國立交通大學

運輸科技與管理學系

博士論文

反應規模經濟與需求波動之供應鏈網路設計

Supply Chain Network Design in Response to Scale Economies and Demand Fluctuations

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ABSTRACT

The extremely complexity of designing a supply chain network is due to the need for the configuration to adhere to customer demands, and manufacturer's capacity and production must treat demand fluctuations. In supply chain network design phases, manufacturers merely use average estimated demand patterns, where peak and off-peak periods are covered. However, the uncertainty surrounding input parameters complicates the network design. A flexible supply chain network design that could better respond to demand fluctuations is more appropriate for operational planning. Regarding delivery strategies, the goal is to reduce logistics costs and satisfy customer needs. The assumption of constant demand is highly controversial, since demand varies with time, space and consumer socioeconomic characteristics. Serving all customers without considering the above causes high logistics cost and low customer satisfaction, thus a reduced profit.

This study aims to investigate the supply chain network design problems in response to economies of scale and demand fluctuations. A series of models are formulated to systematically investigate the problems and analyze manufacturers' decisions on how much and how often material/product to purchase/transport among/to suppliers/customers as well as the optimal capacity and production amount for multiple plants with economies of scale in an uncertain environment. According to the issues of significance, the dissertation is divided into five distinct parts. The first part formulates an integrated plant capacity and production model, which aims to investigate how economies of scale, customer demand levels and investment conditions in different locations influence the supply chain network design. The second part focuses on evaluating the reliability of the network design from the first part on condition that abnormal demand fluctuations occur. Two mathematical programming models are further developed to determine the optimal adjustment decisions regarding production reallocation among plant under different fluctuating demand. In the third part, the network design model is extended to include the inbound and outbound dispatching decisions with shipping economies in the supply chain. Then, the network is narrowed down to two echelons, such as plants and customers in the forth part, to focus on the logistics issues in the supply chain network. The demand-supply interaction models, which optimize a delivery service strategy, are developed as they cope with time and spatial dependent demand, demand-supply interaction. Moreover, the impacts of demand-supply interaction on the optimal capacity and production allocation among the manufacturing plants are also investigated. Furthermore, in the fifth part of the dissertation, this study focuses on the end consumer shopping behavior and employs Internet shopping as the study object. The impacts of consumer characteristics on the optimal delivery service problems are emphasized. Specifically, in addition to the determination of the optimal number and duration of service cycles by exploring demand-supply interaction and time-dependent consumer demand, this part also investigates how variations in consumer socioeconomic, temporal and spatial distributions influence consumer demand and, thereby, profit.

A series of case studies are performed to demonstrate the applications of the study. The results show the benefits in terms of cost savings brought by centralized production are larger than the increased transportation cost as a result of decentralization. The results also show performing an adjustment in response to demand expansion benefits the manufacturer in way that total production cost is reduced and revenue loss is avoided, which outweigh the additional costs. The results also show the total monthly material/product flows between two locations impacts more than their distance does on the optimal shipping frequency. The results also imply for two locations that are distant apart; there must be a large economical shipment size or less frequent shipment. The results show that without considering demand-supply interaction, the manufacturer typically pursues minimized logistics cost by assuming inelastic customer demand and applying less delivery service cycles. However, this strategy overestimates customer demand and yields higher production cost, leading to a reduced profit. In sum, the results of the study provide a reference for the manufacturer in the decision making procedures of network planning with economies of scale and demand fluctuations, as they cope with related benefits and costs.

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CHAPTER 1

Introduction

The general field of interest in this dissertation is supply chain network design problems for high-tech product manufacturer in response to scale economies and demand fluctuations. This chapter presents an overview of the motivation, problem statement, research objectives and approaches, and illustrates the framework of this dissertation.

1.1 Motivations and background

Manufacturing industries are usually characterized with high capital cost, especially high-tech products. High capital costs are usually involved in the investment of capacity held by high-tech manufacturers, while there exists economies of scale that allows manufacturers with the large size capacity to operate more efficiently than those with the small size. Furthermore, increased specialization also requires increased transportation. As a result, the profits may shrink due to the geographical spread of their suppliers and customers, leading to a higher transportation cost. The extremely complexity of designing a supply chain network is due to the need for the configuration to adhere to customer demands, and manufacturer's capacity and production must treat demand fluctuations. In supply chain network design phases, manufacturers merely use average estimated demand patterns, where peak and off-peak periods might be covered. However, the uncertainty surrounding input parameters complicates the network design. A flexible supply chain network design that could better respond to demand fluctuations is more appropriate for operational planning.

High-tech products manufacturing firms are characterized as having high capital costs due to the expense of sophisticated equipment, land acquisition, and plant and warehouse construction. For example, semiconductor manufacturers spend almost a billion US dollars to construct an 8-inch wafer fabrication (FAB), and thirty billion US dollars for a 12-inch FAB. In addition, it costs more to produce one piece of 12-inch wafer than it does producing an 8-inch wafer. However, there is an advantage to a 12-inch FAB over an 8-inch FAB in terms of lower per-unit product production costs due the fact that the production is done on a larger scale, which further leads to a larger amount of final products.

The benefits brought by operating large-scale manufacturing plants shrink and production costs dramatically increase when the market demand is insufficient to realize scale economies and the capacity utilization is low. On the other hand, revenue loss arises and customer performance downgrades when supply does not match with high market demand. Strategic supply chain network design is a prerequisite for efficient tactical operations, and therefore has a long lasting impact on the manufacturers. The majority of supply chain network problems uses average estimated customer demand patterns for the manufacturers over planning years. Unfortunately, unexpected abnormal events occur and continue for a period of time, which further influence customer demand and affect network performance. The continued survival and effectiveness lie in manufacturers' ability to respond promptly to environmental turbulence (Lloréns et al., 2005).

Regarding key-components purchase, manufacturers usually maintain their long-term contractual basis with particular suppliers, in which the total procurement meets the annual or monthly demands. To remain adaptable, the manufacturer has the flexibility of scheduling dispatching decisions, i.e. shipping frequency and shipment size to satisfy their contracted annual or monthly demands. To avoid large inventories on hand, the manufacturer may determine a more frequent shipment; however, this results in a higher shipping cost due to shipping diseconomies. On the other hand, to take advantage of shipping economies, larger shipment sizes are encouraged. However, this may result in less frequent shipments for an equal total shipment amount, and consequently resulting in a high inventory cost. These inbound and outbound dispatching decisions involve the trade-off between inventory and shipping costs as a result of variations in the total amount of flows between two locations and their spatial distances. According to Daganzo (1991), some cost components may not be paid by the manufacture, e.g. the key-component shipping fee and the inventory cost of the final products at customers. However, an optimization without these costs tends to transfer the burden of the operation from the manufacturer to the customers and the suppliers, since their costs are not being considered. In other words, the customers and suppliers may be less willing to participate in the operation.

High-tech product demands from customers in various geographical regions can be also described as featured with time-dependent distribution. For example, peak demand likely occurs during Christmas holiday for most western markets, while customers from China might order more during the Chinese New Year. To prevent profit loss resulting from stockout, retailers (customers) often increase their inventory level, which leads to a high inventory cost. To solve this problem and improve customer service performance, transporting parts in frequent shipments of small lots is encouraged for the manufacturer. However, this strategy makes it expensive to serve and deliver product to customers whose distance are far away and the shipment size is not sufficient to achieve shipping economies. Serving all customers via the same service delivery strategy without considering variations in cumulative product amount during each service cycle and geographical spread among plants and customers causes high logistics cost under time-dependent customer demand. In addition, distribution network combined with service delivery strategy has a dramatic influence on customer intention to purchase the manufacturer product, since it determines delay in receiving products. A trade-off relationship exists between logistics cost, given the sum of transportation cost and inventory cost, and customer demand for the manufacturer's products, such that a low average logistics cost could be realized by a least delivery cycle but customer intention to purchase is reduced.

Regarding end consumers, the goal of delivery strategies is to reduce logistics costs and satisfy consumer needs. A crucial factor in optimizing a delivery service strategy is consumer demand. The assumption of constant demand is highly controversial, since in reality demand varies with time, space, and consumer socioeconomic characteristics. In addition to time-dependent consumer demand, consumer demand for retailers is also characterized by socioeconomic characteristics, and temporal and spatial variations. Even when served by the same service cycles, consumers with different characteristics perceive differently, which may further influence consumer demand for retailer goods and, thus, profit. In summary, how to determine an optimal delivery service strategy for retailers by considering demand-supply interaction, time-dependent consumer demand and consumer characteristics has become important.

There have been a lot of studies conducted from different perspective for the supply chain network design. The emphasized decision variables can be classified as facility selection, production/shipment quantities and supplier selections, etc. According to Chopra and Meindl (2004), a supply chain design problem comprises the decisions regarding the number and location of production facilities, the capacity at each facility, the assignment of each market region to one or more location and supplier selection, etc. The most emphasized area in supply chain network design modeling is to address the coordination of logistics operations and the design of effective production and distribution systems (e.g. Jayaraman and Pirkul, 2001; Miranda and Garrido, 2004).

