# An Integrated Model of Cellular Manufacturing and Supplier Selection Considering Product Quality

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**Abstract**

Today's business environment has forced manufacturers to produce high-quality products at low cost in the shortest possible delivery time. To cope with this challenge, manufacturing organizations need to optimize the manufacturing and other functions that are in logical association with each other. Therefore, manufacturing system design and supplier selection process are linked together as two major and interrelated decisions involved in viability of production firm. As a matter of fact, production and purchasing functions interact in the form of an organization's overall operation and jointly determine corporate success. In this research, we tried to show the relationship between designing cellular manufacturing system (CMS) and supplier selection process by providing product quality considerations as well as the imprecise nature of some input parameters including parts' demands and defects rates. A unified fuzzy mixed integer linear programming model is developed to make the interrelated cell formation and supplier selection decisions simultaneously and to obtain the advantages of this integrated approach with product quality and reduction of total cost, consequently. Computational results also display the efficiency of the proposed mathematical model for simultaneous consideration of cellular manufacturing design and supplier selection as compared to when these two decisions are separately taken into account.

*Keywords:* Cellular manufacturing, Supplier selection, Product quality, Integrated model.

## 1. Introduction

Cellular manufacturing system (CMS) is a plant layout approach which tries to decompose all or part of the manufacturing plant into easy manageable manufacturing cells. A cluster of functionally dissimilar machines is placed in each specific cell to process a group of similar parts in manufacturing and design. Successful implementation of CMS has resulted in quality improvement and production control, increment in productivity, and flexibility through reduction in set-up times, throughput times, lead times, lot sizes, work in process inventories, material handling cost, etc. (Heragu, 1994; Wemmerlov and Hyer, 1989; Wemmerlov and Johnson, 1997). One of the first problems encountered in the implementation of CMS is the cell formation (CF) that includes clustering machines in cells and parts as part groups (i.e., also called part families).

In the past several years, many solution methods have been developed for solving CF problem using a binary machine-part incidence matrix. Mahdavi et al. (2007) proposed a mathematical model for CF problem based on the cell utilization concept. Arkat et al. (2011) presented a bi-objective mathematical model to minimize the number of exceptional elements and the number of voids in the machine-part incidence matrix. They developed an ε-constraint method to solve the model and to generate the efficient solutions. Elbenani and Ferland (2012) introduced a linear binary mathematical programing formulation to generate a solution for the CF problem. They utilized a heuristic approach to solve the problem.

On the other hand, there are a number of research papers dealing with more pragmatic issues including routing flexibilities, operation sequences, reliability of machines, production volumes, set-up and processing times, machine capacities, duplicate machines, and some other production design factors encountered in real factory situation. Caux et al. (2000) addressed the problem of manufacturing CF with alternative process plans and machine capacity constraints. Given the alternative routings for parts processing, capacities of machines, and parts' demands, the problem includes the grouping machines and part process plan selection. The objective was to minimize the intercellular traffic according to machine capacity constraints. Jabal Ameli and Arkat (2008) presented a pure integer linear programming approach for the CF problem considering alternative processing routes, process sequences, machine reliability,

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layout to CMS. A total cost model, including set-up cost, work in process inventory cost, quality cost, and set-up time reduction cost, was developed to study the performance and financial aspects of the CMS as an integrated manner. Bootaki et al. (2014) presented a bi-objective cubic CF with two non-homogeneous objective functions in order to minimize the intercellular movements and maximize the part quality index. They suggested a hybrid GA-Augmented ε-constraint method for solving the problem.

