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Stochastic Multi-Stage Manufacturing Supply Chain Design Considering Layered Mini-Cellular System Concept

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1. Introduction

Supply chain design attempts to deploy resources to synchronize product flow through multiple tiers of the network and eventually fulfill customers' requirements (Lee, 2000). Traditionally, due to limited sales information and trade barriers, consumers chose local products. But nowadays consumers access the ever opening global market much easier with the help of the globalization. Though overall demand keeps increasing, the market competition becomes fierce as more and more competitors emerge. The highly dynamic market results in difficulties in predicting the demand for companies' products. Furthermore, the demand uncertainties exacerbate the challenge for synchronizing production. Companies start to build more safety stock and hold excess capacity, resulting in decrease of system efficiency. Thus, resource allocation becomes a critical part in the supply chain design. Three levels of resource allocation in supply chain design are summarized in Figure 1. This is only an attempt to present multiple perspectives of resource allocation problems without guaranteeing the coverage of all industrial circumstances. The exceptions and variations in this framework could always be found in the real world applications.

As the market boosts globally, where to manufacture, store and sell various products become the first decision in resource allocation. "Where" could refer to the market such as North American and East Asian (market and production allocation). In this case, managerial decisions related to marketing strategy and business practice are involved. Some auto manufacturers such as Toyota and Honda open local manufacturing facilities in every market they enter. They take the advantage of local resources to increase responsiveness to local market. Furthermore, the risks caused by demand fluctuation are limited to individual markets and does not adversely affect other operations located throughout the world.

"Where" could also mean a specific geographical location for a specific facility in the supply chain network (facility location). By keeping products manufactured or stocked in one central place, company could benefit from economics of scale and increase its efficiency; however, they might reduce responsiveness. Locating resources dispersedly but close to the consumers could improve customer's satisfaction level, but this increases complexity in

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coordination of product flow. Though Honda and Toyota open facilities for each local market, their local manufacturing facilities are clustered within a certain area to facilitate just-in-time system thereby reducing leadtime tremendously. On the contrary, Seven-Eleven builds its supply facilities close to its convenience stores in Japan. Each store could efficiently manage its inventory by using the Total Information System, where each order is tracked and recorded by the scanner terminal. Distribution centers receive food from manufacturing plants and directly transfer it to the trucks instead of carrying any inventory for fast food. Thus, Seven-Eleven is able to provide fresh product such as lunch box, sandwiches, bakery and bread and improve its responsiveness (Chopra & Meindl, 2007).

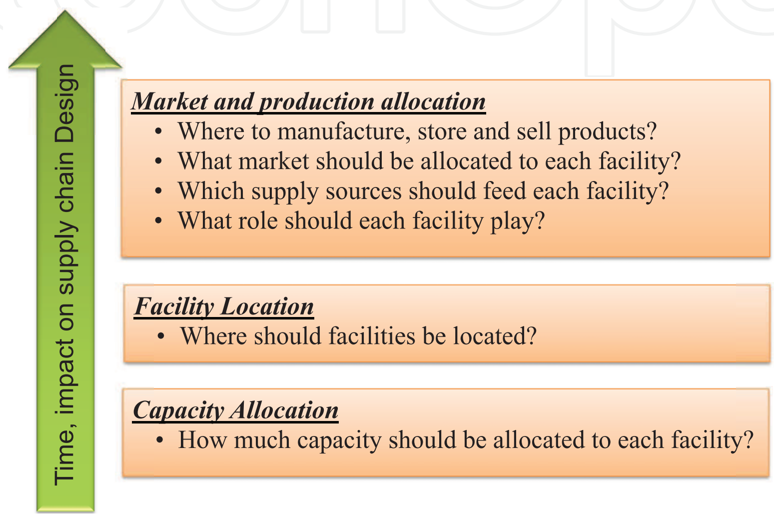

Fig. 1. Three main issues in supply chain design

In the supply chain operational phase, "where" refers to a specific capacity in the shop floor, warehouse, or transportation (capacity allocation). Quantitative models are applied to study machine capacity planning and transportation planning problems where machine or vehicle utilization could be optimized to meet the demand on time under various demand patterns.

Market and production allocation was discussed by Dicken and summarized as: "globally concentrated production", "host market production", "product-specialization for a global or regional market", and "transnational vertical integration" (Dicken, 1992). Globally concentrated production holds production in one base and ships products worldwide. No doubt, production cost could be reduced if production is located in a low-labor cost country; however, the risks of delayed response to the market change arise. Host market production eliminates this risk by dispersing production to each individual market without allowing sales across market boundaries. A better understanding of local customers could be developed and sensitivity to market change could be maintained in each individual market. In the third type of production location strategy, each of the markets manufactures only one product group that is sold to other markets as well. This strategy creates a large-scale and highly specialized manufacturing environment where production cost decreases but transportation cost increases. Transnational vertical integration strategy assigns components or semi-finished products to each of the markets based on manufacturing process, and eventually assemble finished products in one market. It takes advantage of geographical variation of production cost, especially the labor cost. For example, producing low-tech components in developing countries but core components in developed countries could minimize the cost while maintaining product quality. However, additional transportation cost is added if finished products are sold back to the market where components are manufactured.

Managerial decisions related to marketing strategy and business practice are involved in making appropriate market and production allocation decisions. Thus, this chapter assumes that "transnational vertical integration" strategy is adopted, where components are produced in various geographical locations and sold in North American market.

Facility location and capacity allocation decisions are then addressed and solved by a quantitative model in this chapter. Facility location and capacity allocation determines the location, allocation, and production/delivery volume of the flow of goods in a supply chain. Efficient use of all resources to handle supply chain uncertainties is important to facilitate supply chain coordination thereby improving companies' competitiveness (Lee, 2005).

Demand uncertainty is one of the main obstacles in making appropriate decisions. To satisfy demand, supply chain designer tends to reserve extra capacity; however this results in low utilization and therefore higher production cost. Reserving too little capacity results in demand shortage and low responsiveness.

In addition, supply chain design and manufacturing system design are traditionally two sequential steps (Rao & Monhanty, 2003; Cosner, 2008; Schaller, 2008). Roughly estimated capacity requirements are used to locate facility and allocate the production. Various manufacturing systems are then formed within each selected facility. Inaccuracy of estimated capacity requirements results in unsuitable supply chain design and further decreases the manufacturing performance in each facility.

We are proposing a four-phase approach to design and implement the layered mini-cellular system for a multi-stage manufacturing supply chain. In this study, the manufacturing system design and supply chain design are integrated into one scenario. A layered mini-cellular manufacturing system is adopted in the production facility, which is discussed in detail later. Mini-cells are first formed based on probabilistic demand. The mini-cell formation results then serve as inputs to a capacitated plant location model to determine which potential manufacturing plant is selected and how much capacity is allocated to this plant for each manufacturing stage. To continue studying on supply chain operational decisions, a production planning model is proposed to help decide detailed production quantity in each mini-cell for each manufacturing stage in each period.

The remainder of the chapter is organized as follows. The proposed layered mini-cellular system is introduced in section 2. In section 3, solution methodologies are discussed in detail. Experimentation results of proposed system are reported in section 4. In section 5, the performance of layered design is investigated and compared with a classical system. The conclusion is drawn in section 6.