There is a large number of optimization based approaches that have been proposed for the design of supply chain networks (e.g. Arntzen et al., 1995; Jayaraman and Pirkul, 2001; Cohen and Moon, 1991). Others 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 proven to be extremely difficult for solving optimality, most of the research focused on model improvements and algorithms to solve the developed models. Though such network designs can be seen as bases for short-run manufacturers' operational references, the performance results of network designs, apart from demand fluctuations, were not evaluated yet.

The impacts of uncertainties on manufacturer efficiency have prompted a lot of studies to address stochastic parameters in supply chain planning phase. At the static and operational levels, there is a great deal of research developing production/inventory models that deal with various uncertain factors in the environment. The attention has been focused mostly on the probabilistic modeling of the customer demand side (e.g. Cachon and Fisher, 2000; Gavirneni et al., 1997; Gavirneni, 2002). Other studies dealt with supply uncertainties, such as machine breakdowns, strikes, shortages in material availability, etc. The majority of the research employed and modified economic order quantity (EOQ) formulas to include random variables reflecting different uncertainties (e.g. Hariga and Haouari, 1999; Wang and Gerchak, 1996). These studies have shown how the company's performance is affected by uncertain environment and provided tools to tackle these uncertainties and ease these influences. The planning frame of these studies is focused on operational level, rather than strategic design from systematic perspectives.

Taking another 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 that solve the stochastic integer programming models and presenting computational results on supply chain network involving different number of nodes, arcs or products. However, abnormal states occur unexpectedly, resulting in severe demand fluctuations and affecting the performance of a well-design network within the abnormal state continues. Instead of reconstructing the whole network, it is important to propose adjustment method for the manufacturer so as to maintain overall global network design objectives. To summarize, few studies have combined supply chain network modeling and economy theory to formulate integrated models, as they cope with scale economies and demand fluctuations.

Numerous studies have addressed supplier selection issues in supply chain management. Some of them investigated the important factors for selecting suppliers by collecting data and by conducting hypothesis (e.g. Verma and Pullman, 1998; Jahnukaiene and Lahti, 1999). The important criteria include price, quality and delivery reliability, etc. Other studies focused on the quantification-factors and discussed the supplier selection problem as a cost-minimization formulation problem. Supplier selections also influence the design problem structure with additional factors such as geographical location of the suppliers and the manufacturing plants. There are few studies that consider the effects of spatial distance between suppliers and manufacturing plants in the optimal supplier selection process.

To sum up, several important issues in the field of supply chain network design deserve further investigation; however, these issues are rarely emphasized and theoretically formulated. This study aims to investigate the supply chain network design problems in response to scale economies and demand fluctuations. A series models are formulated to systematically investigate the problems and analyze manufacturers' decisions on how much and how often raw material/product to purchase/transport among/to suppliers/customers as well as the optimal capacity and the production amount for multiple plants in response to production and shipping economies in an uncertain environment. Furthermore, the scope of the study is downstream to the end users and aims at optimizing a delivery service strategy for retailers, i.e. Internet store operators, by considering time-dependent consumer demand, demand-supply interaction and consumer socioeconomic characteristics.

1.2 Research objectives

The overall goal of this dissertation is to develop a better understanding of the supply chain network problems and to make contributions in improving the performance of the network. Specifically, the purpose of this dissertation is to investigate the supply chain design problems for high-tech product manufacturers, as they capture the impacts of scale economies and demand fluctuations on the network. In view of this, a series of models are constructed in accordance with issues emphasized. According to the issues of significance, there are five distinct parts in this dissertation, which can be addressed as: integrated plant capacity and production model with economies of scales; incorporating dispatching decisions into supply chain design with production and shipping economies; reliability evaluation and adjustment for supply chain network design with demand fluctuations; and determining optimal delivery service strategies for supply chain network and Internet shopping with time-dependent demand. These five parts can be illustrated as follows.

In the first part of this dissertation, this study aims at investigating how economies of scale, customer demand level and investment conditions in different locations influence the supply chain network design. This study also investigates how the capacity utilization as well as production amount in a short run and the capacity of multiple plants in the long run relates and those two factors influence the total cost. Note that the supply chain network design model developed in this part is the base of the dissertation. The models in the other parts are developed and extended from this network design model to tackle and deal with different issues in the supply chain network.

Following the results from the first part, the second part of this dissertation focuses on evaluating the reliability of the network design on the condition that abnormal demand fluctuations occur. To lessen the impacts of the abnormal demand on the manufacturer cost, this study further proposes adjustment procedures as they cope with different abnormal demand fluctuations. The decisions on performing an adjustment or do nothing are also investigated by comparing between the results if no adjustments are made and if adjustment are made during the duration of an abnormal state.

In the third part of this dissertation, this study extends the models developed in the first part to further include the inbound and outbound dispatching decisions with shipping economies in the supply chain. The impacts of different flow values, total material/product amount of flows between two locations as well as their spatial distance on the optimal shipping frequency and size are specially explored.

Then, the forth part of this dissertation turns the emphasis from the strategic level upon the static level. And the network is narrowed down to two echelons, such as manufacturing plants and customers in different locations, to focus on the logistics aspect in the supply chain network. The issue arises from time-dependent demand and wide spread between the manufacturing plants and customers in different locations. This part of the dissertation aims at investigating the delivery service problems for the manufacturer by considering time-dependent demand and demand-supply interactions. In view of this, the demand-supply interaction models, which optimize a delivery service strategy for high-tech product manufacturer, are developed as they cope with time-dependent demand, demand-supply interaction and geographical spreads of plants and customers. Moreover, the impacts of demand-supply interaction on the optimal capacity and production allocation among the manufacturing plants are also investigated.

Furthermore, in the fifth part of the dissertation, this study focuses on the end consumer shopping behavior and employs Internet shopping as the study object. The impacts of consumer characteristics on the optimal delivery service problems are emphasized in this part. Specifically, in addition to the determination of the optimal number and duration of service cycles by exploring demand-supply interaction and time-dependent consumer demand, this part also investigates how variations in consumer socioeconomic, temporal and spatial distributions influence consumer demand and, thereby, profit.

Specifically, the objectives and contributions of this dissertation are addressed, respectively, as follows.

(1) This study constructs a nonlinear MIP model which attempts to minimize the average total cost per unit-product subject to constraints such as satisfying customer demand in various geographic regions, relationship between supply flows and demand flows within the physical configuration and the production limitation of different-size plants. A heuristic solution approach, based on the simulated annealing (SA), is also developed to solve the optimal problem. This study shows how economies of scale can be considered in solving the capacity and production problems. This study also shows the capacity utilization as well as production

allocation among the manufacturing plants in a short run and the size of capacity of multiple plants in a long run are related and those two factors influence the total cost.

(2) This study develops a series models to systematically investigate the supply chain design problems in response to production economies scale and demand fluctuations. A reliability evaluation method is developed in responding different demand fluctuations. The reliability in the study is defined, as the probability that initially proposed capacity of the manufacturing plant will operate effectively under demand fluctuations. This study further formulates supply chain network adjustment models with respect to demand expansion and shrinkage, as they cope with different fluctuant demands combined with various durations where the abnormal events continue. This study shows how the advantage and disadvantage brought by the adjustment can be carefully considered in advance when solving the network adjustment problems. This study also shows how the duration of an abnormal state and the related allocation costs influence the judgment on whether or not performing an adjustment.

(3) This study constructed a MIP model to incorporate the inbound and outbound dispatching decisions into a supply chain network design problem. This study also explores the impacts of different flow values, total amount of flows between two locations as well as their spatial distance on the optimal shipping frequency and size. Moreover, the impacts of the key-component price by suppliers, which are located at different distance to the plants, on the optimal supplier selection are also investigated.

(4) This study explores how to optimize not only decisions on the first part but also the delivery service strategy for the manufacturer in terms of service cycle frequency

and duration for different customers in various regions as well as their corresponding plant assignments in response to time and spatial dependent customer demand. Furthermore, the impacts of demand-supply interaction with on the optimal capacity and production of the manufacturing plants are investigated.

(5) This study develops a mathematical programming model that can determine the optimal number and duration of service cycles for Internet shopping by exploring demand-supply interaction and time-dependent consumer demand. In the demand side, this study formulates a consumer choice probability model for choosing between Internet and conventional shopping modes. Furthermore, this study investigates how consumer demand for goods from Internet stores influences logistics costs for Internet store operators by formulating average logistics cost for both uniform and discriminating service strategies. The optimal service strategy is also obtained by comparing profit between using discriminating and uniform service strategies.

1.3 Research scope and approaches

This study aims at developing a series supply chain network models for a high-tech product manufacturer who operates multiple plants at different regions. According to the specific issues emphasized in different parts, the planning frame of this dissertation includes strategic level and timeframe between tactic and operational levels. The research scope is shown as Figure 1.1.

