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Reliability evaluation and adjustment of supply chain network design with demand fluctuations

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ABSTRACT

This study focuses on supply chain network design problems by considering economies of scale and demand fluctuations. A reliability evaluation method is developed to evaluate the performance of plants under demand fluctuations. In addition, two mathematical programming models are developed to determine the optimal adjustment decisions regarding production reallocation among plants under different fluctuating demands. The judgments to adjust or to do-nothing are investigated by comparing the results if the adjustment is made or not made. Results show that making adjustments benefits the manufacturers by reducing total production cost and avoiding revenue loss, which outweighs the extra costs, especially for high value-added products. Results also suggest that the manufacturer should ignore a short period abnormal state, since the benefits to respond to it might not compensate the high allocation costs. The results of this study provide a reference for the manufacturer in their decision making process of network planning with demand fluctuations, when they have to cope with benefits and costs during abnormal states.

1. Introduction

In the strategic supply chain network-planning phase, the problem generally involves deciding the configuration of the network that satisfies customer demand while minimizing the costs of manufactures. Although large-scale capacity is encouraged because there are economies of scale reducing costs, the advantage depends on the level of the market demand. The benefit brought by operating large-scale plants shrinks, and production costs dramatically increase when the market demand is insufficient to realize the economies of scale and the capacity utilization is low. On the other hand, revenue losses arise when supply does not match with a high market demand. The strategic supply chain network is a key factor influencing the efficiency of tactical operations and therefore has a long lasting impact on the manufacturers. The majority of the supply chain network problems use the average estimated customer demand patterns of the manufacturers over the planning years, covering both peak and off-peak periods. Unfortunately, unexpected abnormal events occur and may even continue for a period of time, thereby further influencing customer demand and affecting network performance. Therefore, survival and effectiveness lie in the ability of the manufacturers to respond promptly to environmental turbulence (Lloréns et al., 2005). Since the supply chain network design involves a commitment of meeting customer demand, how to design a flexible supply chain network by considering economies of scale and demand fluctuations is important.

A large number of optimization based approaches have been proposed for the design of supply chain networks (e.g. Arntzen et al., 1995; Jayaraman and Pirkul, 2001; Cohen and Moon, 1991). Other approaches focused on addressing the coordination of logistics operations in terms of the design of effective production and distribution systems (e.g. Cohen and Lee, 1988; Vidal and Goetschalckx, 1997; Eskigun et al. 2005). Due to the fact that large-scale models have been proven to be extremely difficult for solving optimality, most of related research has developed deterministic mixed integer programming models and focused on model improvements and algorithms to solve the developed models. Although such network designs can be seen as bases for short-run manufacturers' operational references, the performance results of network designs, apart from demand fluctuations, have not yet been evaluated.

The impact of uncertainty on manufacturer efficiency has prompted a lot of studies addressing the stochastic parameters in the supply chain planning phase. At the static and operational levels, there are great deals of research developing production/inventory models that deal with various uncertainty factors in the environment. The attention has been focused mostly on the

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probabilistic modeling of the customer demand side (e.g. Cachon and Fisher, 2000; Gavirneni et al., 1997; Gavirneni, 2002). Other studies have dealt with supply uncertainties, such as machine breakdowns, strikes, shortages in material availability, etc. The majority of these research employed and modified EOQ formulas to include random variables reflecting different uncertainties (e.g. Hariga and Haouari, 1999; Wang and Gerchak, 1996). They showed how a company's performance is affected by an uncertain environment, and provided tools to tackle these uncertainties and ease their influence. The planning frame of these studies is focused on the operational level, rather than strategic design.

Taking a different approach, several studies have employed stochastic programming models to formulate optimization problems that involve uncertain input parameters (e.g. Santoso et al., 2005; Tsiakis et al., 2001). These studies focused mainly on providing efficient algorithms to solve the stochastic integer programming models, and presented computational results for the supply chain network involving different numbers of nodes, arcs or products. Our earlier work, i.e. Hsu and Li (2009) has developed a deterministic mixed integer programming model to investigate plant capacity and production allocation problems by considering average monthly market demand and economies of scale for wafer fabrication industry. The study showed that the capacity utilization and the production amount in the short run, and the capacity of multiple plants in the long run are related, and that those two factors influence the total cost. However, abnormal states do occur unexpectedly, resulting in severe demand fluctuations, and affecting the performance of a well-designed network as the abnormal state continues. In other words, the network performance is affected such that the larger difference in demand fluctuation is from the forecasted, and the longer that difference remains in place, the larger the accumulated loss of revenue will be for the manufacturer. Instead of reconstructing the entire network, it is important to propose an adjustment method for the manufacturer that maintains overall network design objectives.

However, little research has investigated how the impacts of demand fluctuation are in terms of its magnitude and duration on the network performance, which is important for the manufacturer to determine an adjustment strategy. In short, few studies have combined supply chain network modeling and economy theory to formulate an integrated model to cope with both production economies and demand fluctuations. The present study attempts to explore the above issues by formulating a series of models. The study formulates different supply chain network adjustment models based on demand expansion and reduction, to cope with different fluctuating demands combined with various durations when the abnormal state continues.

When there is an abnormal event resulting in demand fluctuations, it is important for the manufacturer to investigate whether the capacity utilization of the plants maintains cost economies and customer service level. A reliability evaluation method is necessary to tackle how well the initially proposed capacity of plants will operate effectively under different demand fluctuations. When the proposed results are detected to have low reliability, an adjustment of the network is considered to prevent incurring costs and revenue loss. This study focuses on two issues: the reliability evaluation for the proposed network design and the adjustment for the supply chain network to deal with the demand fluctuation. To simplify the study, the inventory is not considered in this research. The two problems are solving simultaneously in response to different demand fluctuations.

This study first designs a supply chain network for a manufacturer who operates multiple plants in different regions and the modeling of the problem herein follows that of Hsu and Li (2009). The discussions of the problem focused on how economies of scale influence the optimal capacity and production allocation among the plants. We further investigate how demand fluctuations from different markets influence the production of the plants and how they affect their performance. A reliability evaluation method is presented for assessing how well the result of network design will work under future potential short-run abnormal demand fluctuations.

Demand expansion may result in unsatisfied customers and heavy revenue loss due to limited capacity. Based on the unreliable situations, this study proposes a production adjustment strategy that suggests for other reliable plants with the remaining capacity to produce more, or to book the overcapacity with outsourcing firms. The induced costs and benefits associated with these adjustment decisions are also discussed. This study proposes a mathematical programming model for determining the optimal adjustment decisions in terms of production reallocations among all plants by minimizing total adjustment cost during months with excessive demand, given the sum of allocation cost, extra material purchase cost, difference in production cost, penalty cost and transportation cost. On the other hand, when there is a decline in customer demand, the potential production amount of plants is significantly reduced, resulting in production diseconomies. The study proposes a production adjustment strategy in response to demand reduction, as opposed to demand expansion, such that the production can be focused on a few economical plants, instead of being dispersed over all the plants. The study formulates a mathematical programming model for determining the optimal production reallocation among the plants by minimizing the total adjustment cost during months with a reduced demand, given by the sum of allocation cost, difference in production cost and transportation cost. The decision to perform an adjustment or do-nothing is also investigated, comparing the results of not making an adjustment with that if an adjustment is made during the duration of an abnormal state.

The basic input data when designing a supply chain network are the estimated demands from different markets. Past literature relied heavily on simple forecast techniques, such as the simple moving average method and the exponential smoothing method, to forecast demand from operational perspectives (e.g. Xu et al., 2000). The accuracy of these forecast results is directly dependent on the volumes of available data. However, uncertain socio-economic conditions and the short life of high-tech products complicate demand forecasts. This study employs gray time-series models, GM(1,1), proposed by Deng (1985), to forecast the customer demand pattern as the basic input data in the supply chain network design models. Gray theory deals with systems with poor information, and it needs only 4 data to formulate the Gray forecasting model. In addition, such a demand forecasting model incorporates the effects of uncertain conditions, thereby fully accounting for the dynamic aspects of demand changes (Hsu and Wen, 2002).

The rest of this paper is organized as follows. Section 2 describes the supply chain network design problem and presents the reliability evaluation method. Section 3 provides a fine-tuning method for adjusting the production allocation among plants in response to different demand fluctuations. A case study is provided in Section 4 to illustrate the application of the models, and finally we draw our conclusions in Section 5.

2. Description and formulation of the problems

This study aims to design a supply chain network for a manufacturer who operates multiple plants in different regions. The supply chain design problem in this paper is defined as follows. Given customer demand and their locations, determine the location, capacity and production amounts for all the plants, and the material/product flows from the suppliers/plants to the plants/customers in different areas, so as to satisfy customer demand and minimize average per-unit product cost, given by the sum of inbound, production and outbound costs. The modeling of supply chain network design problem herein follows that of Hsu and Li (2009).

2.1. Supply chain network design programming model

Consider a supply chain network **G**(***N***, ***A***), where ***N*** and ***A*** represent a set of nodes and a set of links, respectively, in a directed graph **G**. In the supply chain network, a node can be referred to a specific supplier, plant and customer as in the material supply, manufacturing and customer echelons, while the links represent the relationships between the plant and its suppliers at the upper echelon and between the plant and its customers at the lower echelon. Let k be a specific plant operated by the manufacturer with production amount f_k and capacity v_k, where $f_k \le v_k$, while s represents a specific qualified supplier. The capacity utilization of plant k can be defined as $Y_k = (f_k/v_k)$. A specific customer is denoted by c with demand f_c. In the present paper, all the quantities apply for 1 month. Moreover, let w be the required material flows for producing one unit product and wf_k be the required material amount of plant k. The production of plant k is not processed if the material flows from all its active suppliers do not match the total required amount. The total output from k is to satisfy the demands of the customers served. These relationships between a specific plant and its active suppliers and between the plant and its customers can be formulated as follows:

$$wf_k = \sum_{\forall s} f_k^s \delta_k^s \tag{1}$$

$$f_k = \sum_{\forall c} f_c^k \beta_c^k \tag{2}$$

where f_k^s and f_c^k represent, respectively, the material flows/product flows from supplier s/plant k to plant k/customer c. And, δ_k^s and β_c^k are both indicator variables representing whether supplier s serves plant k and customer c is served by plant k, respectively. Since the demand from all customers should be satisfied, the following equation holds: $\sum_{\forall k} f_k = \sum_{\forall c} f_c$.