For most industries, purchasing function and its associated decisions account for more than 70% of all companies' expenses (Ghodsypour and O'Brien, 2001). Hence, suppliers are directly engaged with corporate success. Raw materials represent a substantial part of the quality of products. Insuring quality at the production input point is one of the crucial determinants for producers that wish to assure right quality products to the customers. Conventionally, designing manufacturing systems and selecting raw material suppliers are two separate decisions. However, production system design can be affected by its interactions with other functions that are logically associated with it. Integrating different aspects of CMS design with supplier selection related issues can lead to a better designed manufacturing system to obtain the advantages of CMS with product quality, and finally reduction of total cost. Although several studies have focused on the quantitative modeling for supplier selection in manufacturing systems, little attention was given in the literature to supplier selection in CMSs. Benhalla et al. (2011) developed a new integrated mathematical model for a multiple plant CMS design on existing factories, taking into consideration the raw material supply process, associated supplier selection, as well as raw material delivery cost to a multi-plant multi-stage CMS design cost. Paydar et al. (2014) proposed a mixed integer linear programming model (MILP) for CMS to integrate CF problem, machine layout, and supplier selection considering the imprecise nature of some critical parameters such as customer demands and machine capacities. They developed a robust optimization method to solve the model with the objective of minimizing total costs including intracellular and intercellular movements costs, machine investment cost, inventory cost, and procurement cost.

The rest of this paper is organized as follows. The problem description and unified mathematical model areis provided in section 2. Solution approach is presented in section 3. Efficiency of the proposed model is validated by means of a numerical illustration in section 4, and finally conclusion is reported in section 5.

## 2. Problem Description and Mathematical Model

### *2.1. Description*

Consider a two-echelon supply chain consisting of multiple supplier plants and one manufacturer producing multiple products. The integration of making the CF and supplier selection decisions in designing cellular manufacturing and supply chain simultaneously is considered; thus, we face with two implicitly interrelated decisions including:

#### *2.1.1. Supplier Selection Process*

According to a survey on 78 related articles appeared in the international journals from 2000 to 2008 conducted by Ho et al. (2010), quality is the most popular criterion (68 papers or 87.18%) in the supplier selection process, and delivery is the second most popular criterion (64 papers or 82.05%), and the third most popular criterion (63 papers or 80.77%) is price/cost. We tried to apply these three main criteria in our presented mathematical model. Due to the variety and technological requirements, there are differences among the inputs or raw materials provided by suppliers with regard to maximum capacity, quality level, lead time, unit price, and not all the suppliers can also produce all kinds of raw materials. The manufacturer, as a seller, has historical performance data on the basis of past records related to quality level and extra time beyond the due date taken to delivery of raw materials by each supplier. The manufacturing organization has to bear extra costs due to quality deficiency and late arrival of raw materials that lead to poor quality level of the finished products and delay in delivery. Moreover, the quality department of the manufacturing organization determines a maximum allowable deficiency level and rejects poor quality raw materials. The suppliers also consider a minimum acceptable utilized capacity for each type of raw material, that is, each supplier only accepts orders for which the utilized capacity would be equal to or greater than economic pre-determined value. The quantity of each type of raw material provided by each supplier plant should be determined.

#### *2.1.2. CF design*

In the considered manufacturing plant with cellular layout, required operations of several part types are processed on different machines with limited capacities, which have been placed in the number of pre-determined manufacturing cells. The customers' demands for each part type are uncertain. To cope with this uncertainty, triangular fuzzy number (figure 1) is used on the basis of experts' knowledge. Machines can be replicated to meet capacity constraints and to reduce intercellular movements. Each part type has one or more processing routes along which required operations are performed in a given sequence. In order to better monitor cells, the upper and lower bounds of the number of machines in each cell are specified in advance. The existence of too many machines in one cell creates cluttered flows, reducing monitoring machines. A production lot of parts can be split into processing routes with different defect rates, and the optimal lot splitting should be determined to minimize

*2.2.4. Objective Function and Constraints*

Minimize Z =

$$\sum_{m=1}^{M}\sum_{k=1}^{C} IC_m.N_{mk} + \sum_{p=1}^{P}\sum_{j=1}^{J_{pr}}\sum_{r=1}^{R_p}\sum_{m=1}^{M}\sum_{k=1}^{C} PT_{pjr}.a_{pjrm}.OC_m.$$

$$\sum_{p=1}^{P}\sum_{r=1}^{R_p} SC_{pr}.z_{pr} \quad \textbf{(1)}$$

$$+\sum_{p=1}^{P}\sum_{j=1}^{J_{pr}-1}\sum_{r=1}^{R_p}\sum_{k=1}^{C} IMC_p.x^{+}_{pjrk} + \sum_{p=1}^{P}\sum_{r=1}^{R_p} RC_p.dq_{pr} +$$