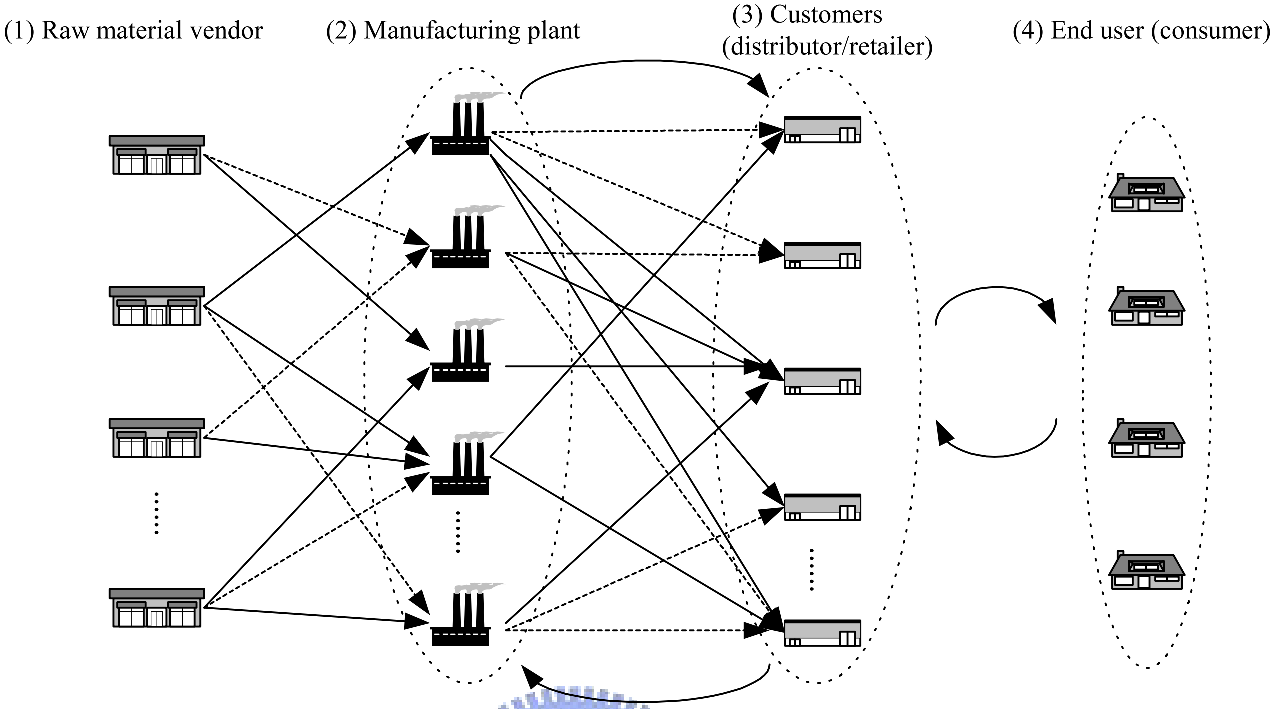

Figure 1.1 The research scope

The research approach with respect to different parts is described as follows. Following past literature in the field of supply chain network design problems, the first and third parts of this dissertation apply mixed integer programming (MIP) formulations and attempt to minimize the average total cost per unit product subject to constraints such as satisfying customer demand in various geographic regions, relationships between supply flows and demand flows within the physical configuration and the production limitation of different size plants. The average total cost per unit-product in the study is given by the sum of inbound, production and outbound cost and constructed, respectively by analytical approaches.

The second part devises a reliability evaluation method for the manufacturer in assessing how well the results of a supply chain network design perform under potential abnormal demand fluctuations. In the study, the capacity utilization is assumed to be the basic criterion for evaluating the reliability of the manufacturing plants under demand fluctuations. To lessen the impacts of the unreliable situations on the overall performance, this study investigates the advantage and disadvantage brought by the adjustment decisions under different fluctuant demand, by analytical approaches. Finally, this study develops the mathematical programming models and proposes adjustment procedures for the supply chain network for determining the optimal adjustment decisions, as they cope with different abnormal demand fluctuations. The judgment on performing an adjustment or do nothing is also investigated by comparing between the results if no adjustments are made and if adjustment are made during the duration of an abnormal state.

In the forth part of this dissertation, this study integrates the logistics aspect in the supply chain and customer demand analysis into one model, and aims at analyzing the impacts of service delivery strategy on customer choices and customer demands for the manufacturer's product with time and spatial dependent demand, and to incorporate demand-supply interaction into network design. The logistics cost, including transportation cost and inventory cost, are formulated by analytical approaches to tackle the impacts of time-dependent demand from various customers, service frequencies with respect to different customers and different assignments of manufacturing plants to customers on manufacturer total costs. This study further deals with dynamic and time-sensitive customer demand, and investigate how service cycle durations affects customer demand for manufacturer products. This study applies a binary logit model to determine customer choice probabilities for manufacturer products. The dependent variables include product prices and delay in receiving products from the manufacturer, where these factors are influenced by the manufacturer's delivery service strategy. Furthermore, a nonlinear mixed integer programming model is formulated for determining the optimal number and duration of service cycles for different customers and the plants assignment decisions, by maximizing profit for the manufacturer subject to demand-supply equality.

In the fifth part of this dissertation, this study applies a binary logit model to determine consumer choice probabilities for both Internet and conventional shopping. The model further captures variations in consumer characteristics by employing consumer income distribution and individual logit model to estimate and aggregate the expected choice probability of choosing Internet shopping for all consumers. Then, the average logistics cost functions for discriminating service strategy is formulated by an analytical approach. Because of various numbers of orders accumulating during different service cycles during the entire study period, the average logistics cost during the study period is estimated using the weighting average method based on service cycle number and duration. Combing the choice probability function with the average logistics cost function, this study further devises a mathematical programming model for determining the optimal number and duration of service cycles during the entire study period by considering the relationship between consumer demand and logistics costs and assuming that Internet store operators are seeking to maximize profit. Due to the complexity in solving a nonlinear programming problem, some approximate methods are required and the greedy algorithm is applied in this study due to its simple implementation and speed. The initial values, including the number and duration of service cycles, are randomly generated. Then the greedy algorithm is applied to obtain the best results for service duration for a specific number of service cycles. To verify this optimal solution, this study tests a variety of initial values for the duration of a specific number of service cycles. After several trials, the optimal duration for a specific number of service cycles can then be determined.

In sum, this dissertation applies network design modeling techniques, non-linear mixed integer programming formulation, disaggregate choice and demand forecast models to develop a series models on analyzing high-tech firms' decision, such as the plant capacity and production allocation among the manufacturing plants, dispatching decisions, reliability evaluation and adjustment and delivery service strategies, as they cope with production and shipping economies, demand characteristics, demand-supply interaction in an uncertain environment. The objectives functions, costs and constraints considered in different parts of this dissertation are listed in Table 1.1. Moreover, the decision variables with respect to the mathematical programming models developed in different parts are shown in Table 1.2.

Table 1.1 The objectives functions, costs and constraints considered in different parts of this dissertation

	Objective function	Cost functions	Constraints
Part 1			
An integrated plant capacity and production model with economies of scales	Minimize the total average cost per unit product for high-tech product manufacturers	(1) Fixed cost (2) Inbound cost: raw material purchase cost and transportation cost (3) Production cost: capital cost and variable production cost (4) Outbound cost: transportation cost	(1) Customer demand (2) Relationships between supply and demand flows (3) Demand flows within the physical configuration (4) Production limitation of different size plants
Part 2.1			
Supply chain network adjustment model in response to demand expansion	Minimize total adjustment cost over months with expansive demand	(1) Allocation cost (2) Extra material purchase cost (3) Difference in production cost (4) Penalty cost (5) Transportation cost	(1) Relationships between adjusted and unadjusted production amount (2) Outsourcing amount limitations
Part 2.2			
Supply chain network adjustment model in response to demand shrinkage	Minimize total adjustment cost over months with shrunk demand	(1) Allocation cost (2) Difference in production cost (3) Transportation cost	(1) Relationships between adjusted and unadjusted production amount
Part 3			
Incorporating dispatching decisions into supply chain network design with production and shipping economies	Minimize the total average cost per unit product for high-tech product manufacturers	(1) Fixed cost (2) Inbound cost: purchase cost, shipping cost and inventory cost (3) Production cost (4) Outbound cost: shipping cost and inventory cost	(1) Customer demand (2) Relationships between supply and demand flows (3) Demand flows within the physical configuration (4) Production limitation

Table 1.1 (continued)