2. Proposed layered mini-cellular system

The manufacturing systems can be categorized into fixed, product, process, and cellular layout in terms of its production layout. Fixed layout is particularly designed for heavy or fragile products such as airplanes, submarines and trains. The product stays in a fixed position, and machines are moved around the product to finish tasks. Product layout is usually adopted by the system with low product diversity but high volume. Each product line is designed for a specific product and performs very efficient production with short throughput time and low work-in-process inventory. On the other hand, process layout is appropriate for a system with high product variety but low volume. Similar processes/machines are grouped and shared by different products, therefore increasing utilization. However, the multidirectional production flow brings challenge in shop floor control. In a cellular layout, products are grouped into families based on the process similarities first and then produced in their own cells. Cellular layout integrates the essentials of both the product layout (product dedication) and process layout (process similarity) into one scenario. It is able to deal with high product variation, in the meanwhile, still maintain a relatively synchronized flow within each cell. The further advantages of cellular system include shorter set-up times, shorter leadtimes, less work-in-process inventory, and fewer defects.

In a classical cellular manufacturing system, each cell is dedicated to only one product family. The cell requirements may vary significantly under a highly fluctuating demand situation, which results in poor utilization of resources. Süer (Süer et al., 2010) brought more flexibility into the cellular system by introducing shared and remainder cells. Assume that the capacity requirements are computed based on the normally distributed demand and processing times (more detailed discussion is in section 3.1) as represented in Table 1. Both expected utilization of X^{th} cell and accumulated demand coverage by X cells are reported in Table 1. For instance, 0.009/0.999 implies that the 4^{th} cell of family 1 is utilized 0.9% of the time, and four cells together could cover demand of family 1 99.9% of the time. To be able to cover the production demand 99.9% of the time, 4+3=7 cells are required for product families 1 and 2. It is clear that the 4^{th} cell of family 1 and the 3^{rd} cell of family 2 are rarely utilized. The demand of family 1 is still covered 99% of the time even without the 4^{th} cell, thus, we may eliminate this cell. However, the 3^{rd} cell of family 2 could not be avoided; otherwise the demand of family 2 will be only covered 86% of the time. In this case, we may group the 3^{rd} cell of family 2 with the 3^{rd} cell of family 1. The capacity requirement is reduced, in the mean time, the desired demand coverage (99%) for each product family is also guaranteed.

Expected Utilization / Demand Coverage	Family 1	Family 2
1st Cell	0.98/0.02	0.99/0.3
2nd Cell	0.9/0.39	0.84/0.86
3rd Cell	0.75/0.99	0.05/0.993
4th Cell	0.009/0.999	

Table 1. An example of capacity requirements

In the layered cellular system, a cell with poor utilization might be combined with another cell. In a shared cell, two product families can be processed. A remainder cell can handle more than two product families. Troubles caused by unstable demand are limited to 'shared' and 'remainder' mini-cells, and demand compensation effect among various product families could help to stabilize demand. The layered system is illustrated in Figure 2, where the production flow is assumed to be unidirectional in each cell. Considering that the chapter mainly studies the supply chain design, the batch production is assumed to simplify the capacity computations.

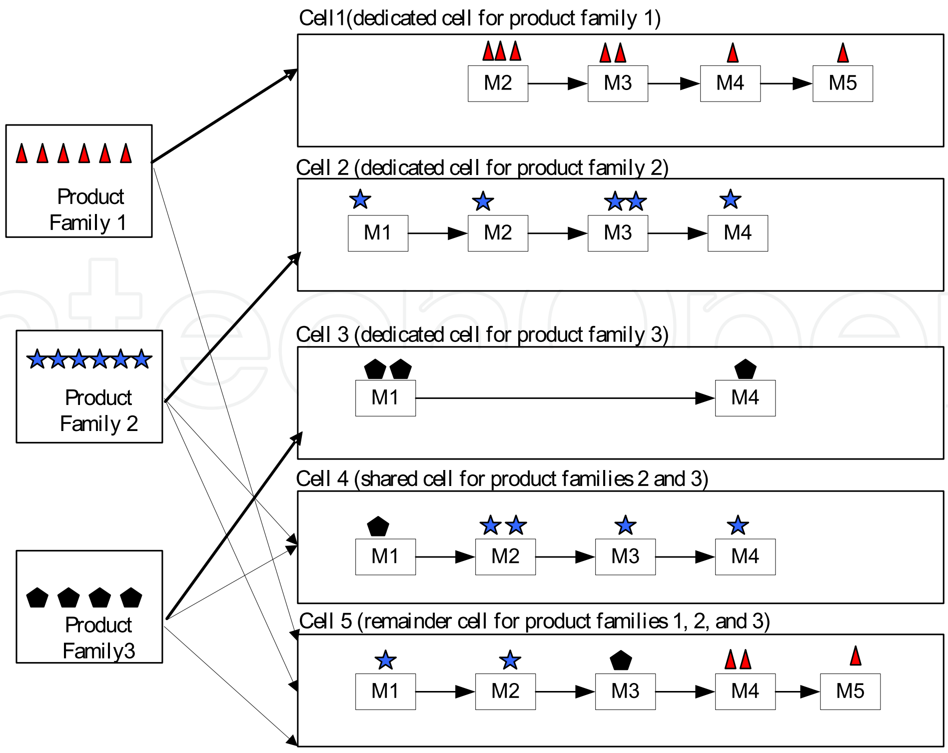

Fig. 2. Three main issues in supply chain design (adopted from Süer et al., 2010)

The layered cellular system proposed by Süer (Süer et al., 2010) assumes a single-stage manufacturing system. In the real-world applications, a multi-stage manufacturing system is usually involved in the manufacturing tier of a supply chain, where each manufacturing facility only performs partial production. In this chapter, 'cell' concept is evolved to a 'mini-cell' concept. A cell performs full package production, while a mini-cell performs operations in a specific manufacturing stage.

3. Stochastic multi-stage manufacturing supply chain design

A four-phase approach is proposed to design and implement the layered mini-cellular system for solving resource management problem in a multi-stage manufacturing system. Table 2 summarizes phases and methodologies used in each phase.