The production cost incorporates both the capital cost and the variable production cost. The capital cost includes the costs attributed to the purchasing and installation of related equipment, plant construction, land rental fee, etc., which differs among plants due to different locations and capacity size. The variable production cost includes those paid for input factors other than materials, such as labor, utility, insurance, etc. The average production cost per-unit product for the manufacturer is expressed as follows:

$$\frac{\sum_{\forall k} C(v_k) + c(v_k) f_k}{\sum_{\forall k} f_k} \tag{3}$$

where $C(v_k)$ and $c(v_k)$ represent the capital cost and the variable production cost of plant k, respectively.

Inbound costs originating from material acquirement include the fixed costs of a contract with active suppliers, material purchase and transportation costs. The average inbound cost per-unit product for the manufacturer can be expressed as the sum of the average fixed, material purchase and transportation costs, which can be stated as

$$\frac{1}{\sum_{\forall k} f_k}\left(\sum_{\forall k}(V_s\gamma_s + p_s\sum_{\forall k} f_k^s\delta_k^s) + \sum_{\forall k}\sum_{\forall s} t_k^s f_k^s \delta_k^s\right) \tag{4}$$

where V_s be the fixed cost of the manufacturer with material supplier s, γ_s is an indicator variable representing whether supplier s is active for the manufacturer, p_s denotes the unit-material purchase price charged by supplier s and t_k^s is the unit-material transportation cost from supplier s to plant k.

The outbound cost in this study represents the costs resulting from the distance between customers and plants and depends on the assignments from customers in different areas to different plants. The average outbound cost per-unit product for the manufacturer is expressed as

$$\frac{1}{\sum_{\forall k} f_k}\sum_{\forall c}\sum_{\forall k} t_c^k f_c^k \beta_c^k \tag{5}$$

where t_c^k represents the unit-product transportation cost from plant k to customer c.

Following Hsu and Li (2009), the nonlinear MIP model for the design of the supply chain network (P1) can now be formulated as follows:

P1 : min

$$\frac{\sum_{\forall k} C(v_k) + c(v_k) f_k}{\sum_{\forall k} f_k} + \frac{1}{\sum_{\forall k} f_k}\left(\sum_{\forall k}\left(V_s\gamma_s + p_s\sum_{\forall k} f_k^s\delta_k^s\right) + \sum_{\forall k}\sum_{\forall s} t_k^s f_k^s \delta_k^s\right) + \frac{1}{\sum_{\forall k} f_k}\sum_{\forall c}\sum_{\forall k} t_c^k f_c^k \beta_c^k \tag{6a}$$

$$\text{s.t.} \quad wf_k = \sum_{\forall s} f_k^s \delta_k^s \quad \forall k \tag{6b}$$

$$f_k = \sum_{\forall c} f_c^k \beta_c^k \quad \forall k \tag{6c}$$

$$\sum_{\forall k} f_k = \sum_{\forall c} f_c \tag{6d}$$

$$Y_k = \frac{f_k}{v_k} \quad \forall k \tag{6e}$$

$$v_k, f_c^k, f_k^s \ge 0 \text{ and integer} \quad \forall k\ \forall s\ \forall c \tag{6f}$$

$$Y_k \ge 0 \quad \forall k \tag{6g}$$

$$\delta_k^s = 0 \text{ or } 1 \quad \forall k\ \forall s \tag{6h}$$

$$\beta_c^k = 0 \text{ or } 1 \quad \forall k\ \forall c \tag{6i}$$

Eq. (6a) is the objective function that minimizes the total average cost per-unit product. Eq. (6b) expresses that the material flows from the suppliers to the plant must equal the required material amount. Eq. (6c) defines the relationship between the production amount and the product flows from the plant to the customers served. Eq. (6d) constrains the total production amount to meet the total customer demand. Eq. (6e) defines the capacity utilization. Eq. (6f) constrains the decision variables v_k, f_c^k and f_k^s to be non-negative integers. Eq. (6g) constrains the decision variable Y_k to be non-negative. Finally, Eqs. (6h) and (6i) constrain the decision variables δ_k^s and β_c^k to be binary.

2.2. Reliability evaluation methods

The discussions so far have dealt with supply chain network design problems, and focused on how economies of scale influence the optimal capacity and production allocation among the plants. In this section we further investigate how demand fluctuations from different markets influence the production of the plants and how they affect their performance. Reliability engineering is a well-established area of engineering, which has been widely applied to software reliability, mechanical reliability, transportation network reliability, etc (e.g. Billinton and Allan, 1983; Chen et al., 1999, 2002). Hsu and Wen (2002) developed a reliability evaluation method for airline network design, evaluating the reliability of initial proposed flight frequencies under normal/abnormal demand fluctuations. In their paper, they also presented a priori adjustment of flight frequencies. Lai et al. (2002) developed a measurement instrument for supply chain performance in transport logistics.

This study revises the definition of reliability in Hsu and Wen (2002) to capture the characteristics of the issues concerned. The unreliability problem arises from the condition that the proposed capacity cannot match the customer demand due to the fact that an abnormal event occurred. When abnormal events lead to a reduced demand, there is an excess of supply, which leads to increased production cost due to low capacity utilization. On the other hand, even though an increase in demand decreases the production cost, a loss in revenue follows once the proposed capacity cannot meet the excessive demand. Thus, the supply chain network design, i.e. the proposed capacity and production allocation, only produce reliability for the manufacturer when the demand fluctuates within a range that allows the capacity utilization of the plants to maintain cost economies and customer service level. This study defines reliability as the probability that the initially proposed capacity of the plant will operate effectively under demand fluctuations.

The proposed capacities and production amounts of the plants resulting from supply chain network design together with the input of average forecasted monthly customer demand are initially reliable. Let the capacity utilization be the basic criterion for evaluating the reliability of the plant under demand fluctuations. The capacity utilization of plant k with respect to random production amount $\tilde{f}_k^t$ in month t, $Y_k(\tilde{f}_k^t)$, is defined as

$$Y_k(\tilde{f}_k^t) = \frac{\tilde{f}_k^t}{v_k^*} \tag{7}$$

Since the proposed capacity, v_k^*, is fixed, $Y_k(\tilde{f}_k^t)$ is in direct proportion to the realizations of $\tilde{f}_k^t$ for month t. Let $\overline{f}_k^t$ represent a random realization of $\tilde{f}_k^t$ and a potential value of the production amount of plant k under all demand fluctuations over month t. If $Y_k(\overline{f}_k^t)=0$, it implies that the potential production amount is zero, i.e. $\overline{f}_k^t=0$, and if $Y_k(\overline{f}_k^t)\geq 1$ it shows that the plant is under full-capacity production or that the potential production amount exceeds its capacity, which in turn implies that the capacity cannot satisfy the excess demand. This study assumes $\overline{Y}_k=1$ to be the maximally acceptable capacity utilization of plant k, which has a lowest unit-product production cost, and let $\underline{Y}_k$ be the minimally acceptable capacity utilization, which assumes a tolerable minimum revenue for the manufacturer.

When the proposed capacity is applied under fluctuating demand, and if $\tilde{f}_k^t$ leads $Y_k(\tilde{f}_k^t)$ to $\underline{Y}_k \leq Y_k(\tilde{f}_k^t) \leq \overline{Y}_k$, then plant k is defined as reliable in month t. Inversely, if $\tilde{f}_k^t$ leads $Y_k(\tilde{f}_k^t)$ to $\underline{Y}_k > Y_k(\tilde{f}_k^t)$ or $Y_k(\tilde{f}_k^t) > \overline{Y}_k$, then plant k is unreliable under demand fluctuations in month t. In other words, the reliability of a specific plant is defined as the probability that the capacity utilization falls between the acceptable limits, namely:

$$\begin{aligned} R(\tilde{f}_k^t) &= \Pr[\underline{Y}_k \leq Y_k(\tilde{f}_k^t) \leq \overline{Y}_k] \\ &= \Pr[\underline{Y}_k v_k^* \leq \tilde{f}_k^t \leq \overline{Y}_k v_k^*] \end{aligned} \tag{8}$$

The impacts of fluctuating customer demands on the production amount of different plants are further analyzed. Let θ_k be the ratio of the production from plant k to that from all plants, which is the result of the initially proposed production allocation among the plants, namely:

$$\theta_K = \frac{f_k}{\sum_{\forall k} f_k} \tag{9}$$

Variable θ_k also indicates the magnitude of a plant to the manufacturer, in that the larger the production of a plant, the more the manufacturer relies on its output to serve customers, and $\sum_{\forall k}\theta_k=1$. Since the total production amount from all plants is restricted to meet demands from all customers, $\sum_{\forall k} f_k$ in Eq. (9) can be substituted by $\sum_{\forall c} f_c$, yielding $\theta_k=(f_k/\sum_{\forall c} f_c)$. Furthermore, Eq. (9) can be rewritten as

$$\tilde{f}_k^t = \theta_k \sum_{\forall c} \tilde{f}_c^t \tag{10}$$

Substituting Eq. (10) for $\tilde{f}_k$ in Eq. (8), Eq. (8) can be rewritten in terms of customer demand as

$$R_k(\tilde{f}_k^t) = \Pr\left[\frac{\underline{Y}_k v_k^*}{\theta_k} \leq \sum_{\forall c} \tilde{f}_c^t \leq \frac{\overline{Y}_k v_k^*}{\theta_k}\right] \tag{11}$$

The random variable $\tilde{f}_c^t$ is assumed to follow a normal distribution with parameters $\overline{f}_{n_s}^t$ and $\sigma(\tilde{f}_c^t)$. A similar assumption of normal distribution used to treat fluctuations of customer demand can be found in Miranda and Garrido (2004) and Ouyang et al. (2004). The total fluctuating demand, $\sum_{\forall c}\tilde{f}_c^t$, is also a random variable, distributing with a normal distribution with mean $\sum_{\forall c}\overline{f}_c^t$ and standard deviation $\sqrt{\sigma^2(\sum_{\forall c}\tilde{f}_c^t)}$, where $\sigma^2(\sum_{\forall c}\tilde{f}_c^t)=\sum_{\forall c}\sigma^2(\tilde{f}_c^t)+2\sum_{\forall c}\sum_{\dot{c}\neq c}\mathrm{Cov}(\tilde{f}_{\dot{c}}^t,\tilde{f}_c^t)$. The reliability of plant k can now be evaluated using the cumulative distribution functions of a normal distribution:

$$R_k(\tilde{f}_k^t) = \Phi\left(\frac{(\overline{Y}_k v_k^*/\theta_k) - \sum_{\forall c}\overline{f}_c^t}{\sqrt{\sum_{\forall c}\sigma^2(\tilde{f}_c^t)}}\right) - \Phi\left(\frac{\left(\underline{Y}_k v_k^*/\theta_k\right) - \sum_{\forall c}\overline{f}_c^t}{\sqrt{\sum_{\forall c}\sigma^2\left(\tilde{f}_c^t\right)}}\right) \tag{12}$$

where $\Phi(z)$ is the cumulative distribution function of the standard normal distribution.