	Objective function	Cost functions	Constraints
Part 4			
Optimal delivery service strategy for high-tech product manufacturers with time-dependent demand	Maximize profit of the manufacturer throughout the entire study period	(1) Production cost (2) Logistics cost: transportation cost and inventory cost	(1) Production limitation (2) Relationships between the study period and service cycles
Part 5			
Optimal delivery service strategy for Internet shopping with time-dependent demand	Maximize profit of the Internet store operator throughout the entire study period	(1) Transportation cost (2) Inventory cost	Relationships between the study period and service cycles

Table 1.2 The decision variables with respect to the mathematical programming models developed in different parts

	Decision variables
Part 1 An integrated plant capacity and production model with economies of scales	(1) The capacity and production amount of the manufacturing plants (2) The raw material amount from the vendors to the manufacturing plants (3) Which manufacturing plants should produce how much production to serve customers in different regions (4) The optimal capacity utilization of the manufacturing plants and the optimal number of active vendors
Part 2.1 Supply chain network adjustment model in response to demand expansion	(1) Production reallocation among the manufacturing plants (2) The optimal outsourcing firms as well as the outsourcing amount (3) Whether or not performing an adjustment
Part 2.2 Supply chain network adjustment model in response to demand shrinkage	(1) Production reallocation among the manufacturing plants (2) Whether or not performing an adjustment
Part 3 Incorporating dispatching decisions into supply chain network design with production and shipping economies	(1) The capacity and monthly production amount of the manufacturing plants (2) The monthly procurement amount of key-component from suppliers to plants (3) Which manufacturing plants should produce how much production to serve customers in different regions (4) The average shipping frequency and shipment size between different combinations of suppliers and plants and between those of plants to customers

Table 1.2 (continued)

	Decision variables
Part 4	
Optimal delivery service strategy for high-tech product manufacturers with time-dependent demand	(1) The optimal capacity and production amount of the manufacturing plants (2) The optimal delivery service cycles and durations for the customers in different regions (3) The assignments of plants to customers during each service cycle
Part 5	
Optimal delivery service strategy for Internet shopping with time-dependent demand	(1) The optimal delivery service cycles during the study period (2) The time when the operator orders batch of each service cycle (3) The number of items ordered in each batch ordering

1.4 Dissertation framework

The framework and organization of this dissertation is shown in Figure 1.2. Figure 1.2 depicts the content and models of each part of this dissertation. Chapter 1 illustrates the overview of this dissertation in terms of motivations and background, objectives, spectrum and approach of the framework. Chapter 2 reviews literature in the relevant topics and distinguishes the study from past studies, in which the contributions of each part of this dissertation are also emphasized. Chapter 3 presents a basic supply chain network design model, where the decisions on plant capacity and production amount of the manufacturing plants are emphasized. In the model, how the demand from customers in different locations, investment conditions and scale economies influence the capacity and production allocation among the manufacturing plants are analyzed. The supply chain network design model is formulated as a MIP model, which attempts to minimize the average total cost per unit-product subject to constraints such as satisfying customer demand in various geographic regions, relationships between supply flows and demand flows within the physical configuration and the production limitation of different size plants.

Chapter 4 evaluates the performance of the results from Chapter 3 on condition that abnormal demand fluctuations occur. In accordance with the unreliable situations, the adjustment strategy is proposed, where the pro and con of the adjustment are analyzed by analytical approaches. Two mathematical programming models with respect to demand expansion and demand shrinkage are further developed to determine the optimal adjustment decisions, regarding production reallocations, manufacturing plants-customers reassignments and outsourcing firms selections, etc. The judgment on performing an adjustment or do nothing is also investigated by comparing between the results if no adjustments are made and if adjustment are made during the duration of an abnormal state.

Chapter 5 focuses on investigating supply chain network design problems when incorporating inbound and outbound dispatching decisions by considering production and shipping economies. A MIP model is also formulated to determine not only decisions as Chapter 3 but also to determine the optimal shipping size and frequency between supply and demand by minimizing the sum of the average inbound, production and outbound costs. In the model, the impacts on the optimal shipping frequency and shipment size and resulting costs because of the geographical combinations of suppliers and manufacturing plants and the total monthly procurement/product amount between them are analyzed. Moreover, the impacts of the key-component price by suppliers, which are located at different distance to the manufacturing plants, on the optimal supplier selection are also investigated.

Chapters 6 and 7 focuses on the logistics issues with regard to delivery service strategies in the supply chain with time-dependent demand. Time and spatial dependent customer demand are first analyzed in Chapter 6. Then, this study formulates manufacturer cost functions as they cope with time and spatial dependent customer demand, where the impacts of production and transportation cost economies on total costs are also incorporated. The customer choice probability are formulated to capture the influences of delay in receiving products from the manufacturer, depended on the spatial distance and service cycles, and the product price charged by the manufacturer. The customer demand model is further estimated by aggregating time and spatial dependent customer demand. Combining with the customer demand function and the manufacturer cost function, a mathematical programming model is formulated for determining an optimal delivery service strategy in terms of the number and duration of service cycles for various customers and the assignments of the manufacturing plants in serving these customers by taking demand-supply interaction into account. The demand-supply interactions on the delivery service strategy programming are discussed. Moreover, the impacts of demand-supply interaction on the determinations of capacity and production of the manufacturing plants are also investigated.

Turning the focus from the customers (retailers) into end users, Chapter 7 designs a consumer choice probability model for choosing between Internet and conventional shopping modes, by taking various factors into account. These factors include differences in consumer socioeconomic characteristics, temporal variations in ordering time of consumer goods, and spatial variations in consumer locations and competitions between Internet stores and retail stores in urban and non-urban areas. Moreover, total customer demand for Internet store goods during different service cycles are estimated by multiplying time-dependent consumer demand and the expected probability of selecting Internet shopping. Regarding the supply side, the logistics cost function, including transportation cost and inventory cost, is developed to analyze how consumer demand for goods influences logistics cost for Internet store operators. Combining with consumer choice model and operator logistic cost function, the optimal delivery service strategy problem is formulated as a mathematical programming model by maximizing operator profit during the study period.

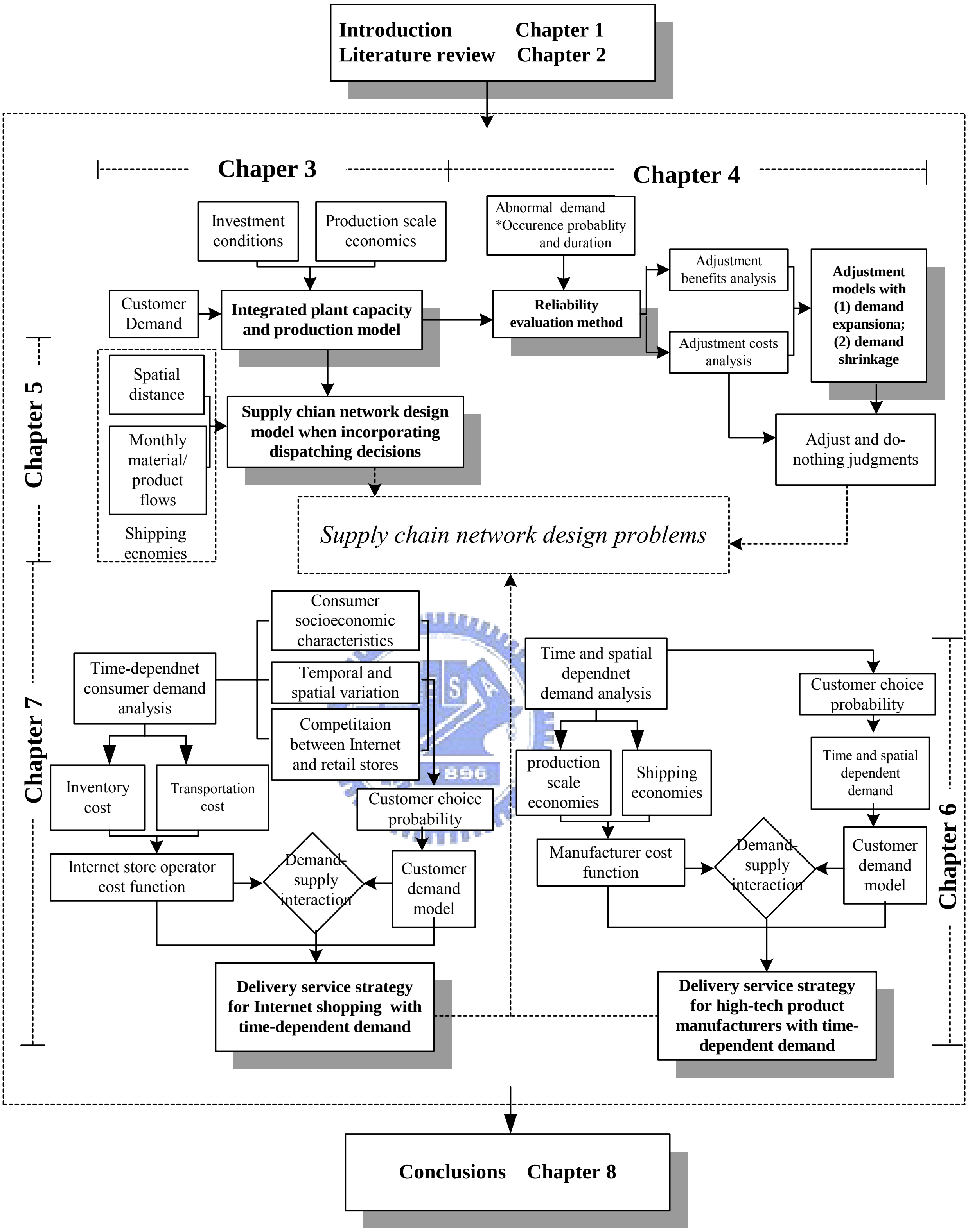

Figure 1.2 The framework of the dissertation

Figure 1.3 depicts the research processes and the steps can be expressed in detail as follows.