Phase	Objective	Solution Method
1. Expected mini-cell utilization determination	Computing the number of mini-cells and their expected utilizations for each manufacturing stage	Probability Theory
2. Mini-cell formation	Grouping mini-cells for each manufacturing stage	Heuristic Procedure
3. Supply chain network design	Selecting production facilities and allocating mini-cells to the selected facilities	Mixed Integer Linear Programming
4. Simulation	Multi-period production planning	Mixed Integer Linear Programming

Table 2. Summary of stochastic multi-stage manufacturing supply chain design

3.1 Determining expected mini-cell utilization

In this phase, mini-cell requirement for each manufacturing stage is computed based on product demand and processing times. Mean and standard deviation of capacity requirements (in hours) for product family i is determined by the processing time (in minutes) of bottleneck operation in manufacturing stage j shown in Equations 1 and 2, where N_i is the number of parts in product family i, $\mu_{Deamand_{in}}$ is the demand mean of part n in product family i, $\sigma_{Deamand_{in}}$ is the demand standard deviation of part n in product family i, and $PTBottleneck_{ijn}$ is the processing time of bottleneck machine for part n in product family i at stage j.

$$\mu_{CRij} = \sum_{n=1}^{N_i} (\mu_{Demand_{in}} \times PTBottleneck_{ijn} / 60) \tag{1}$$

$$\sigma_{CRij} = \sqrt{\sum_{n=1}^{N_i} \left[(\sigma_{Demand_{in}} \times PTBottleneck_{ijn} / 60)^2 \right]} \tag{2}$$

Each mini-cell is assumed to work 40 hours per week. Thus, the probability of covering the demand by a mini-cell is computed as shown in Equation 3, where $X^{th}C_{ij}$ implies the X^{th} mini-cell required by product family i in stage j.

$$P(X^{th}C_{ij}) = cdf_{Normal}((40 \times X - \mu_{CRij}) / \sigma_{CRij}) \tag{3}$$

The expected utilization of the X^{th} mini-cell for product family i in stage j is given in Equation 4. $P(NCR_{ij}>X)$ indicates the probability that the number of mini-cells required by product i in stage j is greater than X as given in Equation 5, while $P(X\text{-}1<=NCR_{ij}<=X)$ means the probability that mini-cells required is between X-1 and X as given in Equation 6. PU_1 is the utilization of X^{th} mini-cell when mini-cell requirement is greater than X, therefore it is fixed as 1. PU_2 is computed as given in Equation 7, where μ_i is the mean demand of product family i, and σ_i is the standard deviation of the demand.

$$E(X^{th}C_{ij}) = P(NCR_{ij} > X) \times PU_1 + P(X-1 \le NCR_{ij} \le X) \times PU_2 \tag{4}$$

$$P(NCR_{ij} > X) = 1 - P(X^{th}C_{ij}) \tag{5}$$

$$P(X-1 \le NCR_{ij} \le X) = \begin{cases} P(X^{th}C_{ij}) & X = 1 \\ P(X^{th}C_{ij}) - P((X-1)^{th}C_{ij}) & X \ne 1 \end{cases} \tag{6}$$

$$PU_2 = \int_{40(X-1)}^{40X} \frac{y \times \frac{1}{\sigma_i \sqrt{2\pi}} e^{-(y-\mu_i)^2 \frac{1}{2\sigma_i^2}}}{40 \times P(X-1 \le NCR_{ij} \le X)} dy - (X-1) \tag{7}$$

An example result of mini-cell capacity estimation for manufacturing stage j is shown in Table 3. The results imply that 4+4+3=11 mini-cells are required to cover the demand of these three product families. The expected utilization and demand coverage of each mini-cell are also given in the same table. Please note that, we will continue to use this small example to illustrate the procedures that will be discussed in the following sections.

Expected Utilization / Demand Coverage	Family 1	Family 2	Family 3
1st Mini-Cell	0.99/0.002	0.99/0.5	0.98/0.6
2nd Mini-Cell	0.87/0.39	0.79/0.86	0.55/0.91
3rd Mini-Cell	0.32/0.96	0.1/0.98	0.02/0.999
4th Mini-Cell	0.03/0.999	0.003/0.999	

Table 3. An example of mini-Cell utilization and demand coverage

3.2 Grouping mini-cells

In Table 3, obviously, several mini-cells are rarely utilized (e.g. 0.3% utilization of fourth mini-cell for family 2). A heuristic procedure is introduced in this section to reduce the number of required mini-cells by grouping mini-cell segments. The grouping process is implemented based on process similarities among product families. Another important criterion of the grouping process is demand coverage. For example, in Table 3, three mini-cells are able to cover the demand for product family 1 96% of the time, therefore, the fourth mini-cell might not be required.

Figure 3 illustrates the heuristic procedure, where XC_i implies X^{th} mini-cell for product family i, XCU_i is the utilization of this mini-cell, C_j is the newly formed mini-cell j, and LC_j is the leftover utilization for newly formed mini-cell j. Heuristic procedure attempts to form dedicated, shared and remainder mini-cells with the objective of reducing the total number of mini-cell requirements. In the meantime, it prefers to group product families with similar manufacturing operations in order to avoid increasing machine/workforce numbers and operational complexities within a mini-cell. This heuristic procedure is repeated for each manufacturing stage.

An example result of grouping 11 dedicated mini-cells (see Table 3) for manufacturing stage j is shown in Figure 4. After the grouping procedure is applied, four dedicated mini-cells stay, and two dedicated mini-cells are grouped into a shared mini-cell. The other three mini-cells originally dedicated to product families 1, 2, and 3 are grouped into a single remainder mini-cell. Since three mini-cells are able to cover the demand for product family 1 96% of the time, the fourth mini-cell required by product family 1 (noted in the red block) is abandoned during the grouping process. The same procedure is applied to the fourth mini-cell required by product family 2. It is observed that 11 mini-cells cover the demand all the time, and the grouping process reduces the number of mini-cells to six still covering demand 96% of the time.