In practice, some abnormal events may occur at a particular market and continue for a period of time, such as a financial crisis, war or a natural disaster, or a downturn/upswing in the economy, which will cause the demand from that market to fluctuate more than usual. An abnormal state is one in which monthly customer demand values do not follow the normal demand distributions, as estimated from all survey years, due to the occurrence of an abnormal event. For customer c, let K_c represent the set of all distinct states that occur on the market during the planning year and let $K_c \equiv \{w_c^0, w_c^1, .., w_c^i, \ldots w_c^W\}$, where w_c^i denotes a specific abnormal state, where W indicates the number of distinct abnormal states, and w_c^0 represents a normal state in which no abnormal fluctuation occurs. Let $\Pr(w_c^i)$ be the probability that state w_c^i occurs during the planning year, where $\Pr(w_c^i)\geq 0$ and $\sum_{i=0}^{W}\Pr(w_c^i)=1$.

Suppose that, during the planning year, an abnormal state w_c^i occurs at time t_i^* with duration $\tilde{g}_c^i$, where t_i^* is the time elapsed from the beginning of the year, expressed in units of 1 month. The duration of w_c^i, $\tilde{g}_c^i$, is considered to be a random variable. For the sake of simplicity, $\tilde{g}_c^i$ is supposed to have a finite discrete distribution: $\{(g_c^{ij}, p_j),\ j=1,2\ldots,G_c\}$, where g_c^{ij} is a realization of $\tilde{g}_c^i$ with probability p_j, and G_c is the number of realizations of $\tilde{g}_c^i$. Let I be the set of all the months during the planning year, and let $I_c^{i,j}$ represent the set of months when an abnormal state w_c^i continues, i.e. $I_c^{i,j} \equiv \{t\,|\,\lceil t_i^*\rceil \leq t < \lceil t_i^* + g_c^{ij}\rceil\}$, given a state duration g_c^{ij}. Moreover, suppose that the monthly demand from customer c in abnormal state w_c^i follows a normal distribution with different parametric values. That is, the monthly demand associated with abnormal state w_c^i follows a different random variable, $\tilde{f}_{c,ij}^t, \forall t \in I_c^{i,j}$. Note that the mean and standard deviation of the distribution $\tilde{f}_{c,ij}$ is related to the effect and duration of the event corresponding to state w_c^i. Consider different durations of abnormal state w_c^i, v_c^{ij}, and their probabilities p_j, then the average demand from customer c in month t given the abnormal state w_c^i, $\tilde{f}_{c,i}^t$, can be expressed as

$$\tilde{f}_{c,i}^t = \sum_{j=1}^{V_c} p_j \tilde{f}_{c,ij}^t \tag{13}$$

Furthermore, the expected fluctuating demand from customer n_s in month t, depending on the occurrence of abnormal states, is obtained as $\tilde{f}_c^t = \sum_{i=1}^{W} \Pr(w_c^i)\tilde{f}_{c,i}^t$. The reliability of plant k in month t subject to abnormal demand can further be calculated using Eq. (12).

3. Supply chain network adjustment model

Some plants may be found to have low reliability when their initial proposed capacity and production allocation results experience severe demand fluctuations. To prevent incurring these costs, one should consider adjusting the network. Since the manufacturing echelon is the most value-added, this study focuses on adjusting the production allocation of the plants for the manufacturer.

3.1. Customer demand expansion

Demand expansion resulting from an abnormal state may result in the potential production amount exceeding the capacity, given that the customer demand is being satisfied. Because there is limited capacity, demand expansion usually results in unsatisfied customers. In addition, an excessive demand burdens the manufacturer with a heavy revenue loss if that abnormal state lasts for a long period of time. Based on these unreliable situations, this study proposes a production adjustment strategy that suggests for other reliable plants with the remaining capacity to produce more, or to book the overcapacity with outsourcing firms. The induced costs and benefits associated with these adjustment decisions are also discussed. This study proposes a mathematical programming model for determining the optimal adjustment decisions in terms of production reallocations among all plants by minimizing total adjustment cost during months with excessive demand, given the sum of allocation cost, extra material purchase cost, difference in production cost, penalty cost and transportation cost.

Let $\mathbf{t} \equiv \{I_c^{i,j}, \forall n_s, \forall i\}$ represent the set of months of the time interval within which excessive demand arises and continues and $n(\mathbf{t})$ is the number of months in $\mathbf{t}$ where the adjustment is scheduled and executed. Let $\mathbf{K}$ be the set of the plants operated by the manufacturer, let $\mathbf{J} \equiv \{\dot{k}\}$ be the set of the detected unreliable plants, and $\bar{k}$, $\bar{k} \in \mathbf{K}-\mathbf{J}$, represents a reliable plant, where $Y_{\dot{k}}(\tilde{f}_{\dot{k}}) > 1$ and $Y_{\bar{k}}(\tilde{f}_{\bar{k}}) \le 1$, respectively. Moreover, let o be a specific alternative outsourcing firm, where the product quality is indifferent from that of the manufacturer. For the sake of simplicity, this study averages the total customer demands and denotes $\bar{f}_C$ as the average monthly customer demand for the manufacturer during $n(\mathbf{t})$ months, $\bar{f}_C = (1/n(\mathbf{t}))\sum_{\forall t}\sum_{\forall c}\bar{f}_c^t$, where $\bar{f}_c^t$ is a realization demand from customer c in month t, $t \in$ t. Then the expected average monthly production amount of plant k can be estimated as $\bar{f}_k = \theta_k \bar{f}_c$.

The allocation cost includes the fixed allocation costs and the variable allocation costs. The fixed allocation costs are those expenses associated with changing the production schedule, contract costs for the outsourcing firms, etc. and are incurred once the manufacturer determines to make an adjustment. The variable allocation costs can be divided into two categories: outsourcing cost and compensation cost, where the former are costs charged by the outsourcing firms, and the latter reflects the cost of additional labor, extra utilities, etc, since the overproduction must be scheduled in a reliable plant. Let c_o be the unit-product outsourcing cost paid to outsourcing firm o and let $h_{\bar{k}}$ be the unit-production compensation cost for plant $\bar{k}$. The outsourcing cost reflects not only the production and material costs borne by the outsourcing firm, but also the premium charged, and thus it can be concluded that $c_o \ge h_{\bar{k}}$. Consequently the total allocation cost over $n(\mathbf{t})$ months can be formulated as

$$O + n(\mathbf{t})\left(\sum_{\forall o} c_o \sum_{\forall \dot{k}} q_{\dot{k},o} x_o^{\dot{k}} + \sum_{\forall \bar{k}} h_{\bar{k}} \sum_{\forall \dot{k}} \Delta_{\dot{k},\bar{k}} y_{\bar{k}}^{\dot{k}}\right) \tag{14}$$

where O represents the fixed allocation cost, and $q_{\dot{k},o}$ and $\Delta_{\dot{k},\bar{k}}$ are the production amounts allocated from plant $\dot{k}$ to outsourcing firm o and to reliable plant $\bar{k}$, respectively. Indicators $x_o^{\dot{k}}$ and $y_{\bar{k}}^{\dot{k}}$ represent, respectively, whether there exist a production allocation relationship between $\dot{k}$ and o and between $\dot{k}$ and $\bar{k}$. Moreover, $\sum_{\forall \dot{k}} q_{\dot{k},o} x_o^{\dot{k}}$ and $\sum_{\forall \dot{k}} \Delta_{\dot{k},\bar{k}} y_{\bar{k}}^{\dot{k}}$ in Eq. (14) indicate the outsourcing amount for outsourcing firm o, and the additional production amount of $\bar{k}$, respectively.

The extra material cost is due to the fact that there most likely is not sufficient material available to support the additional production. Let $\bar{p}$ be the average unit-material cost. In this case $\bar{p}$ will be high since it is an emergency purchase during a high demand period in the market. The extra material cost over $n(\mathbf{t})$ months is given as

$$n(\mathbf{t})\bar{p}\sum_{\forall \dot{k}}\sum_{\forall \bar{k}} \Delta_{\dot{k},\bar{k}} y_{\bar{k}}^{\dot{k}} \tag{15}$$

The differences in production costs discussed herein reflect the benefits brought by production reallocation. In other words, there are chances of scheduling full-capacity production for all plants under demand expansion, thereby reducing the production cost. Let $\bar{f}_{\dot{k}}$ and $\bar{f}_{\bar{k}}$ represent, respectively, the realized average monthly production amount of plant $\dot{k}$ and $\bar{k}$ under demand expansion, i.e. unadjusted amounts, while $f'_{\dot{k}}$ and $f'_{\bar{k}}$ are the adjusted amounts, respectively. Then, the relationship between the adjusted and unadjusted production amounts can be expressed as follows:

$$\sum_{\dot{k}} (\bar{f}_{\dot{k}} - f'_{\dot{k}}) = \sum_{\dot{k}}\sum_{o} q_{\dot{k},o} x_o^{\dot{k}} + \sum_{\dot{k}}\sum_{\bar{k}} \Delta_{\dot{k},\bar{k}} y_{\bar{k}}^{\dot{k}} \tag{16a}$$

$$f'_{\bar{k}} = \bar{f}_{\bar{k}} + \sum_{\forall \dot{k}} \Delta_{\dot{k},\bar{k}} y_{\bar{k}}^{\dot{k}} \tag{16b}$$

$$f'_{\dot{k}} = \bar{f}_{\dot{k}} - \sum_{\forall \bar{k}} \Delta_{\dot{k},\bar{k}} y_{\bar{k}}^{\dot{k}} - \sum_{\forall o} q_{\dot{k},o} x_o^{\dot{k}} \tag{16c}$$