1. Define the research problems

According to the motivation and backgrounds, the research problems, issues, scope and objectives are first identified.

2. Literature review

To better understand the problems, this dissertation comprehensively reviews the existing literature in the relevant topics so as to understand the important factors when designing the supply chain network and when determining the optimal delivery service strategy, and to illuminate the contributions of this research.

3. Customer demand and manufacturer cost analysis

Next, customer demand characteristics are investigated. From long-term planning perspectives, events as well as important factors affecting customer demand are identified. Meanwhile, the derivative costs in serving customers are also investigated. These demand and supply analysis are the fundamentals of the model constructions.

4. Supply chain network design model

Based on the analysis in Step 3, the essential cost functions can be formulated. Employing the mixed integer programming models and related analytical techniques, this dissertation formulates a series of supply chain network design models, in which various topics are emphasized.

4.1 Reliability evaluation method

This dissertation further discusses how the performance of the manufacturing plants will be influenced by demand fluctuations by means of investigating the relationships between customer demand and production allocation. After some assumptions are made, this dissertation further formulates reliability evaluation method so as to evaluate the performance of the manufacturing plants on condition that an abnormal event occurs.

4.2 Adjustment method

In view of how economies of scale and customer demand affect manufacturer costs, various adjustment methods in accordance with different fluctuant demand are proposed. Furthermore, the advantage and disadvantage of the proposed adjustment methods are also discussed by constructing analytical models.

4.3 Supply chain network adjustment model

The mathematical programming model is employed herein to determine the optimal adjustment decisions. And the judgment of do-nothing and adjustment is also done by comparing the objective functions under condition that if and if not an adjustment is performed.

5. Demand-supply interaction

The other major part of this dissertation aims at designing the optimal delivery service strategy under different pattern of fluctuant demand, i.e. time-dependent customer demand. Based on the analysis in Step 3, how the customer demand is affected by the service provided and the interrelationship between customer demand and manufacturer costs can be analyzed and developed by analytical approaches.

6. Mathematical programming model for the optimal delivery service strategy

The demand-supply interactions on the delivery service strategy programming are analyzed, by integrating supply and demand models and using an algorithm to solve the problem.

7. Case studies and sensitivity analysis

Case studies and sensitivity analysis are provided in each parts of this dissertation to illustrate the application of the models and to demonstrate the proposed models' effectiveness.

8. Conclusions and suggestions

Finally, the summary, conclusions and the future studies of this dissertation are presented.

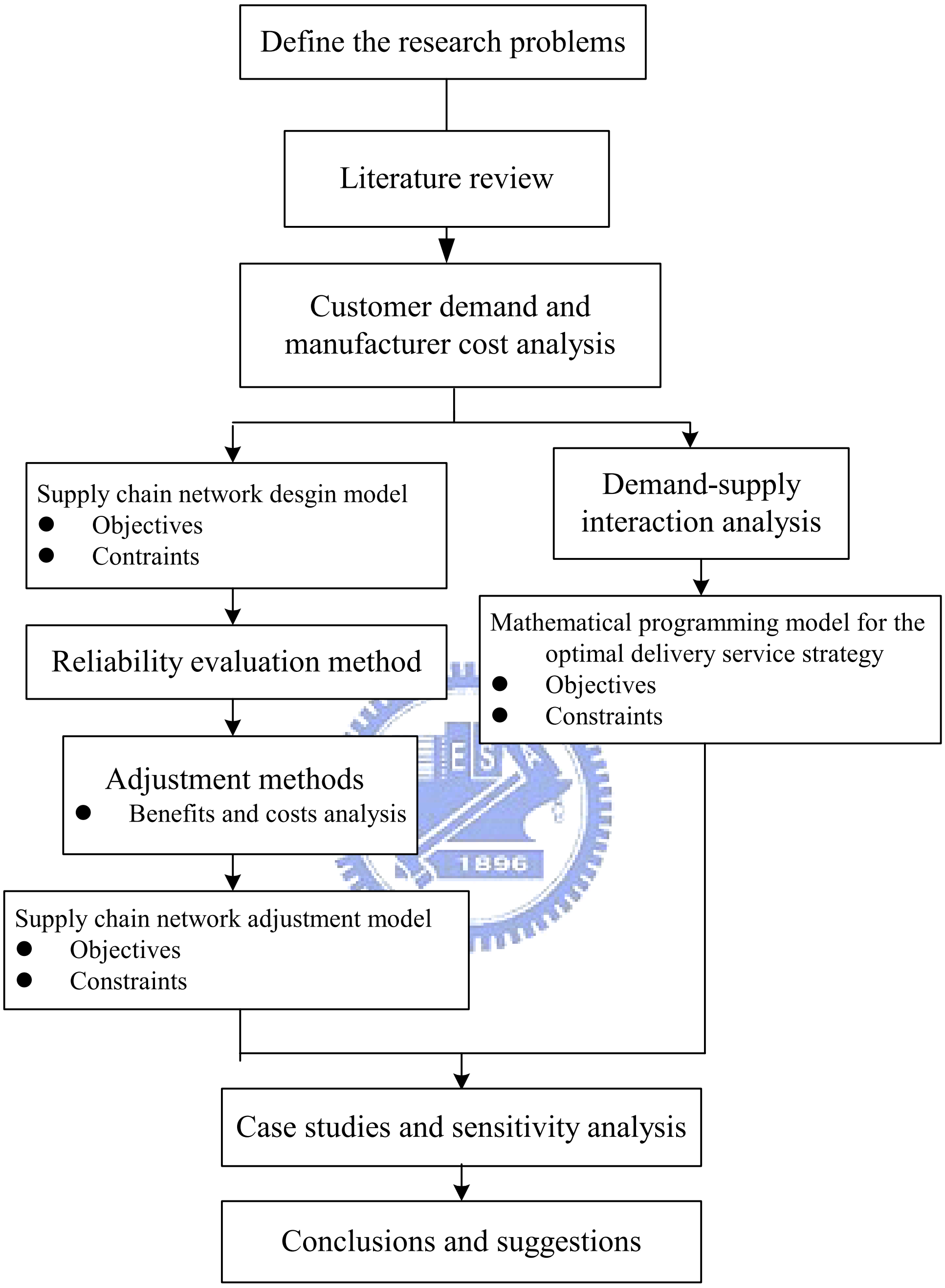

Figure 1.3 The research process flowchart

CHAPTER 2

Literature review

This chapter reviews the literature on related areas including: 2.1 Supply chain management related issues; 2.2 Supply chain network design models; 2.3 Logistics and transportation issues in supply chain; 2.4 Internet shopping and physical distribution problems; 2.5 MIP formulations. Issues, theoretical methods and contributions of the relevant studies are discusses and summarized in this chapter. Furthermore, the contributions of the study are also clarified in Section 2.6.

2.1 Supply chain management related issues

Since the introduction of the term "supply chain management" (SCM) in 1982, it has received a lot of interests both in the literature and practice. According to Christopher (1998), a supply chain (SC) can be defined as a network of organizations that are involved, through upstream and downstream linkages in the different processes and activities that produce value in the form of products and services in the hand of the ultimate consumers. Therefore, supply chain management is the task of integrating materials, information and financial flows in order to fulfill customer demands with the aim of improving competitiveness of the SC as a whole (Stadtler, 2005). Furthermore, supply chain management can be viewed as logistics outside the firm to include customer and suppliers (Lamber and Cooper, 2000). The planning tasks can be classified to different levels depending on the time horizon, namely strategic, tactical and operational. The operational planning includes vehicle routing, scheduling, etc; the tactical planning involves the procurement, inventory and transportation system, etc; and the strategic planning includes the determinations of plant sites, the number of plants, etc. Specifically, the main determinations of strategic level include (1) the number, location, capacity of manufacturing plants; (2) the active suppliers; (3) the amount of raw materials and products to produce and ship among suppliers, plants and customers, etc (Vidal and Goetschalckx, 1997). In practice, the short-term operational flexibility is directly related to the strategic decisions.