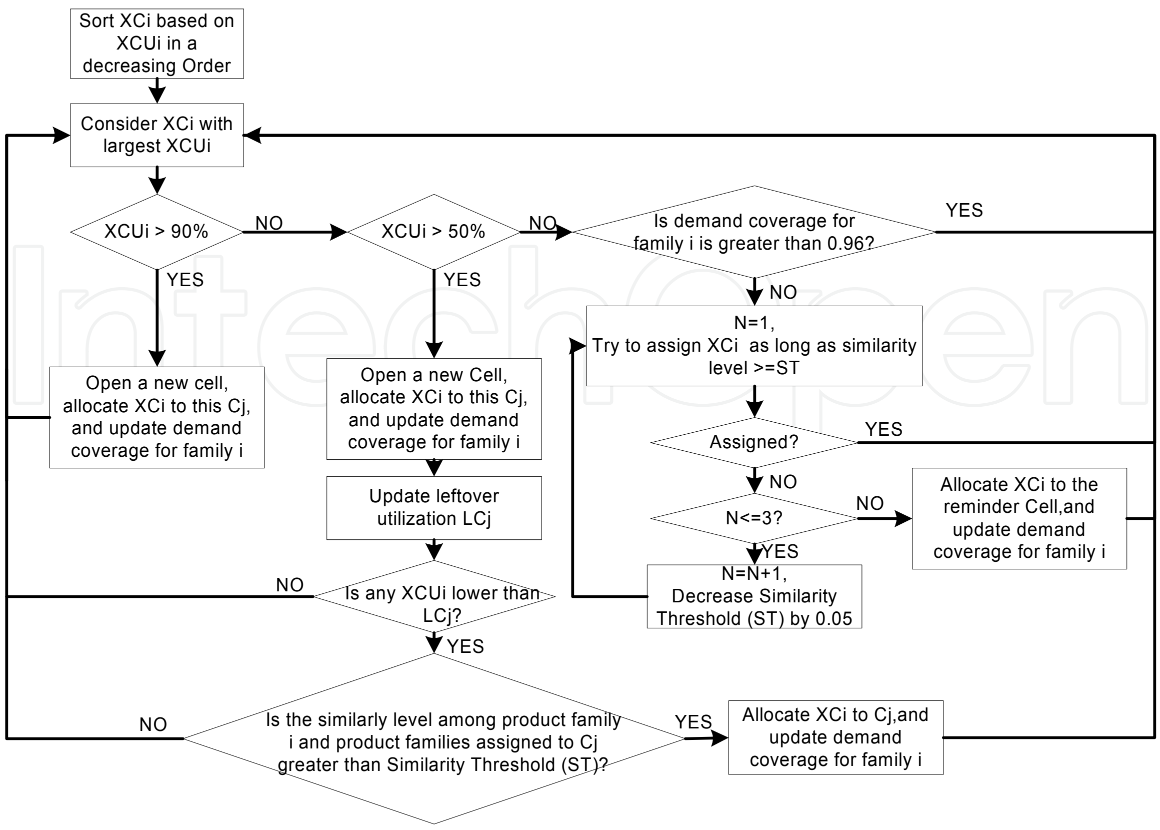

Fig. 3. Flowchart of heuristic procedure

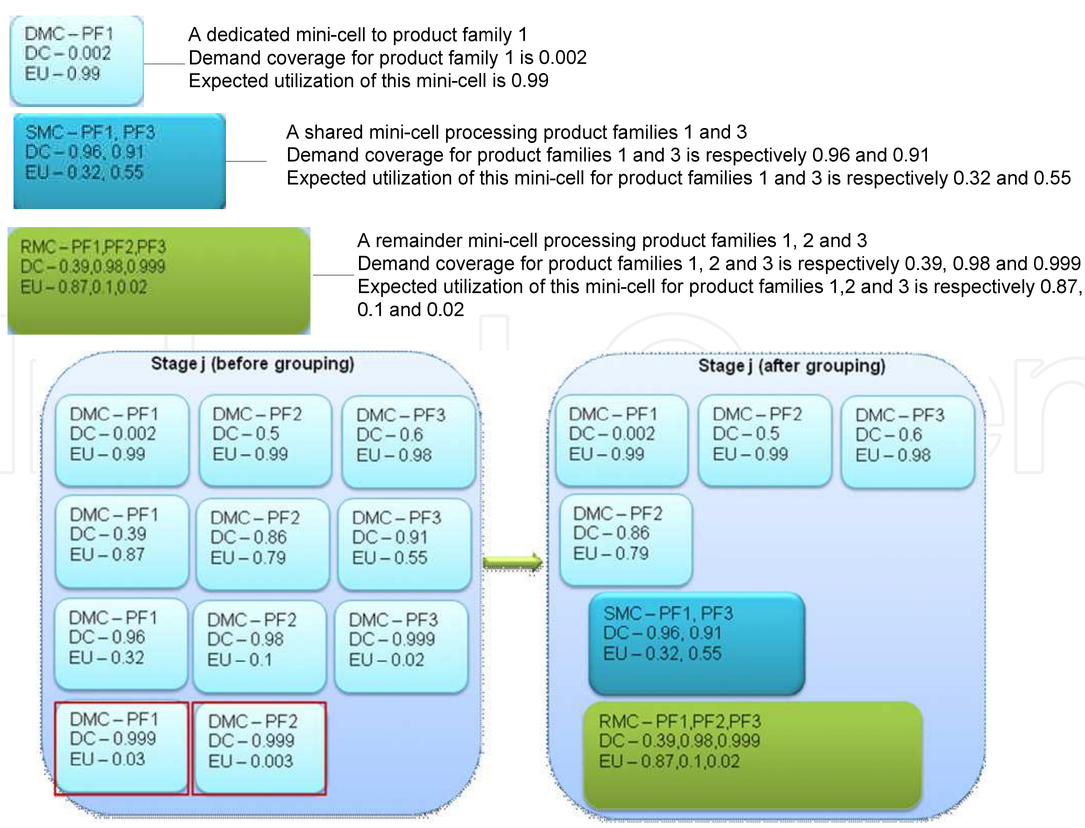

Fig. 4. An example of grouping mini-cells

3.3 Locating facility and allocating mini-cells

A capacitated plant location mathematical model is built to allocate mini-cells to the candidate plants. The objective of this model is to minimize the total cost including production cost, investment cost, and transportation cost as given in Equation 9. Candidate plants are located in different areas with limited capacities, and various production and investment costs. Transportation costs include the costs of transporting products between two consecutive manufacturing stages, and also the costs of shipping products to the market. A single market is assumed. Equation 10 guarantees that the capacity allocated to a plant does not exceed the maximum available capacity. A mini-cell can be assigned to only one facility as presented in Equation 11. Equations 12 and 13 maintain transportation balance, in other words, the quantity of products shipped into a plant should match product quantity shipped out of this plant. Equation 14 enforces investment cost of opening a manufacturing stage in a plant. Parameter EQ_{ik} is roughly estimated as given in Equation 8, where EU_{ik} is the expected utilization of product family in in mini-cell k, and PT_{ij} is the processing time (in minutes) of bottleneck operation in stage j for family i.

$$Q_{ik} = 40 \times 60 \times EU_{ik} \ / \ PT_{ij} \tag{8}$$

Indices:

i Product family index
j Manufacturing stage index
k Mini-cell index
m Plant index

Parameters:

I Number of product families
J Number of manufacturing stages
K Number of mini-cells required
M Number of potential plants
NM_k Number of machines/workforce in mini-cell k
U_{jk} 1, if mini-cell k performs operations in manufacturing stage j; 0, otherwise.
EQ_{ik} Estimated quantity of product family i produced in mini-cell k
LOI_{ij} Previous stage index of stage j for product family i. 0 implies stage j is the first stage for family i or family i does not require manufacturing stage j
$MAXC_{jm}$ Available number of mini-cells for stage j in plant m
IC_{jm} Weekly equivalent investment cost for stage j in plant m
PC_{jm} Production cost for stage j in plant m ($/40hour)
UTC Unit transportation cost ($/mile/unit)
D_{mn} Distance from plant n to plant m
DM_m Distance from plant m to market
M Big value

Decision variables:

X_{km} 1, if mini-cell k is allocated to plant m; 0, otherwise

W_{jm} 1, if stage j is opened in plant m; 0, otherwise
TQ_{ijmn} Transportation quantity of family i from plant n to plant m from stage j-1 to stage j

Objective Function:

$$\begin{aligned} \min \quad Z = & \sum_{j=1}^{J}\sum_{m=1}^{M}(PC_{jm} \times \sum_{k=1}^{K}(NM_k \times U_{jk} \times X_{km}) + IC_{jm} \times W_{jm}) \\ & + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{M}\sum_{m=1}^{M}(TQ_{ijmn} \times D_{mn} \times UTC) \\ & + \sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{k=1}^{K}(X_{km} \times U_{Jk} \times EQ_{ik} \times DM_m \times UTC) \end{aligned} \tag{9}$$