Note that the adjusted production amount is restricted by the capacity, $f'_{\dot{k}} \le v_{\dot{k}}$ and $f'_{\bar{k}} \le v_{\bar{k}}$. As shown in Eq. (16b), a reliable plant produces more after production reallocation, $f'_{\bar{k}} \ge \bar{f}_{\bar{k}}$, which leads to a lower production cost. Considering all the plants, which do not reach their full-capacity production before production reallocation, the total difference in production cost over $n(\mathbf{t})$ months can then be formulated as

$$n(\mathbf{t})\sum_{\forall \bar{k}}\left(\frac{C(v_{\bar{k}}^*) + c(v_{\bar{k}}^*)\bar{f}_{\bar{k}}}{\bar{f}_{\bar{k}}} - \frac{C_{\bar{k}}(v_{\bar{k}}^*) + c(v_{\bar{k}}^*)f'_{\bar{k}}}{f'_{\bar{k}}}\right)f'_{\bar{k}} \tag{17}$$

Substituting Eq. (16b) for $f'_{\bar{k}}$ in Eq. (17), Eq. (17) can be rewritten as

$$n(\mathbf{t})\sum_{\forall\bar{k}}\frac{C(v_{\bar{k}}^{*})\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}}{f_{\bar{k}}} \tag{18}$$

where $n(\mathbf{t})\sum_{\forall\bar{k}}(C(v_{\bar{k}}^{*})\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}/f_{\bar{k}})>0$ reveals that there is always a cost saving due to production reallocation, and that the total benefits are significant when the amount of additional production, $\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}$, and the number of months with excessive demands, $n(\mathbf{t})$ is considerable.

Of course the manufacturer can also decide to keep the status quo and do-nothing. In that case the production allocation among the plants remains the same as initially proposed. However, loss of revenue and/or service downgrading by the customer due to unsatisfied demands are the result. The production penalty cost is introduced to represent the loss of revenue. The unit-product penalty cost can be estimated based on the unit-product price, P, and the ratio of penalty cost to unit-product price, ϕ. The total penalty cost over $n(\mathbf{t})$ months is given by

$$n(\mathbf{t})\phi P\sum_{\forall\dot{k}}(\bar{f}_{\dot{k}}-f_{\dot{k}}) \tag{19}$$

Production reallocation may avoid high penalty costs and result in decreased production costs. Nevertheless, it can lead to increased transportation costs if the product is shipped from a distant plant or an outsourcing firm to customers in different regions. Let $\bar{t}_{\bar{k}}$ and $\bar{t}_{o}$ be the average unit-product transportation costs from plant $\bar{k}$ to the customers and that from outsourcing firm o to the customers, respectively; then the total transportation cost over $n(\mathbf{t})$ months can be formulated as

$$n(\mathbf{t})\left(\sum_{\forall\bar{k}}\bar{t}_{\bar{k}}\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}+\sum_{\forall o}\bar{t}_{o}\sum_{\forall\dot{k}}q_{\dot{k},o}x_{o}^{\dot{k}}\right) \tag{20}$$

The supply chain network adjustment model in response to customer demand expansion can be determined by solving the following programming model:

P2 : min

$$O+n(\mathbf{t})\left(\sum_{\forall o}(c_o+\bar{t}_o)\sum_{\forall\dot{k}}q_{\dot{k},o}x_{o}^{\dot{k}}+\sum_{\forall\bar{k}}h_{\bar{k}}\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}+\bar{p}\sum_{\forall\dot{k}}\sum_{\forall\bar{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}+\phi P\sum_{\forall\dot{k}}(\bar{f}_{\dot{k}}-f_{\dot{k}})\right.$$
$$\left.\frac{+\sum_{\forall\bar{k}}\bar{t}_{\bar{k}}\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}-\sum_{\forall\bar{k}}C(v_{\bar{k}}^{*})\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}}{f_{\bar{k}}}\right) \tag{21a}$$

$$\text{s.t.}\quad \sum_{\dot{k}}(\bar{f}_{\dot{k}}-f'_{\dot{k}})=\sum_{\dot{k}}\sum_{o}q_{\dot{k},o}x_{o}^{\dot{k}}+\sum_{\dot{k}}\sum_{\bar{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}} \tag{21b}$$

$$f'_{\bar{k}}=\bar{f}_{\bar{k}}+\sum_{\forall\dot{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}\quad\forall\bar{k} \tag{21c}$$

$$f'_{\dot{k}}=\bar{f}_{\dot{k}}-\sum_{\forall\bar{k}}\Delta_{\dot{k},\bar{k}}y_{\bar{k}}^{\dot{k}}-\sum_{\forall o}q_{\dot{k},o}x_{o}^{\dot{k}}\quad\forall\dot{k} \tag{21d}$$

$$x_{o}^{\dot{k}}=0\ \text{or}\ 1\quad\forall\dot{k}\ \forall o \tag{21e}$$

$$y_{\bar{k}}^{\dot{k}}=0\ \text{or}\ 1\quad\forall\dot{k}\ \forall\bar{k} \tag{21f}$$

$$q_{\dot{k},o}\ \text{and}\ \Delta_{\dot{k},\bar{k}}\geq 0\ \text{and integer}\quad\forall\dot{k}\ \forall\bar{k}\ \forall o \tag{21g}$$

Eq. (21a) is the objective function that minimizes the total adjustment cost over $n(\mathbf{t})$ months. Eqs. (21b), (21c) and (21d) express the relationships between the adjusted and unadjusted production amounts of the plants. Eqs. (21e) and (21f) constrain the decision variables $x_{o}^{\dot{k}}$ and $y_{\bar{k}}^{\dot{k}}$ to be binary. Finally, Eq. (21g) defines decision variables $q_{\dot{k},o}$ and $\Delta_{\dot{k},\bar{k}}$ to be non-negative integers.

3.2. Customer demand reduction

The potential production amount of plants is significantly reduced whenever there is a decline in customer demand, resulting in production diseconomies. These production costs will be even higher if most of the plants are located in regions with a high commodity price index. This study proposes a production adjustment strategy in response to demand reduction, as opposed to demand expansion, such that the production can be focused on a few economical plants, instead of being dispersed over all the plants. This study considers the costs and benefits associated with production adjustment. It formulates a mathematical programming model for determining the optimal production reallocation among the plants by minimizing the total adjustment cost during months with a reduced demand, given by the sum of allocation cost, difference in production cost and transportation cost.

Let $\mathbf{y}\equiv\{I_{c}^{i,j},\forall c,\forall i\}$ represent the set of months belonging to the time interval within which a reduced demand occurs and $n(\mathbf{y})$ is the number of months in $\mathbf{y}$, in which the adjustment is scheduled and executed. Let $\mathbf{I}\equiv\{\ddot{k}\}$ be the set of the unreliable plants, and $\hat{k}$, $\hat{k}\in\mathbf{K}-\mathbf{I}$, represents a reliable plant under demand reduction, respectively. Moreover, let $\bar{f}_{\ddot{k}}$ and $f'_{\ddot{k}}$ represent the unadjusted and adjusted average monthly production amounts of plant $\ddot{k}$, and let $\bar{f}_{\hat{k}}$ and $f'_{\hat{k}}$ be the unadjusted and adjusted production amounts of plant $\hat{k}$ over $n(\mathbf{y})$ months, respectively. The relationships between unadjusted and adjusted production amounts are stated as follows:

$$f'_{\ddot{k}}=\bar{f}_{\ddot{k}}-\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q_{\hat{k}}^{\ddot{k}} \tag{22a}$$

$$f'_{\hat{k}}=\bar{f}_{\hat{k}}+\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q_{\hat{k}}^{\ddot{k}} \tag{22b}$$

where $e_{\ddot{k},\hat{k}}$ represents the allocated amount and $q_{\hat{k}}^{\ddot{k}}$ is an indicator representing whether there is a reallocation relationship between plants $\ddot{k}$ and $\hat{k}$. Indicator $e_{\ddot{k},\hat{k}}$ can be either positive or negative, depending on whether the production amount is allocated from plant $\ddot{k}$ to $\hat{k}$, and $e_{\ddot{k},\hat{k}}>0$ implies that there is production amount, $e_{\ddot{k},\hat{k}}$, reallocated from $\ddot{k}$ to $\hat{k}$.

Let $w_{\ddot{k}}$ and $w_{\hat{k}}$ represent, respectively, the unit-product allocation costs of plants $\ddot{k}$ and $\hat{k}$, respectively, depending on the commodity price indexes in different regions. The total variable allocation costs of plants $\ddot{k}$ and $\hat{k}$ over $n(\mathbf{y})$ months are given, respectively, as

$$n(\mathbf{y})w_{\ddot{k}}\max\left\{\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q_{\hat{k}}^{\ddot{k}},0\right\} \tag{23a}$$

$$n(\mathbf{y})w_{\hat{k}}\max\left\{\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q_{\hat{k}}^{\ddot{k}},0\right\} \tag{23b}$$

The total allocation cost over $n(\mathbf{y})$ months can be obtained by summing up the fixed allocation cost and the variable allocation cost of all plants as follows:

$$O+\sum_{\forall\ddot{k}}n(\mathbf{y})w_{\ddot{k}}\max\left\{\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q_{\hat{k}}^{\ddot{k}},0\right\}+\sum_{\forall\hat{k}}n(\mathbf{y})w_{\hat{k}}\max\left\{\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q_{\hat{k}}^{\ddot{k}},0\right\} \tag{24}$$

Although the production cost of a plant with additional production amount is correspondingly reduced, the production costs of the other plants are raised since there is less production to share the high capital cost. The manufacturer should carefully investigate the difference in production cost for all plants when it comes to production reallocation in response to demand reduction. The total difference in production costs for all unreliable plants and for all reliable plants over $n(\mathbf{y})$ months can be formulated as follows:

$$n(\mathbf{y})\sum_{\ddot{k}}\left(\frac{C(v^*_{\ddot{k}})+c(v^*_{\ddot{k}})\bar{f}_{\ddot{k}}}{\bar{f}_{\ddot{k}}}-\frac{C(v^*_{\ddot{k}})+c(v^*_{\ddot{k}})f'_{\ddot{k}}}{f'_{\ddot{k}}}\right)f'_{\ddot{k}} \tag{25a}$$

$$n(\mathbf{y})\sum_{\hat{k}}\left(\frac{C(v^*_{\hat{k}})+c(v^*_{\hat{k}})\bar{f}_{\hat{k}}}{\bar{f}_{\hat{k}}}-\frac{C(v^*_{\hat{k}})+c(v^*_{\hat{k}})f'_{\hat{k}}}{f'_{\hat{k}}}\right)f'_{\hat{k}} \tag{25b}$$

Then, the total difference in production cost over $n(\mathbf{y})$ months can be expressed as

$$n(\mathbf{y})\left(\sum_{\ddot{k}}\frac{C_{\ddot{k}}(v^*_{\ddot{k}})\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}}}{\bar{f}_{\ddot{k}}(\bar{f}_{\ddot{k}}+\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}})}-\sum_{\hat{k}}\frac{C_{\hat{k}}(v^*_{\hat{k}})\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}}}{\bar{f}_{\hat{k}}(\bar{f}_{\hat{k}}-\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}})}\right) \tag{26}$$

If the value of Eq. $(26)>0$, then there is a reduction in production cost; otherwise, the reallocation incurs a cost increase.