There exist different areas of literature associated with supply chain management, such as strategic management, logistics, relationships/partnerships, etc. Among those studies, a lot of studies have concerned about demand amplified, i.e. bullwhip effect in a supply chain, which can be described as the variability of orders increases from down stream to upstream (Simchi-Levi et al., 2000). This phenomenon makes supply chain planning difficult. Different ordering policies were considered and discussed to reduce the order variance. Geary et al. (2006) identified major causes of bullwhip and provided several principles to reduce bullwhip effect. A great deal of literature has investigated the impacts of different ordering policies on the order variability and the most mentioned policies are (s, S) ordering policy (e.g. Kelle and Milne, 1999). In addition to quantify bullwhip effect, some studies proposed different strategies to reduce bullwhip effect, such as accurate demand forecasts (e.g. Metters, 1997) and application of information flows technique (e.g. Cachon and Fisher, 2000). Bourland et al. (1996) exploited timely demand information (TDI) to reduce inventories. The results show that inventory-related benefits are sensitive to demand variability, the service level provided by suppliers, and the degree to which the order and production cycles are out of phase. Berman and Kim (2001) considered a problem of dynamic replenishment of parts in the supply chain consisting of single class of customers, company, and supplier. To sum up, the above literature can be classified as production-inventory models that involve uncertainties in the environment. The most attentions focused on the probabilistic modeling of the customer demand side. The timeframe of the literature can be classified as operational planning in the supply chain management.

In another line of research, the economic order quantity (EOQ) or lot sizes decisions have been discussed extensively in the inventory control literature (e.g. Silver and Peterson, 1985; Wagner, 1980). Schniderjans and Cao (2000) and Fazel et al. (1998) presented an analytical model to evaluate and compare the total purchasing and inventory cost associated with just in time (JIT) and EOQ. The proposed model expanded the classical EOQ to include a quantity discount scheme. Other studies relaxed the assumption from deterministic demand to investigate the impacts of stochastic demand on the optimal ordering policy (e.g. Haneveld and Teunter, 1998). Other studies assumed a stochastic supply and discussed the optimal ordering policy with EOQ (e.g. Hariga and Haouari, 1999; Wang and Gerchak, 1996). Other studies have applied fuzzy theory to investigate the optimal ordering policy, such as Vujošević et al. (1996) assumed both inventory cost and ordering cost as two fuzzy variable and Roy and Maiti (1997) constructed a fuzzy EOQ model with time-dependent unit cost under limited storage capacity. In sum, past EOQ models are mainly based on the time frame, with the active suppliers being known and given.

There are still some studies aiming at reviewing literature about supply chain management. Croom et al. (2000) considered the bodies of literature associated with supply chain management and discussed the different perspectives adopted in different studies. Beamon (1998) provided a focused review of literature in multi-stage supply chain modeling. According to Beamon (1998), the four categories of modeling approach are (1) deterministic analytical models, in which the variables are known and specified, (2) stochastic analytical models, where at least one of the variables is unknown, and is assumed to follow a particular probability distribution, (3) economic models, and (4) simulation models.

The demand forecast methods and information flows technique have been demonstrated important factors influencing inventory cost and customer service performance in past literature. Most of the studies aimed at short-term demand uncertainty and the influencing on company's operational efficiency. However, the extent to which the economic fluctuation influences the market demand of high-tech product is quite apparent. And the duration of different economic fluctuations during the planning year is quite different, which may further influences service quality and cost economies. Though some conventional statistical forecasting models can be applied to generate future customer demand, the fluctuations surrounding customer demand may affect accuracy of forecasted results.

In addition to apply accurate forecast methods, some studies aimed at investigate the relationship between supply side uncertainty and ordering policy. Whybark and William (1976) presented a framework for characterizing and studying the uncertainty which affect inventory level investment and service level performance in a material requirements planning (MRP) system. This study also showed how safety stock or safety lead time can be used for buffering a part against uncertainty. The results showed that under conditions of uncertainty in timing, safety lead time is the preferred technique, while safety stock is preferred under conditions of quantity uncertainty. Petrovic et al. (1998) represented supply chain fuzzy models and a corresponding simulator, developed to assist in decision making on operational supply chain control parameters in an uncertain environment. The objective in this study is to determine the stock levels and order quantities for each inventory in a supply chain during a finite time horizon to obtain an acceptable delivery performance at a reasonable total cost for the whole supply chain. Güllü et al. (1999) analyzed a periodic review, single-item inventory model under supply uncertainty. In the study, the uncertainty in supply was modeled using a three-point probability mass function and the supply is either completely available, partially available, or the supply is unavailable. Machine breakdowns, shortages in the capacity of the supplier, strikes, etc., are possible causes of uncertainty in supply. An algorithm was also given in computing the optimal inventory levels over the planning horizon.

Zimmer (2002) considered a supply chain, consisting of one producer and one supplier in a just in time environment, where the supply of component is uncertain due to uncertain availability of the capacity of the supplier. This study also proposed a coordination mechanism that allows the system to perform just as well as a centralized one. Moinzadeh (2002) considered a supply chain model consisting of a single product, one supplier and multiple retailers and studied the benefits of information-sharing in a supply chain characterized as the availability of online information of retailers' inventory positions to the supplier. Maia and Qassim (1999) presented an analytical solution for an optimization model that determines whenever it is preferable to incur inventory cost or opportunity costs. The results showed that products should be stocked only if opportunity costs are higher than inventory costs.

In another line of research, operational issues in the supply chain for high-tech manufacturing industries have been intensively discussed. Chen et al. (2005) considered production scheduling planning and developed a capacity planning system, which considered the capacity and capability of equipments for multiple semiconductor manufacturing FABs. In their study, "Capacity" refers to the upper threshold on the load on an operating unit and "Capability" refers to a specific processing capability of a machine, respectively. Due to there are often capacity shortages, Mallik and Harker (2004) proposed a game theoretic model to deal with the conflicts in forecasting and capacity allocation to product lines between product and manufacturing managers in a semiconductor manufacturing firm. The result shows that truthful reports of demand and capacities by the managers can be induced through a bonus. Since the capacity expansion is costly and time consuming, it is important to incorporate the economies of scale and demand fluctuation into the production-distribution planning phase.

Numerous studies have addressed supplier selection issues in supply chain management. Some of them investigated the important factors for selecting suppliers by collecting data and by conducting hypothesis (e.g. Verma and Pullman, 1998; Jahnukaiene and Lahti, 1999). The important criteria include price, quality and delivery reliability, etc. Other studies focused on the quantification-factors and discussed the supplier selection problem as a cost-minimization formulation problem. Supplier selections also influence the design problem structure with additional factors such as geographical location of the suppliers and the manufacturing plants. There are few studies that consider the effects of spatial distance between suppliers and manufacturing plants in the optimal supplier selection process. Table 2.1 summarizes main issues and results in the existing literature on supply chain management.

Summary:

There are extensive studies addressing the impacts of uncertainty factors on company's cost and customer service level performance with respect to demand and supply uncertainty. The literature also proposed various strategies to reduce the impacts of uncertainty under different scenarios. These strategies include accurate forecast methods, usage of information exchange system, etc. Since the demand uncertainty has been proven the source of downgrading the performance of a supply chain, forecast methods are emphasized in some studies. Most of these studies focused on the short-term operational issues and constructed analytical models in terms of operation research. However, the performance resulting from demand fluctuation was seldom evaluated based on an economic theory. In addition, past EOQ models are mainly based on the time frame, with the active suppliers being known and given. Few studies have considered the impact on the optimal shipping frequency and size and resulting costs because of geographical combinations of suppliers and manufacturing plants and the total flows between them. This study formulates a series model to investigate the above issues. This study aims at investigating strategic issues of supply chain management. This study also incorporates fluctuations in customer demand into designing a supply chain network and proposes different fine-tune strategies in response to short-term fluctuations.

Table 2.1 Main issues, features and results in literature on supply chain management related issues

Authors	Main issues and features	Important results
Christopher (1998), Stadtler (2005), Lamber and Cooper (2000)	Discuss the issues and modeling approaches in supply chain management	Define supply chain, supply chain management, etc
Croom et al. (2000), Beamon (1998)	Literature review	Four categories of modeling approaches in supply chain management: (1) deterministic, (2) stochastic, (3) economic, and (4) simulation models
Metters (1997), Cachon and Fisher (2000)	Quality bullwhip effect and propose strategies to reduce bullwhip effect	Accurate demand forecasts and apply information technique can effectively reduce the impacts of bullwhip effects
Fazel et al. (1998), Schniederjans and Cao (2002)	The impacts of JIT purchasing and EOQ with a price discount on the total inventory cost	The higher the value of the item, the carrying cost, or the ordering cost associated with the EOQ model, and the smaller the quantity discount rate, the wider will be the range of demand for which JIT remains preferable
Güllü et al. (1999)	Periodic review, single-item inventory model under supply uncertainty	Focus on developing an efficient algorithm in solving the optimal inventory levels
Maia and Qassim (1999)	Develop an analytical solution for determining whenever it is preferable incurring inventory cost or opportunity costs	Products should be stock only if opportunity costs are higher than inventory cost
Mallik and Harker (2004)	Deal with conflicts in forecasting and capacity allocation to product lines between managers from the operational level	Truthful reports of demand and capacities can be induced through a bonus
Verma and Pullman (1998), Jahnukaiene and Lahti (1999)	Investigate important factors for selecting suppliers by collecting data and conducting hypothesis	The important criteria are price, quality and delivery reliability, etc

Source: this study

2.2 Supply chain network design models

There have been a lot of studies conducted from different perspective for the supply chain network design. The emphasized decision variables can be classified as facility selection, production/shipment quantities and supplier selections, etc. According to Vial and Goetschalckx (1997), the most comprehensive strategic problems is the optimization of the complete supply chain. The strategic design of a supply chain requires managers to determine:

- the number, location, capacity, and type of manufacturing plants and warehouse to use;
- the set of suppliers to select;
- the transportation channels to use;
- the amount of raw materials and products to produce and ship among suppliers, plants, warehouses, and customers; and
- the amount of raw materials, intermediate products, and finished goods to hold at various location in the inventory.