Subject to:

$$\sum_{k=1}^{K}(X_{km} \times U_{jk}) \le MAXC_{jm} \quad \text{for } j = 1,\cdots,J \ \& \ m = 1,\cdots,M \tag{10}$$

$$\sum_{m=1}^{M} X_{km} = 1 \quad \text{for } k = 1,\cdots,K \tag{11}$$

$$\begin{aligned} & \sum_{n=1}^{M} TQ_{ijmn} = 0 \Big|_{LOI_{ij}=0} \\ & \sum_{n=1}^{M} TQ_{ijmn} = \sum_{k=1}^{K}(X_{km} \times U_{jk} \times EQ_{ik}) \Big|_{LOI_{ij}\neq 0} \end{aligned} \quad \text{for } i = 1,\cdots,I \ \& \ j = 1,\cdots,J \ \& \ m = 1,\cdots,M \tag{12}$$

$$\begin{aligned} & \sum_{m=1}^{M} TQ_{ijmn} = 0 \Big|_{LOI_{ij}=0} \\ & \sum_{m=1}^{M} TQ_{ijmn} = \sum_{k=1}^{K}(X_{km} \times U_{LOI_{ij}k} \times EQ_{ik}) \Big|_{LOI_{ij}\neq 0} \end{aligned} \quad \text{for } i = 1,\cdots,I \ \& \ j = 1,\cdots,J \ \& \ n = 1,\cdots,M \tag{13}$$

$$M \times W_{jm} \ge \sum_{k=1}^{K}(X_{km} \times U_{jk}) \quad \text{for } j = 1,\cdots,J \ \& \ m = 1,\cdots,M \tag{14}$$

An example of allocation process is demonstrated in Figure 5. The results indicate that four mini-cells including three dedicated mini-cells and one reminder mini-cell are allocated to plant 3. One dedicated mini-cell and one shared mini-cell are to plant 4. Plant 1 is not able to implement any operation of manufacturing stage j, thus, there is no mini-cell allocated to this plant. Plant 2 is not chosen either based on various factors such as capacity, production cost, and distances.

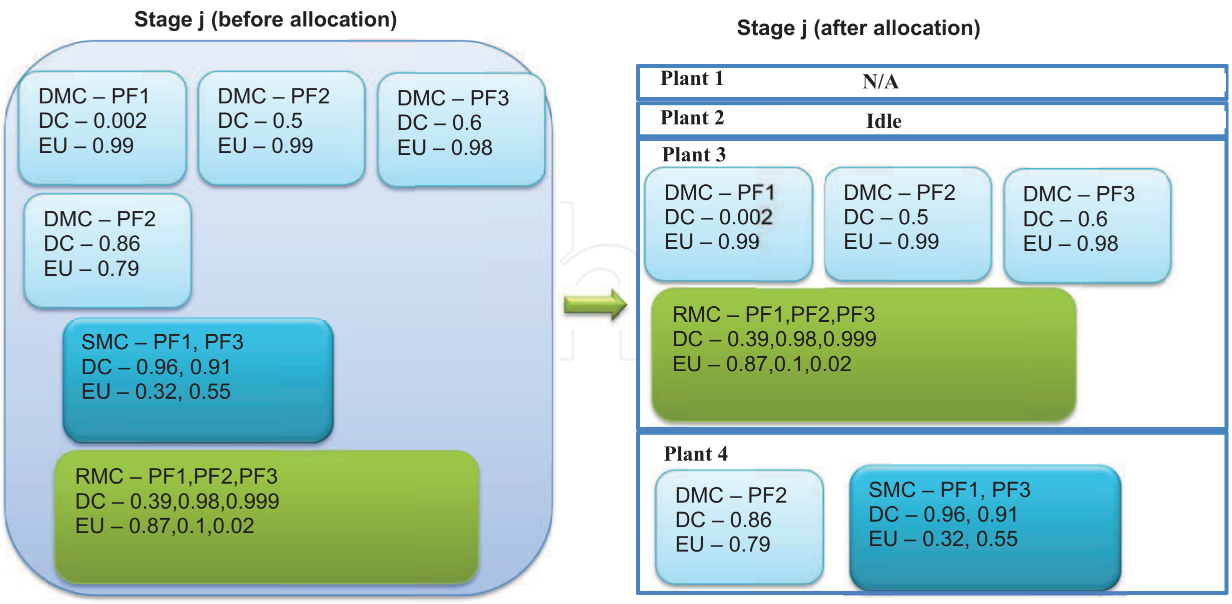

Fig. 5. An example of facility location and mini-cell allocation

3.4 Multi-period production planning

The capacitated plant location model selects plants and determines how many mini-cells should be built in each plant for each manufacturing stage. To continue studying on supply chain operational decisions, a production planning model is proposed to help decide production quantity in each mini-cell for manufacturing stage j in each week. The objective is to minimize demand shortage as given in Equation 15. Equation 16 computes demand shortage for each product family. Equation 17 guarantees that the product family is not assigned to a mini-cell which does not handle that family. Each cell only functions up to 40 hours per week as given in Equation 18. The boundary of decision variable is defined in Equation 19.

Indices:

i Product family index
k Mini-cell index

Parameters:

I Number of product families
K Number of mini-cells required
D_i Demand of product family i for current week
CU_{ik} Expected utilization of family i in mini-cell k
PT_i Processing time (in minutes) of bottleneck operation of family i
M Big value

Decision variables:

Q_{ik} Quantity of product family i produced in mini-cell k
DS_i Demand shortage of product family i

Objective Function:

$$\min \quad Z = \sum_{i=1}^{I} DS_i \tag{15}$$

Subject to:

$$DS_i = \max\left\{0, D_i - \sum_{k=1}^{K} Q_{ik}\right\} \text{ for } i = 1, \cdots, I \tag{16}$$

$$Q_{ik} \le M \times CU_{ik} \text{ for } i = 1, \cdots, I \ \& \ k = 1, \cdots, K \tag{17}$$

$$\sum_{i=1}^{I} (PT_{ik} \times Q_{ik}) \le 40 \times 60 \text{ for } k = 1, \cdots, K \tag{18}$$

$$Q_{ik} \ge 0 \tag{19}$$

An example of production plan giving detailed production quantity of each mini-cell for manufacturing stage j in week n is shown in Figure 6. For example, in plant 3, a dedicated mini-cell to product family 1 needs to produce 35 units of product family 1 in week n.