Similar as discussed in Section 3.1, the transportation cost reflects the different assignment of customers to the plants. Let $\bar{t}_{\ddot{k}}$ and $\bar{t}_{\hat{k}}$represent, respectively, the average unit-product transportation costs from plants $\ddot{k}$ and $\hat{k}$ to the customers. The total transportation cost over $n(\mathbf{y})$ months can be formulated as

$$n(\mathbf{y})\left(\sum_{\forall\ddot{k}}\bar{t}_{\ddot{k}}\max\left\{\sum_{\forall\hat{n}_k}e_{\ddot{k},\hat{n}_k}q^{\ddot{k}}_{\hat{n}_k},0\right\}+\sum_{\forall\hat{n}_k}\bar{t}_{\hat{n}_k}\max\left\{\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{n}_k}q^{\ddot{k}}_{\hat{n}_k},0\right\}\right) \tag{27}$$

The supply chain network adjustment model in response to demand reduction can then be determined by solving the following programming model:

P3 : min

$$O+n(\mathbf{y})\left(\begin{array}{l}\sum_{\forall\ddot{k}}(w_{\ddot{k}}+\bar{t}_{\ddot{k}})\max\{\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}},\ 0\}+\sum_{\forall\hat{k}}(w_{\hat{k}}+\bar{t}_{\hat{k}})\max\{\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}},\ 0\}\\ -\left(\sum_{\ddot{k}}\frac{C_{\ddot{k}}(v^*_{\ddot{k}})\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}}}{\bar{f}_{\ddot{k}}(\bar{f}_{\ddot{k}}+\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}})}-\sum_{\hat{k}}\frac{C_{\hat{k}}(v^*_{\hat{k}})\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}}}{\bar{f}_{\hat{k}}(\bar{f}_{\hat{k}}-\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}})}\right)\end{array}\right) \tag{28a}$$

$$\text{s.t.}\quad f'_{\ddot{k}}=\bar{f}_{\ddot{k}}-\sum_{\forall\hat{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}}\quad\forall\ddot{k} \tag{28b}$$

$$f'_{\hat{k}}=\bar{f}_{\hat{k}}+\sum_{\forall\ddot{k}}e_{\ddot{k},\hat{k}}q^{\ddot{k}}_{\hat{k}}\quad\forall\hat{k} \tag{28c}$$

$$e_{\ddot{k},\hat{k}}\ \text{integer}\quad\forall\ddot{k}\ \forall\hat{k} \tag{28d}$$

$$q^{\ddot{k}}_{\hat{k}}=0\ \text{or}\ 1\quad\forall\ddot{k}\ \forall\hat{k} \tag{28e}$$

Eq. (28a) is the objective function that minimizes the total adjustment cost over $n(\mathbf{y})$ months. Eqs. (28b) and (28c) state the relationships between the adjusted and unadjusted production amounts for the plants. Eq. (28d) constrains decision variable $e_{\ddot{k},\hat{k}}$ to be an integer, and Eq. (28e) defines decision variable $q^{\ddot{k}}_{\hat{k}}$ to be binary.

4. Case study

A numerical example of T-company, which specializes in wafer foundry in the semiconductor industry with its headquarters in Taiwan, is used to demonstrate the application of the proposed models. Base values for the relevant parameters of the cost-function are given to solve the problem of T-company's supply chain network. However, some operating costs are unavailable, and therefore they are estimated using the annual report data in TSMC (2004). In this study, total customers are classified according to their geographical distributions, resulting in five major customers, namely North America, Europe, Japan, China and Taiwan. T-company can operate either 12, 8 or 6 in. wafer fabrications[1] (FABs) to serve customers, which have average monthly capacities of 50,000, 70,000 and 82,000 pieces, respectively. To unify customer demand, capacity and production amounts are measured in terms of pieces of 8 in. equivalent (eq.) wafers. Thus the capacities of 12, 8 and 6 in. FABs can be revised as 112,500, 70,000 and 45,920 pieces of 8 in. eq. wafers, respectively. Regarding plants, there are five available locations for T-company to operate various numbers and sizes of FABs, namely, Taiwan (Hsinchu), Taiwan (Tainan), Shanghai, USA and Singapore. The monthly capital cost for different-sized FABs can be estimated by the total expenses for the FAB construction and equipment set-up and the maximum usage period of the FAB. Following Hsu and Li (2009), the supply chain network in the case study can be illustrated as Fig. 1. The solid lines in the left and right sides of Fig. 1 show that the supplier is active to the plant, i.e. $\delta^s_k=1$ with the flow being f^s_k and the plant serves the customer, i.e. $\beta^k_c=1$ with the flow being f^k_c. In addition to the above decisions, T-company has to determine the production amount and capacity of the plants in different regions, i.e. f_k and v_k. Tables 1 and 2 show the forecast values for each of the five major customer demands in the year 2010, and the base production parameters for different-sized FABs in different locations, respectively. We adopted three models—P1, P2 and P3 to the case study and the details of using the proposed models for the case study are given in Appendix A. Sections 4.1, 4.2 and 4.3 described the application of the three models, respectively.

4.1. Results of P1

This study employs the simulated annealing (SA) heuristic proposed by Kirkpatrick et al. (1983) to obtain the solutions. The initial solutions are listed in Table 3. As shown in Table 3, T-company will operate six 12 in. FABs in five locations, with two 12 in. FABs in Taiwan (Hsinchu), which was possible due to economical incentives provided by the Taiwanese government. To meet the high demands, most FABs are scheduled to reach full-capacity production, i.e. 100% capacity utilization. Although the production amount could efficiently share the high capital cost of constructing a 12 in. FAB in Singapore, the higher production cost in Singapore hinders the FAB from 100% capacity utilization as compared to that in other locations. Similarly, the ratio of output from the FAB in Singapore to that from all FABs is merely 0.125. The results show that the production allocation among the plants depends not only on the capacities but also on labor, utility and insurance costs based on the locations of the plants. The average production cost per 8 in. eq. wafer for a 12 in. FAB is US$ 322.85. The result implies that the manufacturer can reduce the impact of employing a large-size capacity plant on the total costs, scheduling full-capacity production for that plant. The results also imply that the wafer foundry production exhibits economies of scale, and that a large-size capacity plant combined with full-capacity production yields the lowest cost. Table 3 also shows the

[1] Each size FAB can only produce its particular size of wafers, i.e. 12, 8 or 6 in. wafers due to the complexity of technology in the manufacturing process of producing wafers. In terms of area, one piece of 12 in. wafer is 2.25 times the size of that of 8 in. wafer; furthermore, it is 4 times that of a 6 in. wafer.

relationship between the plants and customers in different locations, as well as their monthly product flows. Since demands from customers in North America account for the largest portion for T-company, most of the FABs solely serve customers from North America.

4.2. Results of P2

A hypothetical scenario involving demand expansion can be referred to Appendix A. The resulting reliability values of the plants are listed in Table 4. Due to the proposed full-capacity production of many FABs, the demand expansion in China has led these FABs to have a low reliability, when there are diverse reliability values as shown in Table 4. The acceptable utilization levels often reflect the expectations of T-company for various FABs in different locations. In this study, the maximal acceptable capacity utilization is set to be 1, at a lowest unit-product production cost, while the minimal acceptable capacity utilization is assumed to realize acceptable minimum revenue at the plant. There is a small chance that capacity utilizations fall within a narrow range of acceptable level due to the high expectation for the plants, resulting in low reliability values. The above explains why the two FABs in Taiwan (Hsinchu) exhibit the lowest reliability values, as listed in Table 4. In addition to the acceptable utilization limits, the reliability value also depends on the production allocation among FABs in different locations. Since there is surplus capacity in Singapore, it has a good performance under demand expansion.

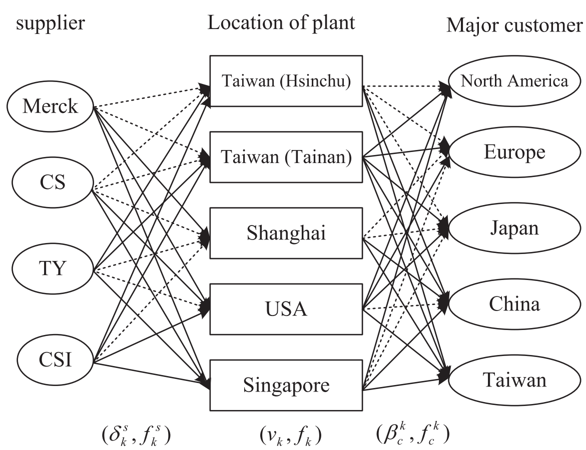

Fig. 1. The profile of the supply chain network.

Table 1
Demand forecasts for five major customers in 2010.
Source: TSMC Annual Report.

Customer in different areas	Annual forecasts	Monthly forecasts
North America	6,165,050	513,754
China	207,774	17,315
Japan	508,312	42,359
Taiwan	333,723	27,810
Europe	497,992	41,499
Total	7,712,851	642,737

Unit: 8 in. eq. wafers.