$$\sum_{i=1}^{I}\sum_{s=1}^{S} IRC_{is}.w_{is}$$

$$+\sum_{s=1}^{S} FC_{is}.u_{is} + \sum_{i=1}^{I}\sum_{s=1}^{S}(1-QL_{is}).UQP_{is}.w_{is} +$$

$$\sum_{i=1}^{I}\sum_{s=1}^{S} LTD_{is}.UDP_{is}.w_{is}$$

Subject to:

$$\sum_{p=1}^{P}\sum_{j=1}^{J_{pr}}\sum_{r=1}^{R_p} PT_{pjr}.a_{pjrm}.x_{pjrk} \le CM_m.N_{mk} \qquad \forall r \quad \textbf{(2)}$$

$$LB_k \le \sum_{m=1}^{M} N_{mk} \le UB_k \qquad \forall k \quad (3)$$

$$\sum_{k=1}^{C} t_{pjrk} = z_{pr} \qquad \forall p, j, r \quad (4)$$

$$x_{pjrk} \le LPN.t_{pjrk} \qquad \forall p, j, r, k \quad (5)$$

$$x_{p,j+1,r,k} - x_{pjrk} = x^{+}_{pjrk} - x^{-}_{pjrk} \qquad \forall p, j \ne J_{pr}, r, k \quad (6)$$

$$y_{pr} = \sum_{k=1}^{C} x_{pjrk} \qquad \forall p, j, r \quad (7)$$

$$\sum_{r=1}^{R_p} y_{pr} = \tilde{D}_p + \sum_{r=1}^{R_p} dq_{pr} \qquad \forall p \quad (8)$$

$$dq_{pr} - dq^{+}_{pr} = \tilde{\lambda}_{pr}.y_{pr} + \tilde{\gamma}_{pr}.z_{pr} \qquad \forall p, r \quad (9)$$

$$\sum_{s=1}^{S} w_{is} = \sum_{p=1}^{P}\sum_{r=1}^{R_p} UR_{ip}.y_{pr} \qquad \forall i \quad (10)$$

$$L_{is}.u_{is} \le w_{is} \le CS_{is}.u_{is} \qquad \forall i, s \quad (11)$$

$$(1-QL_{is}).u_{is} \le MADL \qquad \forall i, s \quad (12)$$

$$x_{pjrk}, y_{pr}, dq_{pr}, w_{is}, x^{+}_{pjrk}, x^{-}_{pjrk}, dq^{+}_{pr} \ge 0 \qquad \forall p, j, r, k, i, s \quad (13)$$

$$N_{mk} \ge 0 \text{ and integer} \qquad \forall m, k \quad (14)$$

$$z_{pr}, u_{is}, t_{pjrk} \in \{0,1\} \qquad \forall p, j, r, k, i, s \quad (15)$$

The objective function given in Eq. (1) seeks to minimize machine investment cost, operational cost, process routes set-up cost, intercellular movements cost, repair cost, raw material procurement cost, raw material selection fixed cost, quality deficiency penalty cost, and lead time delay penalty cost, respectively. Inequality (2) ensures that available time capacity of machines does not exceed. Cell-size limitation is considered in constraint (3). Eq. (4) allocates each operation of each part type along each specific route to only one cell when the route is set up. Constraint (5) prevents the decision variable $x_{pjrk}$ to take a positive value, unless the auxiliary binary variable $t_{pjrk}$ be equal to 1. Eq. (6) is used to account for the number of intercellular movements. Eq. (7) is related to the quantity of parts processed in each specific route. Constraint (8) corresponds to the production quantity for each part type that is equal to the sum of part demand and quantity of defective items. Eq. (9) considers Urban's equation to account for the quantity of defective items. Constraint (10) is related to the quantity of raw materials that should be procured. Minimum acceptable capacity utilization and maximum capacity of suppliers are considered in constraint (11). Constraint (12) guarantees the rejection of poor quality raw materials. Finally, constraints (13)-(15) define variables type.