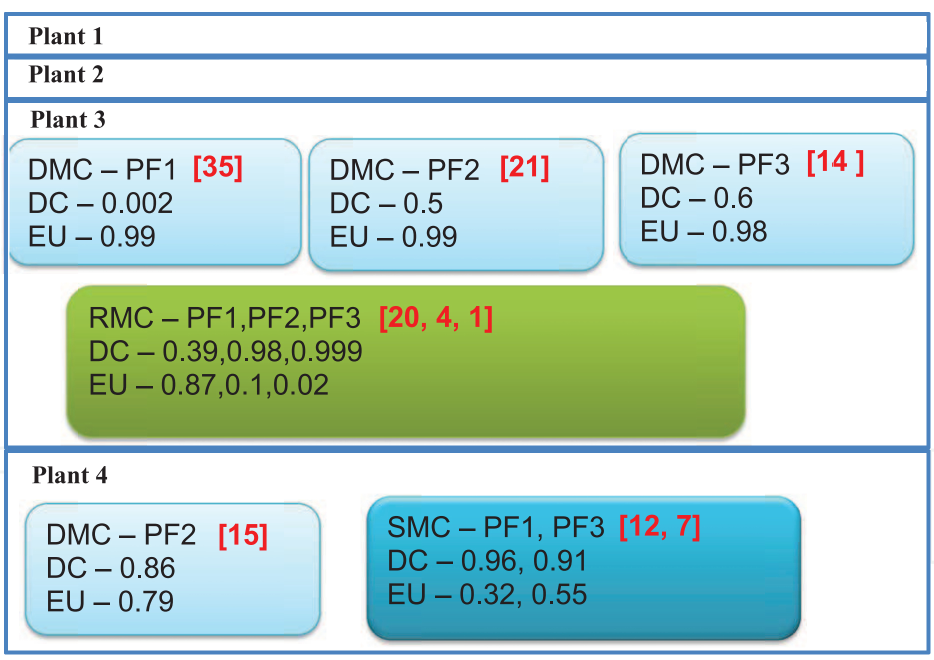

Fig. 6. An example of weekly production planning result

4. The system studied and the preliminary results

An example of supply chain involving a three-stage manufacturing system is studied in this section. This system was originally inspired from a global jewelry manufacturing company. The candidate production plants are mainly located in Caribbean, East Asia, and South East Asia. The jewelry products change along the fashion trend therefore resulting in highly fluctuating demand. It is very challenging to manage capacity to satisfy demand without reserving too much capacity.

The system studied consists of 12 product families with normally distributed weekly demand. The standard deviation is 25% of the average demand. Up to eight operations are required to manufacture a product, and they are grouped into three operation groups since some production facilities are not able to perform some of the operations (e.g. plating operation). All products go through three stages in the same order. In the jewelry manufacturing process, different parts within one product family always require the same operations and processing times are very close, thus, Table 4 shows the processing times and weekly demand for each product family instead of each part. This chapter focuses on supply chain design of manufacturing tier, thus, only one market is assumed.

	Stage	**Manufacturing Operations**	**PF1**	**PF2**	**PF3**	**PF4**	**PF5**	**PF6**	**PF7**	**PF8**	**PF9**	**PF10**	**PF11**	**PF12**
Processing Times (Minutes)	1	Findings (F)		10.6			10.8							11.1
		Casting (C)	10.2		9.7	10.9		13.3	12.6	10.1	10.8	12.5	9.9	
		Tumbling(T)	10.8	11	9.9	12.6	11.2	13.9	13.5	12.3	11.2	13	13.4	12.2
	2	Plating (PL)	9.6	10.9	11.2	9.3	10.1	10.5	9.2	9.2	8.5	12	12.5	11.7
	3	Stone Setting(SS)	9.1	4.6			6.2	4.1					9.3	
		Enameling(E)				5.8	7.5		7.1	7.2		5.6		8.5
		Oven (O)				8.7	6.0		4.9	9.2		8.9		5.5
		Packaging(PA)	12.7	12.8	11.2	11.2	11.4	10.9	10.8	12.7	11.5	12.1	12.3	12.5
Weekly Demand (Units)		mean	1890	795	478	2127	722	520	2582	981	1773	1150	966	474
		SD	472	199	120	532	180	130	646	245	443	288	242	118

Table 4. Processing times and demand

Experimentation of supply chain design on the studied system is implemented by using the proposed four-phase approach. For a three-stage manufacturing system with 12 product families, the mini-cell requirements and expected mini-cell utilizations are computed. Cells consist of multiple machines and equipment. Each machine/equipment requires an operator as well. Table 5 summarizes the number of mini-cells required for each product family as well as the total number of machines/workforce for each stage. The results indicate that a total of

381 mini-cells are required. These 381 mini-cells require a total of 708 machines/equipment and also 708 operators. The number of machines/equipment and operators needed for stages 1, 2, and 3 are computed as 272, 113 and 323, respectively. Due to the space limit, Table 6 only shows partial utilization results for stage 1 for product families which require no more than 6 mini-cells. It is important to notice that many cells are rarely utilized as shown in Table 6 such as 4th, 6th, 6th, and 5th mini-cells for product families 3, 5, 6, and 12, respectively.

	PF	Stage 1	Stage 2	Stage 3	Total Number
Number of Mini-Cells	1	16	14	18	381
	2	7	7	8	
	3	4	4	4	
	4	20	15	18	
	5	6	6	7	
	6	6	5	5	
	7	26	18	21	
	8	9	7	10	
	9	15	12	16	
	10	12	11	11	
	11	10	9	9	
	12	5	5	5	
Number of Machines/Workforce		272	113	323	708

Table 5. Summary of capacity requirement results

Mini-cell	PF3	PF5	PF6	PF12
1st	0.995367	0.999409	0.999131	0.998108
2nd	0.792689	0.98242	0.969661	0.91366
3rd	0.180275	0.835848	0.736627	0.446252
4th	0.003406	0.441633	0.272882	0.050731
5th		0.101697	0.032402	0.000743
6th		0.008137	0.000961	

Table 6. Partial results of mini-cell utilization for stage 1

Heuristic procedure is applied to form dedicated, shared and remainder mini-cells. The results of mini-cell formation are summarized in Table 7. Demand coverage is set to be 0.96 for the heuristic procedure. In other words, product demand will be covered 96% of the time. It is observed that majority of mini-cells are dedicated mini-cells, thus, the operational complexity is limited. By grouping product families into shared and remainder cells, mini-cell requirement is reduced from 381 to 210. Total number of machines/workforce is reduced from 708 to 414.

		Stage 1	Stage 2	Stage 3	Total Number
Number of Mini-Cells	Dedicated	50	40	49	210
	Shared	18	10	17	
	Remainder	8	11	7	
Number of Machines/Workforce		158	61	195	414

Table 7. Summary of mini-cell formation results

There are seven potential production facilities performing operations for different manufacturing stages as shown in Table 8, where 0 implies that the plant doesn't perform operations in this manufacturing stage. For example, plant 4 only performs the plating operation. Distance matrix is given in Table 9. Production costs vary from 32 to 850 representing huge gap of labor costs between developed areas and developing areas.

The math model is solved by ILOG OPL software. The allocation of capacity to production facilities is determined as shown in Figure 7. Plants 1 and 3 are not chosen to perform any operation due to their high production costs. However, production costs are not the only criteria of making decisions. For example, for manufacturing stage 3, production costs in plants 5 and 6 are very low compared with plant 2. But they are not chosen considering the high transportation costs.