Many critical reviews of supply chain network design with emphasize on different perspective can be found. Vidal and Goetschalckx (1997) reviewed strategic production-distribution models. The review was classified into four sections: previous reviews, optimizations models, additional issues for modeling, and case studies and applications. Geoffrion and Powers (1995) reviewed the evolution of the strategic production and distribution models since 1970. Beamon (1998) reviewed strategic, stochastic, simulation, and economic models in the supply chain literature. Meixell and Gargeya (2005) focused on the model-based literature that addresses the global supply chain design problems. In their paper, they mentioned that global supply chain models need to address the composite supply chain design problem by extending models to include both internal manufacturing and external supplier locations.

Arntzen et al. (1995) developed a mixed integer programming (MIP) model considering multiple products, facilities, time periods, and transportation modes. The model aimed at minimizing a composite function of activity days and total production costs, inventory, transportation costs, etc. All the costs considered in the objective function are weighted by a factor α. The objective function represents a weighted combination of time and cost so that either measure or both can be used to derive recommendations (Meixell and Gargeya, 2005). As Vidal and Goetschalckx (1997) mentioned, the main contribution of the study is the inclusion of offset trade, local content, and duty considerations in an international supply chain model that also includes bill of material (BOM) constraints.

Nagurney et al. (2002, 2003, 2005) considered many decision-makers and their independent behaviors in the supply chain and developed network equilibrium models for a competitive supply chain comprised of manufacturer, retailers and customers. In the model, transportation links are associated with different costs. Their models used a variational inequality formulation to derive product shipments and price pattern in the network.

Santoso et al. (2005) proposed a stochastic programming model and solution algorithm for solving supply chain network design problems under uncertainty. The proposed method integrates an accelerated decomposition scheme along with the developed sample average approximation (SAA) method. Goetschalckx et al. (2002) integrated the design of strategic global supply chain network with the determination of tactical production-distribution allocations and transfer prices. The results showed that more savings in computing times can be achieved by simultaneously determining strategic and tactical decisions as compared to the sequential decision process where first the plants are located and then the tactical production-distribution flows are determined.

Eskigun et al. (2005) considered the design of an outbound supply chain network considering lead times, location of distribution facilities and choice of transportation mode. The objective function is to minimize total cost, given by the sum of transportation cost, lead-time cost and fixed cost. In the model, the varying capital and production costs of plants in different regions are neglected and the impacts of spatial distance between two locations on transit time and transportation cost are not mentioned.

From reviewing the literature about supply chain network design to date, the mixed integer programming (MIP) formulation has been intensively used to investigate strategic issues of supply chain management (e.g. Brown et al. 1987; Goetschalckx et al., 2002). Due to large-scale models have been proven to be extremely difficult to solve optimality, solution methods and computational experiences are necessary. Brimberg and ReVelle (1998) formulated a bi-objective plant location models for analyzing the trade-off between total cost and the proportion of the market to be served. In this study, partial satisfaction of demand is considered rather than serving all demand in the traditional plant location problem. The weighted method approach is investigated for obtaining efficient solutions of the model. Jayaraman and Pirkul (2001) extended the plant location problem to incorporate the tactical production-distribution problem for multiple commodities. In the model, a facility or warehouse is constrained to serve one single customer. Miranda and Garrido (2004) proposed a simultaneous approach to incorporate inventory control decision into typical facility location models. Crama et al. (2004) constructed a nonlinear MIP model to determine the optimal procurement decisions in the presence of total quantity discounts and alternative product recipes.

Several studies have recognized the benefits of centralized production. Cohen and Moon (1990) analyzed the impacts of scale and scope cost behavior on the optimal design of supply chain systems. The results showed that there are trade-offs between various costs, such as the fact that the effect of decreasing the fixed cost on the number of plants is largely offset by an increase in inbound cost. Cohen and Moon (1991) formulated a MIP model to determine the optimal assignment of product lines and volumes to a set of capacitated plants. In the model, the capacity of plants is given and fixed and the production cost functions exhibit concavity with respect to each product line volume to reflect economies of scale. Moreover, correlation and regression analyses are employed to analyze the relationship between the cost parameters. The results indicate that focused plants arise in situations with high economies of scale. However, although the capacity utilization of different-size plants will result in various influences on their total cost, its extent is seldom discussed. The models constructed are usually large-scale linear or nonlinear MIP formulations, which are difficult to solve. Therefore, these studies focused mainly on developing an approximation procedure and compared the efficiency of their proposed heuristics with others.

Many solution algorithms have been developed for handling linear MIP models, such as linear approximation, Lagrangian relaxation, branch-and-bound, Benders decomposition and primal decomposition methods (e.g. Jayaraman and Pirkul, 2001; Miranda and Garrido, 2004). Goetschalckx et al. (1994, 1995) presented a generic model for the strategic design of production-distribution systems, including visual capabilities. Based on the generic model, they introduced algorithm components that significantly reduce the solution times compared to standard MIP solutions by a commercial solver. Cohen and Moon (1991) provided an algorithm to solve production-distribution models with piecewise linear concave costs of production. In the algorithm, a variant of the generalized Benders Decomposition technique was applied. Table 2.2 summarizes main issues and features and important results in the existing literature on supply chain network design models.

Table 2.2 Main issues, features and results in literature on supply chain network design models

Authors	Main issues and features	Important results
Vidal and Goetschalckx (1997), Geoffrion and Power (1995), Gargeya (2005)	Review supply chain design models	Global supply chain models need to address the composite supply chain problem by extending models to include both internal manufacturing and external supplier locations
Arntzen et al. (1995)	Develop a MIP model considering multiple products, facilities, time periods and transportation modes	The main contribution is the inclusion of offset trade, local content and duty considerations
Nagurney et al. (2002, 2003, 2005)	Consider many decision-makers and independent behaviors for a competitive supply chain	Use a variational inequality formulation to derive product shipments and price pattern in the network
Santoso et al. (2005)	Propose a stochastic programming model and solution algorithm for supply chain design problems under uncertainty	Focus on developing efficient algorithms in solving the proposed models
Goetschalckx et al. (2002)	Integrate the design of strategic global supply chain network with the determination of tactical production-distribution allocations	Focus on developing efficient algorithms in solving the proposed models
Eskigun et al. (2005)	Design an outbound supply chain network, considering lead times, location and choice of transportation modes	Focus on developing efficient algorithms in solving the proposed models
Cohen and Moon (1990)	Analyze the impacts of scale and scope cost behavior on the optimal design of supply chain systems	The effect of decreasing fixed cost on the number of plants is largely offset by an increased inbound costs
Cohen and Moon (1991)	Determine the optimal assignment of product lines and volumes to a set of capacitated plants	Focused plants arise in situations with high economies of scale

Source: this study

Summary:

There is vast literature conducting supply chain network problems. The majority of this research focused on the production-distribution models. And the mixed integer programming (MIP) method has been extensively used to investigate the problems. Because these models constructed are usually large-scale linear or nonlinear MIP formulations, which are difficult to solve. These studies focused mainly on developing and approximation procedure and comparing the efficiency of their proposed heuristics with others. In addition, though the capacity utilization of different-sized plants will result in various influences on their cost, its extent is seldom discussed. The impacts of high capacity cost on the optimal plant capacity and production among manufacturing plants with different sizes are seldom discussed. Though optimal flows between demand and supply nodes have been discussed and have been included in the supply chain design problems, the shipping frequency and shipment size between different combinations of suppliers and manufacturing plants have not been discussed yet. Furthermore, production and shipping economies and their tradeoff relationships are seldom discussed when designing a supply chain network.