**3. Solution Methodology**

To solve the mathematical model, we need an approach to transform the FMILP model into an equivalent auxiliary crisp MILP. Defuzzification is the procedure of decoding a fuzzy value and computing its corresponding crisp measure. Different fuzzy numbers of ranking methods have been introduced to obtain compromise solutions for dealing with fuzzy mathematical programming models. The defuzzification of triangular fuzzy number can be performed by applying the possibility theory (Chang, 1996; Enea and Piazza, 2004) or centroid methods (Wang and Parkan, 2006). According to Yager (1981), the crisp measure is the abscissa of the center of gravity:

$$A^{R} = \frac{A^{l} + A^{m} + A^{u}}{3} \quad \textbf{(16)}$$

Now, we present the equivalent crisp constraints using the above equation:

$$\sum_{r=1}^{R_p} y_{pr} = \left(\frac{D^{l}_{p} + D^{m}_{p} + D^{u}_{p}}{3}\right) + \sum_{r=1}^{R_p} dq_{pr} \qquad \forall p \quad \textbf{(17)}$$

Table 5
Fixed cost and raw material price data for suppliers (FC, IRC)

| Raw material | Supplier1 | Supplier2 | Supplier3 | Supplier4 | Supplier5 | Supplier6 |
|---|---|---|---|---|---|---|
| 1 | (600, 3.2)* | − | (730, 2.7) | (900, 2.9) | (750, 3.1) | (850, 2.7) |
| 2 | (700, 3.2) | (850, 3) | − | − | (750, 2.7) | (700, 3.1) |
| 3 | − | (650, 4) | (800, 5) | (900, 4.5) | − | (850, 4.9) |
| 4 | (870, 3.5) | (1050, 3.2) | − | − | (730, 4) | (780, 3) |
| 5 | (870, 4.1) | (900, 4.1) | (820, 3.6) | (1020, 4.5) | − | (840, 4) |
| 6 | − | (750, 3.6) | (650, 3) | (700, 4) | − | (860, 3.4) |
| 7 | (560, 3.5) | − | (750, 3.5) | − | (800, 3.5) | (780, 3.5) |
| 8 | (790, 3) | − | − | (850, 3.2) | (910, 3.5) | (860, 3.7) |
| 9 | − | (770, 2.9) | (650, 3) | (800, 3) | (720, 2.7) | − |
| 10 | (990, 2.9) | (800, 3.5) | (800, 3.7) | (950, 3) | (1000, 2.5) | (940, 2.4) |

Table 6
Quality and lead time data (QL, LTD)*.

| Raw material | Supplier1 | Supplier2 | Supplier3 | Supplier4 | Supplier5 | Supplier6 | (UQP, UDP) |
|---|---|---|---|---|---|---|---|
| 1 | (0.92, 2)* | − | (0.87, 1) | (0.90, 0) | (0.91, 0) | (0.87, 3) | (4.2, 0.9) |
| 2 | (0.90, 1) | (0.90, 0) | − | − | (0.92, 1) | (0.93, 4) | (3.8, 0.7) |
| 3 | − | (0.89, 3) | (0.91, 2) | (0.90, 0) | − | (0.94, 2) | (3.6, 0.8) |
| 4 | (0.90, 3) | (0.83, 1) | − | − | (0.91, 2) | (0.90, 1) | (3.5, 0.7) |
| 5 | (0.85, 0) | (0.93, 0) | (0.94, 1) | (0.91, 1) | − | (0.90, 0) | (4.4, 0.5) |
| 6 | − | (0.94, 1) | (0.93, 0) | (0.93, 0) | − | (0.89, 3) | (4, 0.65) |
| 7 | (0.91, 2) | − | (0.90, 1) | − | (0.88, 3) | (0.91, 0) | (3.9, 1.1) |
| 8 | (0.91, 1) | − | − | (0.90, 2) | (0.91, 1) | (0.93, 2) | (3.5, 0.8) |
| 9 | − | (0.91, 0) | (0.93, 1) | (0.92, 2) | (0.90, 0) | − | (3, 1) |
| 10 | (0.88, 4) | (0.92, 0) | (0.95, 1) | (0.87, 3) | (0.90, 0) | (0.91, 4) | (4, 0.85) |