	Stage 1	Stage 2	Stage 3
Plant 1	50/800/30000	40/835/30000	50/840/60000
Plant 2	30/600/5000	0	30/680/5000
Plant 3	60/650/10000	50/850/50000	75/720/30000
Plant 4	0	50/520/5000	0
Plant 5	0	0	50/32/25000
Plant 6	50/76/5000	0	50/61/5000
Plant 7	0	30/52/5000	50/72/5000

Table 8. Capacity (in 40 hours)/production cost ($40 hours) /investment cost

Plant	1	2	3	4	5	6	7
1	0	30	50	300	9000	8300	8500
2	30	0	40	260	8960	8280	8530
3	50	40	0	280	9030	8300	8500
4	300	260	280	0	10200	9300	9200
5	9000	8960	9030	10200	0	500	540
6	8300	8280	8300	9300	500	0	70
7	8500	8530	8500	9200	540	70	0
Market	300	350	310	300	7500	5600	5500

Table 9. Distance Matrix

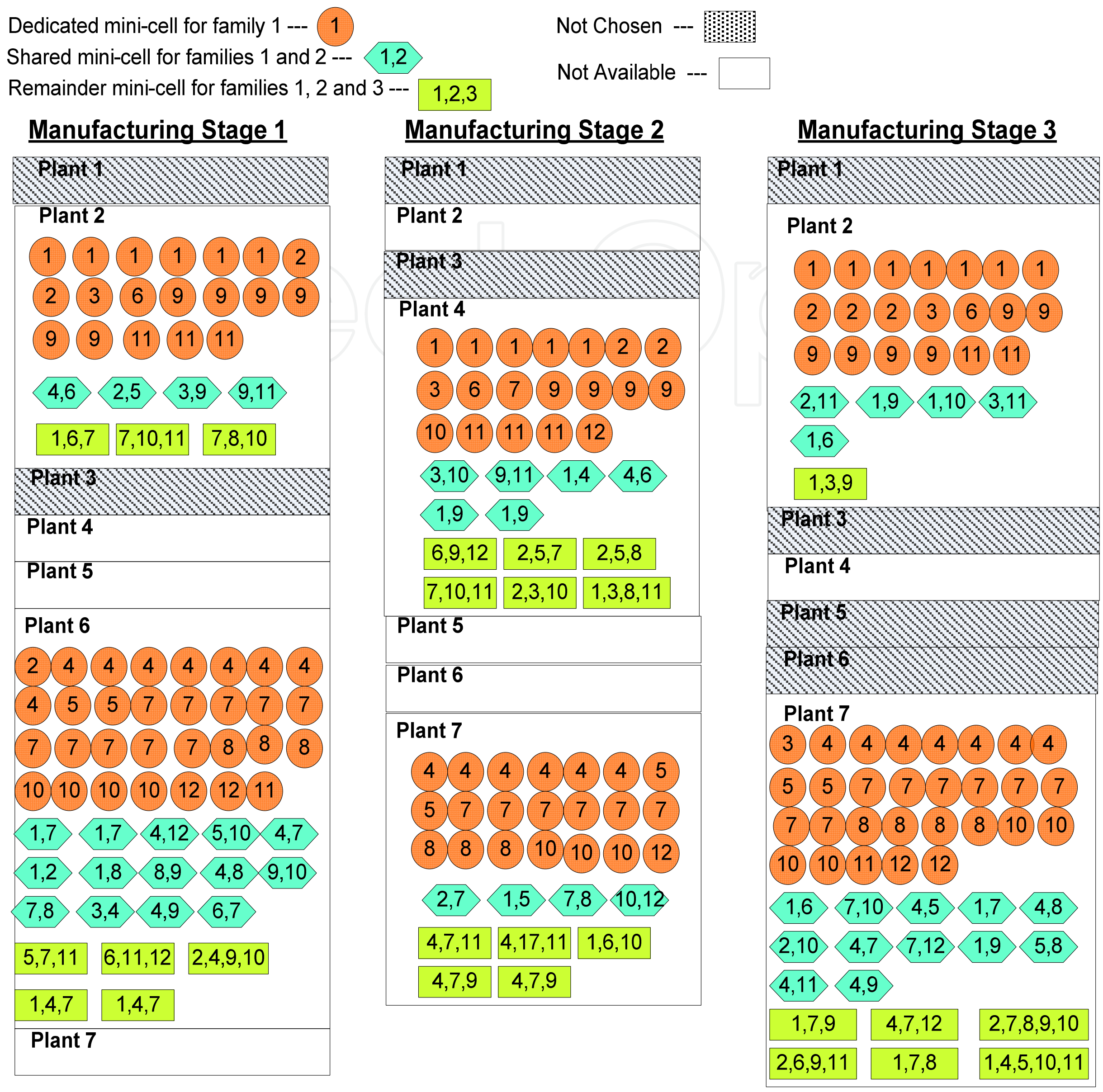

Fig. 7. Capacity allocation and plant location results

For multi-period production planning, the experimentation runs for a year (50 weeks). In each week, demand is randomly generated based on normal distribution. The proposed production model under such demand is solved by using OPL software, the demand shortage for each stage is recorded, and next, it is compared to the results of classical cellular system.

5. Comparison with classical mini-cellular system

In this section, performance of the proposed layered mini-cellular system is compared to that of a classical cellular system. Machine/workforce requirements and demand shortage are used as performance measures to evaluate these two systems. The proposed capacitated plant location model is also capable of solving resource management problems when classical cellular design is adopted in the production facility. However, the model parameters such as NM_k, U_{jk}, and EQ_{ik} are computed differently, since each mini-cell is dedicated to a single product family in the classical cellular system. The number of mini-cells required by product family *i* in stage *j* is computed in Equation 20, where μ_i is demand mean of family *i*, and PT_{ij} is the processing time (in minutes) of bottleneck operation for family *i* in stage *j*. RCU is the reserved cell utilization in order to handle high demand situation. Obviously, the value of RCU affects both performance measures: machine/workforce requirements and demand shortage. Reserving too little capacity leads to high demand shortage; while reserving too much capacity results in redundant machine/workforce therefore increasing production costs. In this section, the preliminary experimentation is carried out to illustrate the procedure, thus, RCU is set to be 10%. In the future, experimentation with various levels of RCU will be implemented and results will be studied.

$$NC_{ij} = \mu_i \times PT_{ij} \,/\, (40 \times 60 \times (1 - RCU)) \tag{20}$$

The capacity requirement is computed for each product family at each stage, and the results are summarized in Table 10. It is observed that classical system requires 176, 73, and 204 machines/workforce for manufacturing stages 1, 2, and 3, respectively; while layered system only requires 158, 61, and 195 machines/workforce.

	PF	Stage 1	Stage 2	Stage 3	Total Number
Number of Mini-Cells	1	9	12	10	245
	2	5	5	5	
	3	3	3	3	
	4	10	12	13	
	5	4	4	4	
	6	3	3	4	
	7	11	13	17	
	8	5	6	6	
	9	7	10	10	
	10	7	7	7	
	11	6	6	6	
	12	3	3	3	
Number of Machines/Workforce		176	73	204	453

Table 10. Summary of capacity requirement results of classical design

The performance of the proposed layered mini-cellular system in terms of handling fluctuating demand is investigated in this section. Fifty demand sets are randomly generated based on normal distribution given in Table 4. The service level for each period is computed based on the demand supplied from the facility network divided by total demand. The results are obtained by using both the layered design and classical cellular design with 10% reserved cell utilization (as shown in Figure 8). For manufacturing stage 1, it can be observed that layered mini-cellular system leads to a high service level (>90%) most of the time. There are only six out of 50 periods when the service level is below 90%. Under most conditions, layered system leads to a higher service level. There are only seven exceptions where classical design leads to a higher service level. The similar pattern could be also observed for manufacturing stages 2 and 3. It is clearly observed that, compared to the classical system, the layered system model requires less number of mini-cells and machines/workforce while still dealing with high demand fluctuation more effectively as evidenced by higher service levels.