The reliability evaluation method provides an effective tool that enables the manufacturer to assess the impact of demand fluctuations on supply chain design performance by taking into account demand variability, probabilities of abnormal situations and production allocations among plants. When the reliability values of plants are detected as low and/or distinctively different from each other, the manufacturer may consider executing an adjustment. As shown in Table 4, the reliability values of five out of six manufacturer's plants are approximately 0.3, while the other is 0.9. The manufacturer is suggested to perform the adjustment model.

The fluctuating demands from customers in Japan, Taiwan, Europe and North America can be classified as normal when comparing the data in Tables 1 and A1. Suppose there are two available outsourcing firms available, one located in Japan and the other in Korea, and both have limited outsourcing amounts. The set of adjustment months, **t**, is **t**={4, 5, 6, 7}, totaling 4 months. Table 5 lists the initial values of the parameters in P2. Table 6 shows the results and the optimal objective function values with and without network adjustments.

As shown in Table 6, the expected production amounts of most FABs exceed their capacities, which are unattainable situations. Under these conditions, T-company could operate the FABs as initially proposed and bear a huge revenue loss of US$ 39,936,000 in case they decide not to make any adjustment, as shown in Table 6. T-company could also alter and increase the production amount at a reliable FAB, i.e. the FAB in Singapore, and at the same time consider outsourcing so that the high demands can be satisfied. As shown in Table 6, performing an adjustment yields a reduction in total production cost, which offsets the derivative additional costs, such as allocation costs, extra material purchase costs, transportation costs, etc. In addition the high penalty cost of loss of revenue is avoided. However, there are still unfulfilled demands due to the limited outsourcing available, leaving a penalty cost of US$ 4,161,600. Comparing the total costs, with and without an adjustment, the production adjustment is shown to benefit the T-company.

In the case study, T-company has a high profit margin on wafer foundry; consequently, it will also suffer a great loss if the market price of the product is high and the adjustment is not made. On the other hand, the outsourcing cost must be paid, including not only the production and material costs borne by the outsourcing firm but also the premium charged. Next we perform a sensitivity analysis to investigate how changes in unit-product penalty cost and outsourcing cost affect the decision to do-nothing or make the adjustments. Let $\bar{c}$ be the average unit-product outsourcing

Table 2
The base production parameters for different-size FAB in different locations.

	6 in.		8 in.		12 in.	
	Capital cost (10^3 US$)	Variable production cost (US$/wafer)	Capital cost (10^3 US$)	Variable production cost (US$/wafer)	Capital cost (10^3 US$)	Variable production cost (US$/wafer)
Taiwan (Hsinchu)	1865	205	3000	323	9700	515
Taiwan (Tainan)	1850	204	2978	321	9900	513
Shanghai	1900	208	3005	327	10,032	520
USA	2100	212	3085	335	10,090	523
Singapore	2030	215	3078	335	10,065	525

Table 3
Initial results of the plants and their relationship with customers in different locations.

Locations	FAB (in.)	Customer in different locations	Monthly flows (8 in. eq. wafer)
Taiwan (Hsinchu)	12	North America	112,500
	12	North America	112,500
Taiwan (Tainan)	12	China	17,315
		Japan	42,359
		Taiwan	27,810
		Europe	25,016
		Total	112,500
Shanghai	12	North America	112,500
USA	12	North America	112,500
Singapore	12	North America	63,755
		Europe	16,480
		Total	80,235

	Locations					
	Taiwan (Hsinchu)		Taiwan (Tainan)	Shanghai	USA	Singapore
FAB (in.)	12	12	12	12	12	12
Capacity utilization (Y_k) (%)	100	100	100	100	100	71.32
Proportion of production to totals (θ_k)	0.175	0.175	0.175	0.175	0.175	0.125

Average production cost per 8 in. eq. wafer (US$): 322.85
Average outbound cost per 8 in. eq. wafer (US$): 8.61

Table 4
Reliability of the plants given the abnormal demand from China.

Location	FAB (in.)	Acceptable max. and min. utilizations	Reliability in abnormal months			
			April	May	June	July
Taiwan (Hsinchu)	12	$\overline{Y}_k=1$, $\underline{Y}_k=0.85$	0.3000	0.3068	0.3009	0.3684
	12	$\overline{Y}_k=1$, $\underline{Y}_k=0.85$	0.3000	0.3068	0.3009	0.3684
Taiwan (Tainan)	12	$\overline{Y}_k=1$, $\underline{Y}_k=0.82$	0.3132	0.3207	0.3114	0.3859
Shanghai	12	$\overline{Y}_k=1$, $\underline{Y}_k=0.70$	0.3228	0.3333	0.3192	0.4010
USA	12	$\overline{Y}_k=1$, $\underline{Y}_k=0.75$	0.3217	0.3319	0.3185	0.3994
Singapore	12	$\overline{Y}_k=1$, $\underline{Y}_k=0.60$	0.8430	0.9788	0.9999	0.9744

Table 5
The initial values of parameters in P2.

Definition	Initial values
Average unit-material purchase cost, $\overline{p}$ (US$)	2.5
Unit-product penalty cost, ϕP (US$)	240
Fixed allocation cost, O (US$)	350,000

		Outsourcing firms in different locations	
	Singapore	Japan	Korea
Unit-product compensation cost, $h_{\overline{k}}$ (US$)	67	–	–
Unit-product outsourcing cost, c_o (US$)	–	402	405
Average unit-product transportation cost (US$)	2.4	2.28	1.5
Limitation of outsourcing production amounts (8 in eq. wafer)	–	2000	3000

cost and ϕP be the unit-product penalty cost. Thus, $\overline{c}/\phi P$ reflects the ratio of the outsourcing to penalty cost. A large value of $\overline{c}/\phi P$ indicates an increased outsourcing cost as compared with the penalty cost, which indicates a situation where the product is of less value or when a high premium is being charged by the outsourcing firms. Fig. 2 shows the threshold of the adjust/do-nothing decision by comparing various unit-product outsourcings and penalty costs. The left-hand and right-hand sides of the solid line in Fig. 2 represent the judgments as being do-nothing and adjustment, respectively.

As stated, do-nothing is suggested if the adjustment benefits cannot offset the adjustment cost, with the adjustment benefits given by the sum of the savings in production cost and by not having to incur the penalty cost. Given the savings in production cost, the consequently decreased penalty cost leads to a reduced adjustment benefit; thus, the tendency toward adopting an adjustment is small, as shown in Fig. 2. Since the penalty cost reflects the market value of the product, the result suggests that the manufacturer should stick to the initial proposed decisions and neglect the abnormal demand if the product value is low. On

Table 6
Initially proposed, expected and adjusted monthly flows, related costs and the results of adjust/do-nothing judgments in response to demand expansion.

Plants: Operated by T-company in different locations	Plants: FAB (in.)	Customer in different locations	Monthly flows (8 in. eq. wafer): Initially proposed	Abnormal months (Apr., May, Jun., Jul.): Expected	Abnormal months (Apr., May, Jun., Jul.): Adjusted
Taiwan (Hsinchu)	12	North America	112,500	122,035	112,500
	12	North America	112,500	122,035	112,500
Taiwan (Tainan)	12	China	17,315		17,315
		Japan	42,359		42,359
		Taiwan	27,810		27,810
		Europe	25,016		25,016
		Total	112,500	122,035	112,500
Shanghai	12	North America	112,500	122,035	112,500
USA	12	North America	112,500	122,035	112,500
Singapore	12	North America	63,755		63,755
		Europe	16,480		16,480
		China	–		32,265
		Total	80,235	87,165	112,500
Japan[a]		China	–		2000
Korea[a]		China	–		3000
Total penalty costs without adjustment (US$)			39,936,000		
Total adjustment costs (US$)			20,284,256		
(+) Allocation costs			17,073,020		
(+) Extra material purchase costs			322,652		
(−) Differences in production costs			1,619,000		
(+) Penalty costs			4,161,600		
(+) Transportation costs			345,984		
Judgment			Adjust		

[a] Outsourcing firms.

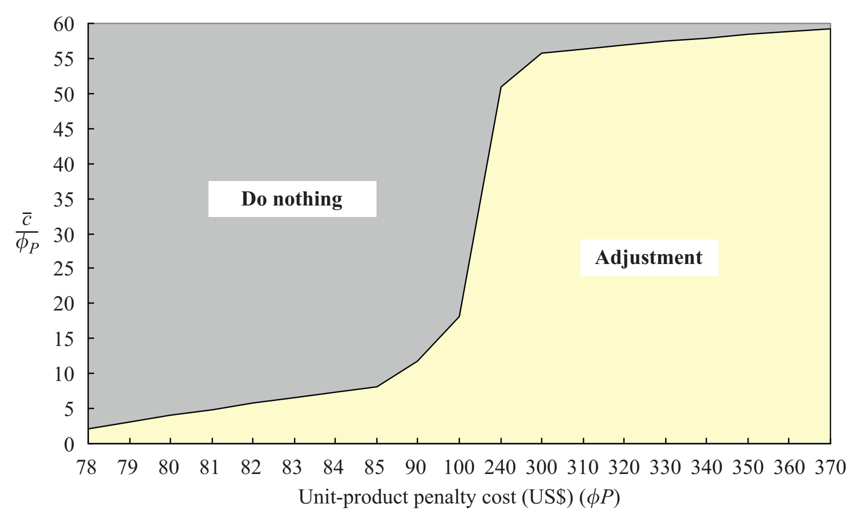

Fig. 2. The threshold of adjust/do-nothing judgments by comparing unit-product outsourcing and penalty costs.

the other hand, it is worth making the adjustment and continuing to outsource when it is a high value-added product, even though the costs are high, as shown in Fig. 2.

In this study, the fixed allocation costs include production schedule change costs at the plants, and the contract cost related to the outsourcing firms, which is triggered once an adjustment is made. The fixed allocation cost can also be explained as the difficulty in searching for qualified outsourcing firms. The fixed allocation cost will be extremely high if there are few qualified outsourcing firms available, in which case the disadvantages may well outweigh the advantages of adjustment. Furthermore, the total adjustment benefits during the execution of an adjustment depend on not only the size of the abnormal demand but also its duration. An increased duration of abnormal months accumulates lots of savings in production costs and exempts the firm from heavy penalty costs, which suggests that an adjustment is recommended. This advantage is diminished if the fixed allocation cost is high, especially when it is combined with a short abnormal period. This study further examines how changes in the duration of abnormal periods and fixed allocation cost affect the judgments to do-nothing or make an adjustment. Fig. 3 shows the threshold of adjust/do-nothing judgments by comparing the durations of abnormal months and the fixed allocation costs, where the left-hand and right-hand sides of the solid line represent do-nothing and adjust judgments, respectively.