Table 7
Minimum acceptable capacity utilization and maximum capacity of suppliers (L, CS)

| Raw material | Supplier1 | Supplier2 | Supplier3 | Supplier4 | Supplier5 | Supplier6 |
|---|---|---|---|---|---|---|
| 1 | (2300, 8500)* | − | (2600, 8000) | (2700, 9000) | (3000, 7000) | (2800, 6500) |
| 2 | (2400, 9000) | (2100, 8500) | − | − | (2000, 8500) | (2500, 7500) |
| 3 | − | (2400, 9000) | (2600, 8500) | (2200, 9000) | − | (2500, 7000) |
| 4 | (3000, 9500) | (3300, 7500) | − | − | (2700, 8500) | (2800, 6200) |
| 5 | (3100, 6500) | (3500, 6000) | (2800, 8000) | (3000, 7500) | − | (3200, 6000) |
| 6 | − | (3200, 9000) | (3000, 8000) | (2400, 7500) | − | (2800, 7000) |
| 7 | (2200, 9000) | − | (2800, 8500) | − | (2700, 9500) | (3000, 6500) |
| 8 | (2400, 7500) | − | − | (2500, 6500) | (2700, 6000) | (2800, 8500) |
| 9 | − | (3100, 6000) | (3200, 7500) | (2900, 8000) | (2900, 8200) | − |
| 10 | (2600, 7500) | (3100, 8500) | (2200, 6500) | (2900, 5500) | (3200, 7000) | (2800, 6500) |

Table 8
Optimal solution for CF design production factors in the integrated approach

| Part | Route | Zpr | $y_{pr}$ | $dq_{pr}$ | Visited cells sequence | Intercellular movements |
|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1471 | 68 | Cell3−Cell3−Cell3 | 0 |
| | 2 | 1 | 3184 | 258 | Cell2−Cell2−Cell2 | 0 |
| | 3 | 1 | 682 | 11 | Cell3−Cell3−Cell1 | 682 |
| 2 | 1 | 1 | 4591 | 491 | Cell1−Cell1 | 0 |
| | 2 | 0 | − | − | − | − |
| 3 | 1 | 1 | 600 | 0 | Cell1−Cell2−Cell2 | 600 |
| | 2 | 1 | 3368 | 368 | Cell3−Cell3−Cell 3 | 0 |
| 4 | 1 | 1 | 1446 | 95 | Cell2−Cell2−Cell1 | 1446 |
| | 2 | 1 | 3075 | 227 | Cell2−Cell2−Cell2 | 0 |
| 5 | 1 | 1 | 614 | 14 | Cell1−Cell3−Cell3 | 614 |
| | 2 | 0 | − | − | − | − |
| | 3 | 1 | 3500 | 300 | Cell1−Cell1−Cell1 | 0 |
| 6 | 1 | 1 | 4376 | 276 | Cell1−Cell1−Cell1 | 0 |
| | 2 | 0 | − | − | − | − |
| 7 | 1 | 1 | 2774 | 227 | Cell3−Cell3 | 0 |
| | 2 | 1 | 1871 | 118 | Cell1−Cell1 | 0 |

Table 9
Machine-cell formation in the integrated approach

| | Cell1 | Cell2 | Cell3 |
|---|---|---|---|
| Machine1 | 0 | 1 | 2 |
| Machine2 | 3 | 1 | 1 |
| Machine3 | 3 | 1 | 1 |
| Machine4 | 1 | 1 | 1 |
| Machine5 | 1 | 1 | 0 |

organization's overall operation. A unified FMILP model was developed to make production and procurement decisions in generalized CF problem and supplier selection simultaneously, together with product quality considerations. Comparing Table 8 with Table 11 as well as Table 9 with Table 12, we found that there are differences among the proposed integrated mathematical model and the conventional two-phase procedure from the perspective of optimal cell configuration and its production design factors. The computational results also showed that the proposed integrated approach with simultaneous consideration of cellular manufacturing design and supplier selection is more effective as compared to when these two decisions are separately taken into account. The unified fuzzy mathematical model attempted in this paper suffers from a large number of constraints and variables, which make it difficult for application in real cases. Hence, meta-heuristic approaches can be developed to cope with real-sized problems in future research studies.

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