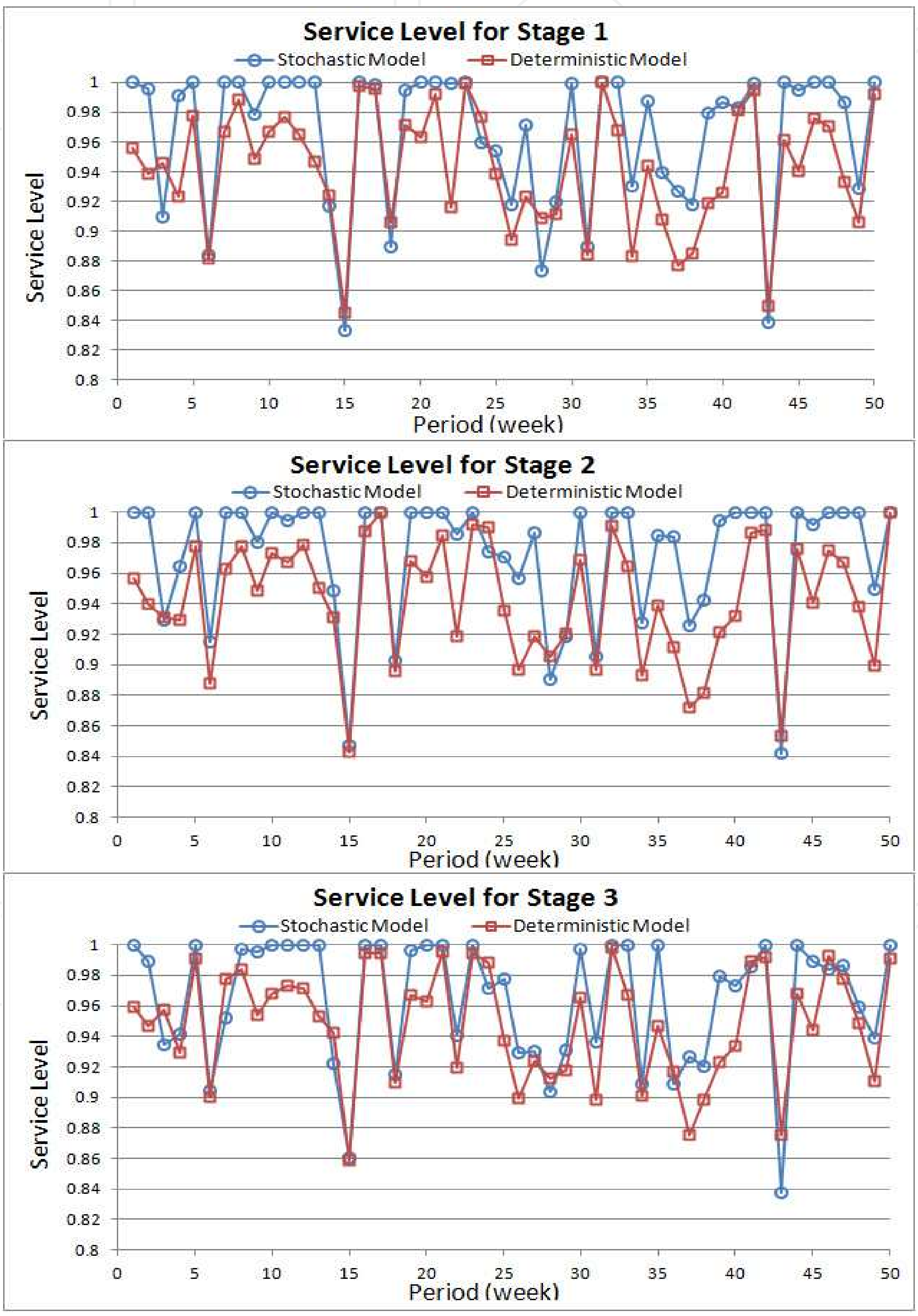

Fig. 8. Demand shortage for each manufacturing stage

6. Conclusion

This chapter studies the design of a supply chain involving multi-stage manufacturing operations with probabilistic product demand. Three levels of supply chain issues are first discussed. In the strategic level, a 'transnational vertical integration' market and production location strategy is taken, where the multi-stage manufacturing system is across various geographical locations and finished goods are sold in North American market. The study then mainly focuses on determining how much capacity should be allocated to which production facility for each manufacturing stage.

Manufacturing configuration in each individual facility is also taken into account in this chapter. The chapter integrates manufacturing system design with supply chain design by proposing a layered mini-cellular system. Each mini-cell is assumed to operate one manufacturing stage with maximum 40 hours weekly capacity. In the classical cellular system, a cell is dedicated to one product family. A layered system not only consists of dedicated mini-cells but also shared and remainder mini-cells. Mini-cell requirements and utilization are first estimated by using probability equations. Mini-cells are then grouped based on operation similarities among product families, and eventually, dedicated, shared and remainder mini-cells are formed. The latter two types of mini-cells deal with more than one product family so that resources are shared and demand fluctuation could be neutralized to a certain level.

A capacitated plant location math model is proposed to form supply chain network as well as allocate mini-cells to each facility for each manufacturing stage. Both mini-cell components and transportation costs are taken into account this model. Next, a capacity planning model determines detailed production quantity based on a specific weekly demand.

Experimentation is conducted and the results indicate the selection of production facilities and allocation of capacity. The performance of layered system is compared with the results of the classical cellular manufacturing system. It is important to notice that despite the lower number of machines/workforce was required by the layered system; the layered system satisfies demand better compared to the classical system. The results indicate that this study provides a complementary analytical model that explores the efficient way to locate and allocate inbound resources so that a certain level of supply chain efficiency and responsiveness could be achieved.

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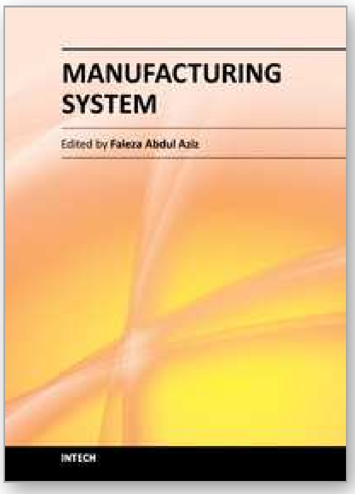

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This book attempts to bring together selected recent advances, tools, application and new ideas in manufacturing systems. Manufacturing system comprise of equipment, products, people, information, control and support functions for the competitive development to satisfy market needs. It provides a comprehensive collection of papers on the latest fundamental and applied industrial research. The book will be of great interest to those involved in manufacturing engineering, systems and management and those involved in manufacturing research.