As long as the adjustment benefits outweigh the adjustment costs, the production reallocation should be performed. In some ways, the adjustment decisions depend on whether the adjusted

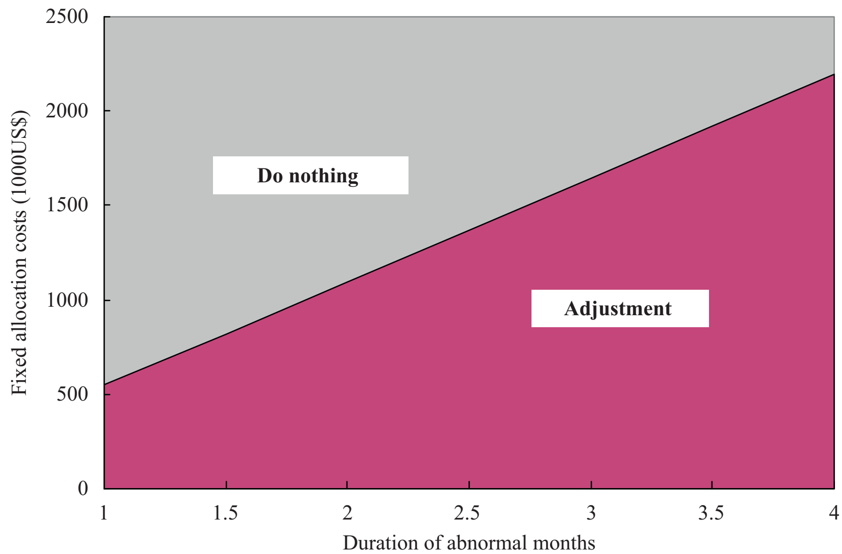

Fig. 3. The threshold of adjust/do-nothing judgments by comparing duration of abnormal months and fixed allocation costs.

production amount can effectively share the high fixed allocation cost. As shown in Fig. 3, the threshold of an adjustment is increased with an increase in the duration of abnormal months. In other words, a high fixed allocation cost will not prevent the manufacturer from performing an adjustment. The results also encourage the manufacturer to look for qualified outsourcing firms and book their capacities when the abnormal event continues. Furthermore, the results also imply that the manufacturer can neglect unreliable situations caused by an abnormal event with a short period, because the accumulated benefits during this short period may not compensate the high allocation costs. The short period can be further defined as that the period for which the accumulated benefits cannot outweigh the allocation cost under an adjustment decision. During the short period of time, the incurring cost will be high if the manufacturer adjusts production factors such as capital or the size of plants. The results of the study provide a reference for the manufacturer in the decision making process of network planning under demand expansion, when they have to cope with related benefits, costs and the duration of abnormal months.

4.3. Results of P3

A hypothetical scenario involving demand reduction can be referred to Appendix A. Demands from North America account for nearly 80% of the output of T-company, as shown in Table 1. To satisfy these considerable demands, most FABs produce their products to serve only the customers of North America, as shown in Table 3. Therefore the occurrence of an abnormal event in North America will have a major impact on the performance of the FABs in different locations. As shown in Table 7, the abnormal demands from North America result in low reliabilities for most FABs, yet the FABs in Shanghai and USA maintain good performance. Although there is no rigid expectation for the 12 in. FAB in Singapore, it exhibits a low reliability value as well. This is because the output from the FAB in Singapore accounts for a relative small proportion of the total output from T-company, i.e. $\theta_k = 0.125$, as compared with $\theta_k = 0.175$ for the others. When total demand declines, the production amount of the 12 in. FAB in Singapore declines even more than the others.

The set of adjustment months, $\mathbf{y}$, is $\mathbf{y} = \{1, 2, 3\}$, totals 3 months. The average monthly customer demands during these 3 months is estimated at 513,754 pieces of 8 in. eq. wafers. Table 8 shows the initial values of the parameters in P3, and Table 9 lists the results and the optimal objective function values.

Table 7
Reliability of the plants given the abnormal demand from North America.

Location	FAB (in.)	Acceptable max. and min. utilizations	Reliability in abnormal months		
			January	February	March
Taiwan (Hsinchu)	12	$\overline{Y}_k = 1$, $\underline{Y}_k = 0.85$	0.4801	0.4129	0.7888
	12	$\overline{Y}_k = 1$, $\underline{Y}_k = 0.85$	0.4801	0.4129	0.7888
Taiwan (Tainan)	12	$\overline{Y}_k = 1$, $\underline{Y}_k = 0.82$	0.7291	0.6915	0.9372
Shanghai	12	$\overline{Y}_k = 1$, $\underline{Y}_k = 0.70$	0.9995	0.9996	0.9978
USA	12	$\overline{Y}_k = 1$, $\underline{Y}_k = 0.75$	0.9850	0.9850	0.9972
Singapore	12	$\overline{Y}_k = 1$, $\underline{Y}_k = 0.60$	0.5675	0.5080	0.8554

Table 8
The initial values of parameters in P3.

Plants		Unit-product compensation cost (US$)	Average unit-product transportation cost (US$)
Location	FAB (in.)		
Taiwan (Hsinchu)	12	58	4.9
	12	58	4.9
Taiwan (Tainan)	12	59	5.0
Shanghai	12	64	4.6
USA	12	66	6.3
Singapore	12	67	6.9

We can expect a fall in the production amounts for all FABs in different locations when there is a demand reduction, as shown in Table 9, yielding a low capacity utilization and thus a high production cost. To avoid these high production costs, an adjustment is considered. As shown in Table 9, the adjusted production amounts of the 12 in. FABs in Taiwan (Hsinchu), Taiwan (Tainan) and Shanghai can run at full-capacity production, since these three locations have low capital cost and variable production costs. Therefore by running them at full capacity the total production cost of these 3 FABs can be effectively reduced.

Table 9
Initially proposed, expected and adjusted monthly flows, related costs and the results of judgments in response to reduction in demand.

Plants		Customer in different locations	Monthly flows (8 in. eq. wafer)		
Location	FAB (in.)		Initially proposed	Abnormal months (Jan., Feb., Mar.)	
				Expected	Adjusted
Taiwan (Hsinchu)	12	North America	112,500		96,020
		Europe	–		16,480
		Total	112,500	96,436	112,500
	12	North America	112,500	96,436	112,500
Taiwan (Tainan)	12	China	17,315		17,315
		Japan	42,359		42,359
		Taiwan	27,810		27,810
		Europe	25,016		25,016
		Total	112,500	96,436	112,500
Shanghai	12	North America	112,500	96,436	112,500
USA	12	North America	112,500	96,436	101,060
Singapore	12	North America	63,755		–
		Europe	16,480		–
		Total	80,235	68,880	–
Total adjustment costs (US$)				−48,978,258	
(+) Allocation costs				1,588,535	
(−) Differences in production costs				50,647,545	
(+) Transportation costs				80,752	
Judgment				Adjust	

Although this adjustment results in an idle FAB in Singapore, which yields a high idle capital cost, the savings in total production costs are still US$ 50,647,545, clearly showing that the effects of an idle FAB on the total production costs are offset by the reduced production costs. These results imply that centralized production is recommended in response to a reduction in demand, and that plants with low capital and variable costs always provide economical incentives to produce more. To serve customers from Europe originally served by the FAB in Singapore, the FAB in Taiwan (Hsinchu) is assigned to serve them due to the low compensation cost. Table 9 also shows that the assignment of the FABs and customers in different locations, as well as their monthly product flows, are similar to those as proposed. These results imply that a partial adjustment (with the least amount of disruption to the status quo) is encouraged, rather than an entire network consideration, as a whole network reconstruction incurs additional and unnecessary costs. Summing up allocation costs, difference in production costs and transportation costs results in a negative value of total adjustment costs, which shows that the adjustment in response to the severe fluctuations benefits T-company.

The adjustment model is to find the minimized adjustment cost during months with fluctuation demand for determining the optimal adjustment decisions in terms of production reallocations among all plants. The results show that the adjustment strategy proposed in the study not only provides flexibility for the manufacturer to cope with different abnormal demand fluctuations, but also improve the production cost function in an effective way.

5. Conclusions

This study developed a series of models to investigate the supply chain design problems for manufacturers in response to economies of scale and demand fluctuations. This study focused on the evaluation of reliability and the adjustment of the supply chain network design to respond to different demand fluctuations. This study demonstrates the application of the models using T-company as an example, a company that specializes in wafer foundry in the semiconductor industry. The results show that when severe demand fluctuations occur, the performances of different plants depend on the production allocation among them, as well as the various expectations of these plants. A full-capacity production plant combined with high expectation often results in the plant having a low reliability value under demand expansion, while other plants with surplus capacities maintain a good performance. On the other hand, demand reduction will cause a further reduction in a plant whose output is originally sparse, yielding a low reliability value.

The results show that performing an adjustment in response to demand expansion benefits the manufacturers by reducing the total production cost and avoiding revenue loss, outweighing the additional costs. The results also suggest that manufacturers should stick to the initial proposed decisions and neglect abnormal demands if low product value is combined with high extra allocation costs. On the other hand, it is worth performing an adjustment and continuing to outsource for a high value-added product, even though the cost may be quite high. Furthermore, the threshold of an adjustment is increased with the increase in duration of abnormal months, meaning that a high fixed allocation cost will not prevent the manufacturer from performing an adjustment if the abnormal state lasts for a long period. The results also imply that the manufacturer can disregard an abnormal state with a short period, because the accumulated benefits during this short period may not compensate for the high allocation costs. The results show that a severe reduction in demand from customers may result in low capacity utilization for most plants, resulting in an overall high production cost. Under these conditions, the result implies that a centralized production is necessary, to determine which plants are the least economical and leave them idle while scheduling the remaining plants for full-capacity production. These results imply that a partial adjustment (with the least amount of disruption to the status quo) is encouraged, rather than an entire network consideration, as a whole network reconstruction incurs additional and unnecessary costs.

