l}$$

$$\sum_{l=1}^{NL} WF_{inl} \le \ CF_{in} * Y_{in} \qquad \forall \mathrm{i,f}$$

$$D_i \square \mathrm{WW}_{i1l} \le \sum_{f=1}^{NF} \mathrm{Z}_{ifl} \qquad \forall \mathrm{i,l}$$

$$\mathrm{Z}_{ifl} \ge 0 \ \ , \quad WF_{ifl} \ge 0 \qquad \forall \mathrm{i,f,l}$$

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