The assumptions in the study can be relaxed and the application of the proposed model still holds. For example, the case study assumes that the maximally and minimally acceptable capacity utilization follow the criteria of the lowest unit-product production cost and a tolerable minimum revenue for the manufacturer, respectively. The manufacturers can apply the proposed model to investigate how the performance of their network is being affected under demand fluctuations in which the values of maximally and minimally acceptable capacity utilizations can be determined according to manufacturer's criteria with respect to the industry. In many practical situations, the distribution information of stochastic demand is often quite limited. The assumption of the normal distribution of customer demand can be relaxed by only assuming that the mean and variance are known and finite. The reliability value can be estimated by applying the statistics methods in Kolmogoroff (1941). Furthermore, in the case study, the customer demands are assumed to be independent to each other. The assumption can be relaxed and the reliability of the plant can be estimated by Eq. (12) in which the estimation of standard deviation of total fluctuating demand should consider the covariance between these demands.

This study can be extended in several ways. In the case study, the demands from different customers are assumed to be independent from each other. Some abnormal event may occur and impact on demand globally. Future studies may address this issue by investigating the relationship of various markets and how to adjust the network in response to a global financial crisis. Second, the fixed allocation cost reflects the difficulty of finding a qualified outsourcing firm. Total costs can be reduced by bargaining with some outsourcing firms and book their capacities in advance. Future studies may expand this study's model and address this issue by investigating the relative influences of the opportunity cost, occurrence duration, abnormal demand distributions and the probabilities on firm selection decisions on outsourcing. Finally, the case study in this study is based on a wafer foundry company in the semiconductor industry, which is characterized by extremely high capital cost. Future studies may apply our proposed model to different industries. Such studies would need to examine the impact of capital cost and customer demand on production allocation among the plants and how the revenue is affected when the demand is not satisfied. A low yield may reduce the qualified production amount, thereby the inventory should be considered since the total production amount cannot meet the demand. To simplify the study, the inventory due to yield problem is not included. Future studies may apply the proposed models to investigate how yield problems affect the design of supply chain network and the performance of proposed results when abnormal events occur.

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Appendix A. The detail of using the proposed models for the case study

In the first part of case study, this study determines the capacity of plants, i.e. the size of the FABs in various locations and their production amounts, as well as the monthly flows from each FAB to customers in different locations using supply chain design model P1 (Eqs. (6a)–(6i)). Then, hypothetical scenarios

Table A1
Hypothetical data regarding the abnormal state of customers in China.

Customers in different locations	State occurrence duration and probability	Abnormal month			
		April	May	June	July
Abnormal demand distributions: $\tilde{f}^t_{c,ij} \sim N(\bar{f}^t_{c,ij}, \sigma(\tilde{f}^t_{c,ij}))$					
China	$g^1=3.2$, $p_1=0.5$	N(46,818, 2620)	N (45,160, 2392)	N(43,646, 2125)	N(18,346, 2000)
	$g^2=3.5$, $p_2=0.3$	N (46,818, 2620)	N(43,904, 2436)	N(43,304, 2330)	N(44,674, 2659)
	$g^3=4.0$, $p_3=0.2$	N (46,818, 2620)	N(44,330, 2330)	N(43,648, 2536)	N(44,297, 2765)
	Expected demand distribution	N (46,818, 1615)	N(44,617, 1477)	N(43,544, 1369)	N(31,435,1394)
Normal demand distributions: $\tilde{f}^t_c \sim N(\bar{f}^t_c, \sigma(\tilde{f}^t_c))$					
Japan	–	N(42,100, 3900)	N(42,155, 3856)	N(42,578, 3912)	N(42,321, 3866)
Taiwan	–	N(26,955, 2881)	N(27,934, 2540)	N(28,142, 2725)	N(28,568, 2506)
Europe	–	N(41,746, 4264)	N(42,078, 4000)	N(42,256, 4231)	N(42,129, 4303)
North America	–	N(513,700, 61,330)	N(513,650, 63,954)	N(514,018, 58,988)	N(513,755, 60,418)

Table A2
Hypothetical data regarding the abnormal state of customers in North America.

Customers in different regions	State occurrence duration and probability	Abnormal month		
		January	February	March
Abnormal demand distributions: $\tilde{f}^t_{c,ij} \sim N(\bar{f}^t_{c,ij}, \sigma(\tilde{f}^t_{c,ij}))$				
North America	$g^1=2.3$, $p_1=0.2$	N(406,936, 45,631)	N(415,972, 41,330)	N(459,639, 40,629)
	$g^2=2.6$, $p_2=0.4$	N(417,712, 47,778)	N(409,685, 44,852)	N(442,366, 38,844)
	$g^3=3.0$, $p_3=0.4$	N(418,964, 45,711)	N(409,119, 41,567)	N(422,587, 44,753)
	Expected demand distribution	N(416,058, 27,979)	N(410,716, 25,820)	N(437,909, 25,058)
Normal demand distributions: $\tilde{f}^t_c \sim N(\bar{f}^t_c, \sigma(\tilde{f}^t_c))$				
China	–	N(17,189, 2021)	N(17,200, 1953)	N(17,239, 2563)
Japan	–	N(42,366, 2963)	N(42,423, 3216)	N(43,019, 3623)
Taiwan	–	N(27,693, 2896)	N(28,131, 2688)	N(27,585, 3022)
Europe	–	N(41,500, 5626)	N(42,015, 6025)	N(42,134, 6060)

involving abnormal states, i.e. demand expansion and demand reduction are considered, respectively, in the case study.

Let us first suppose that there is a sudden high demand from customers in China because the Chinese government is promoting the usage of integrated circuit identity cards, which is one of the end-products of the wafer foundry, for the months of April–July. For the sake of simplification, this study assumes the demands from the customers are independent. The data concerning this abnormal state, including duration, abnormal demand distribution and duration probabilities, are listed in Table A1. The expected demand distribution from the abnormal location, China, is also calculated and shown in Table A1. Moreover, let's consider another hypothetical scenario involving the abnormal situation, of a demand reduction from North America. The scenario is described as follows. Suppose that there is a sudden sharp decline in the demand of customers in North America due to a financial crisis, lasting from January to March. The data concerning this abnormal state, including duration, abnormal demand distributions and duration probabilities, are listed in Table A2. The reliabilities of the FABs, considering the abnormal states, are calculated using Eq. (12).

In the second part, the case study is focused on the unreliable situation arising from the expanded demand from China and proposes an adjustment strategy by solving P2 (Eqs. (21a)–(21g)). In the third part, the study focuses on the unreliable situation arising from the demand reduction in North America and proposes an adjustment strategy by solving P3 (Eqs. (28a)–(28e)).

Appendix B

Notation

$k/s/c$	a specific plant/qualified supplier/customer
$f_k/v_k/Y_k$	production amount/capacity/capacity utilization of plant k
f_c	demand of customer c
w	required material flows for producing one unit product
f_k^s	material flows from supplier s to plant k
f_c^k	product flows from plant k to customer c
δ_k^s	indicator variable representing whether supplier s serves plant k
β_c^k	indicator variable representing whether customer s is served by plant k
$C(v_k)/c(v_k)$	capital cost/variable production cost of plant k
V_s	fixed cost of the manufacturer with material supplier s
γ_s	indicator variable representing whether supplier s is active for the manufacturer
p_s	unit-material purchase price charged by supplier s
t_k^s	unit-material transportation cost from supplier s to plant k
t_c^k	unit-product transportation cost from plant k to customer c
$\tilde{f}_k^t$	random production amount of plant k in month t
$Y_k(\tilde{f}_k^t)$	capacity utilization of plant k with respect to random production amount $\tilde{f}_k^t$ in month t
$\overline{f}_k^t$	random realization of $\tilde{f}_k^t$
$\underline{Y}_k/\overline{Y}_k$	minimally/maximally acceptable capacity utilization of plant k
$R(\tilde{f}_k^t)$	reliability of a specific plant
θ_k	ratio of the production from plant k to that from all plants
$\mathbf{K}_c$	set of all distinct states, which occur on the market of customer c during the planning year
w_c^i	a specific abnormal state on the market of customer c
w_c^0	a normal state in which no abnormal fluctuation occurs on the market of customer c
W	number of distinct abnormal states
$\Pr(w_c^i)$	probability that state w_c^i occurs on the market of customer c during the planning year
$\dot{k}/\overline{k}$	a detected unreliable/reliable plant under demand expansion
$\overline{f}_C$	average monthly customer demand for the manufacturer
$\overline{f}_c^t$	a realization demand from customer c in month t
c_o	unit-product outsourcing cost paid to outsourcing firm o
$h_{\overline{k}}$	unit-production compensation cost for plant $\overline{k}$
O	fixed allocation cost
$q_{\dot{k},o}/\Delta_{\dot{k},\overline{k}}$	production amounts allocated from plant $\dot{k}$ to outsourcing firm o/plant $\overline{k}$
$x_o^{\dot{k}}/y_{\overline{k}}^{\dot{k}}$	indicator representing whether there exist a production allocation relationship between $\dot{k}$ and $o/\overline{k}$
$\overline{p}$	average unit-material cost
$\overline{f}_{\dot{k}}/\overline{f}_{\overline{k}}$	realized average monthly production amount of plant $\dot{k}/\overline{k}$ under demand expansion
$f'_{\dot{k}}/f'_{\overline{k}}$	adjusted amounts of plant $\dot{k}/\overline{k}$
P	unit-product price
ϕ	ratio of penalty cost to unit-product price
$\overline{t}_{\overline{k}}/\overline{t}_o$	average unit-product transportation costs from plant $\overline{k}$/outsourcing firm o to the customers
$\ddot{k}/\hat{k}$	an unreliable/reliable plant under demand reduction
$\overline{f}_{\ddot{k}}/\overline{f}_{\hat{k}}$	unadjusted production amounts of plant $\ddot{k}/\hat{k}$
$f_{\ddot{k}}/f_{\hat{k}}$	adjusted production amounts of plant $\ddot{k}/\hat{k}$
$e_{\ddot{k},\hat{k}}$	allocated amount between plants $\ddot{k}$ and $\hat{k}$
$q_{\hat{k}}^{\ddot{k}}$	indicator representing whether there is a reallocation relationship between plants $\ddot{k}$ and $\hat{k}$
$w_{\ddot{k}}/w_{\hat{k}}$	unit-product allocation costs of plant $\ddot{k}/\hat{k}$
$\overline{t}_{\ddot{k}}/\overline{t}_{\hat{k}}$	average unit-product transportation costs from plant $\ddot{k}/\hat{k}$ to the customers

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