2.3 Logistics and transportation issues in supply chain

The logistics function in supply chain is conceptualized as a service function because its output is not a product but a performance, such as just-in-time delivery of the right amount of goods at the right place (Heskett et al. 1990). Logistics is also a strategic level challenge in a supply chain. In literature of supply chain management, there is a lot of studies have conducted the role of transportation and logistics functions in a supply chain. van Hoek and van Dierdonck (2000) aimed at assessing whether or not final manufacturing activities are actually being postponed and placed in the distribution channel. Based on a survey among 782 companies, the difference in size and scope of applications between manufacturers, wholesalers and logistics service providers are assessed. The results showed that high value adding manufacturing activities are still the primary domain of manufacturers and there are not often outsourced to logistics service providers. Morash and Clinton (1997) investigated and compared supply chain organizational structures and integrative capabilities of approximately two thousand firms from the United States, Japan, Korea, and Australia. Country differences in both supply chain structures and transportation capabilities were identified.

Lai et al. (2002) aimed to investigate the construct of, and develop a measurement instrument for, supply chain performance in transport logistics. A 26-item supply chain performance measurement instrument was constructed, reflecting service effectiveness for shippers, operations efficiency for transport logistics service providers, and service effectiveness for consignees. Mason et al. (2003) demonstrated the potential for integrating the warehousing and transportation functions and so improve customer service through reduced costs and reduced lead-time variability. Thomas and Hackman (2003) analyzed a supply chain environment where a distributor facing price-sensitive demand has the opportunity to contractually commit to a delivery quantity at regular intervals over a finite horizon in exchange for a per-unit cost reduction for units acquired via committed delivery.

Chopra (2003) described a framework for designing the distribution network in a supply chain. In the paper, there are six distinct distribution network designs, such as: (1) manufacturer storage with direct shipping; (2) manufacturer storage with direct shipping and in-transit merge; (3) distributor storage with package carrier delivery; (4) distributor storage with last mile delivery; (5) manufacturer/distributor storage with customer pickup; and (6) retail storage with customer pickup. The strengths and weakness of these designs and various factors influencing the choice of distribution network are also described.

Ambrosino and Scutellà (2005) studied complex distribution network design problems, which involve facility location, warehousing, transportation and inventory decisions. The main contribution of this study is the statement of two kinds of mathematical programming formulations: some formulations aimed at warehouse location-routing problems and other formulations are based on flow variables and constraints. Eskigun et al. (2005) formulated an integer linear programming (ILP) model, which considered the design of an outbound supply chain network for vehicle distribution centers, considering lead times, location of distribution facilities and choice of transportation mode. A Lagrangian heuristic was developed to solve this large-scale integer linear programming model. Results of the scenario analyses indicate that as the lead-time gains importance, the use of trucks increases significantly to deliver the vehicle directly from plants to demand areas in shorter lead-time.

Motivated by observing the chemical industries, where manufacturing often takes place only after the order has been received, Kiesmüller et al. (2005) presented a dual supply model taking into account that the replenishment cycle involves not only the physical distribution of goods, but also the manufacturing of products. This study also investigated a class of order-up-to policies and showed how to compute the optimal policy parameters. The results showed that especially in cases where the manufacturing lead time is long and the difference in cost between fast and slow modes is big and the lead time difference is large, the added value of including the manufacturing lead time for the model is substantial. In industries such as the chemical industry using the models would imply a dramatic shift from road transport to rail or barge transport.

Though the importance of logistic functions to the supply chain efficiency has been demonstrated and discussed included in supply chain design problems. The shipping frequency and shipment size between different combinations of suppliers and manufacturing plants and of manufacturing plants and customers in different regions have not been discussed yet. Furthermore, shipping economies inhering in the supply chain are seldom discussed when design a supply chain network.

A great deal of analytical research has been conducted on solving the physical distribution problems (e.g. Burns et al., 1985; Blumenfeld et al., 1985). Hall (1987) proposed a critical flow concept, that is to say, shipping economies arise when the shipment size exceeds the critical flow. Blumenfeld et al. (1985) pointed out that the optimal shipping route depends on the geographical combinations of production sites, warehouses, and customers. From these studies, the following conclusions can be drawn: a less frequent strategy is suggested when two locations are distant from each other; otherwise, a converse strategy is preferred. Furthermore, according to Daganzo (1991), some cost components may not be paid by the manufacture, e.g. the key-component shipping fee and the inventory cost of the final products at customers. However, an optimization without these costs tends to transfer the burden of the operation from the manufacturer to the customers and the suppliers, since their costs are not being considered. In other words, the customers and suppliers may be less willing to participate in the operation. Table 2.3 summarizes main issues and features and important results in the existing literature on logistics issues in the supply chain.

Summary:

Past literature has demonstrated the importance of logistics functions on the efficiency of a supply chain. However, the shipping frequency and shipment size between different combinations of suppliers and manufacturing plants and of manufacturing plants and customers in different regions have not been discussed yet. Furthermore, shipping economies inhering in the supply chain are seldom discussed when design a supply chain network. The impact of spatial distance on the optimal shipping frequency although having been studied in logistics literature, has not been integrated into the design of supply chain networks.

Table 2.3 Main issues, features and results in literature on logistics issues in the supply chain

Authors	Main issues and features	Important results
van Dierdonck (2000)	Assess whether or not final manufacturing activities are actually being postponed and placed in the distribution channel	High value adding manufacturing activities are still the primary domain of manufaturers
Manson et al. (2003)	Integrate the warehousing and transportation functions of the supply chain	Demonstrate the potential for integrated paradigm to improve customer service through improved efficiencies, reduced costs and reduced lead-time variability
Ambrosino and Scutellà (2005)	Consider complex distribution design problems	The main contribution is the statement of two kinds of mathematical programming formulations
Eskigun et al. (2005)	Design an outbound distribution network for vehicle distribution centers	As the lead-time gains importance, the use of trucks increases significantly to deliver the vehicle directly from plants to demand areas in shorter lead-time
Kiesmüller et al. (2005)	Present a dual supply model taking into account that the replenishment cycle involves not only the physical distribution of goods, but also the manufacturing of products.	When the manufacturing lead time is long and the difference in cost between fast and slow modes is big and the lead time difference is large, the added value of including the manufacturing lead time for the model is substantial
Hall (1987)	Propose analytical research on solving the physical distribution problems	Propose a critical flow concept, i.e. shipping economies arise when the shipment size exceeds the critical flow.
Blumenfeld et al. (1985)	Propose analytical research on solving the physical distribution problems	The optimal shipping route depends on the geographical combinations of production sites, warehouses, and customers.

Source: this study

2.4 Internet shopping and physical distribution problems

The major issues related to Internet shopping have been extensively examined in numerous studies, including marketing, pricing, and payment, etc. (e.g. Pavitt, 1997; Kiang et al., 2000; Peterson et al., 1997). O'cass and Fenech (2003) examined Internet user adoption of the Web for retail/purchase behavior. Burke (1997) noted that the home-shopping system eliminated drive time and checkout time and enabled shoppers to access distant stores and showed the retailing technology is most convenient when it matches shopping and media habits. Verhoef and Langerak (2001) identified delivery delay for ordered goods as major disadvantage of Internet shopping.

Previous studies examining the differences in consumer choice in the contexts Internet shopping and conventional shopping focused mainly on analyzing the pros and cons of Internet shopping or the influencing consumer intention to shop on the Internet using collected empirical data (e.g. Manski and Salomon, 1987; Koppelman et al., 1991; Sim and Koi, 2002). Salomon and Koppelman (1988) established a framework of shopping behavior for examining consumer choices among in-home and out-of-home shopping modes. Their framework comprises a description of the shopping-purchasing process and hypotheses relating to influences on individual choices regarding alternative shopping modes.

Sherman and Topol (1996) investigated emerging technologies, including electronic retailing and interactive shopping, and their influences on consumers, retailers and manufacturers. Other studies examined the demographic and psycho-graphic characteristics of Internet shoppers using local shopper surveys (e.g. Verhoef and Langerak, 2001; Raijas, 2002). Olson and Boyer (2003) investigated how end user viewpoints and characteristics, such as education and tenure in the workforce, influence use of the Internet as a purchasing avenue. Heim and Sinha (2001) provided an empirical analysis which examined the relationship between customer loyalty and the order procurement and fulfillment processes of electronic retailers. They found that short delivery times have a significant influence on customer loyalty. Heim and Sinha (2002) further developed a taxonomy of service processes and attempted to link electronic service processes with customer ratings of service performance. They found that a positive and significant correlation between the ordering of the configurations in the taxonomy and consumer satisfaction with Web site aesthetics, production selection and product information, etc. Furthermore, Nagurney et al. (2001) proposed a network equilibrium framework for analyzing consumer preference for Internet shopping vs. store shopping under an assumption of multicriteria decision makers.

On the supply side of Internet shopping, Huppertz (1999) concluded that the major problem in electronic commerce is that frequent small-sized orders lead to high transportation costs. Khouja (2001) proposed an optimal mix strategy of drop shipping and in-house inventory for e-retailers, and identified optimal solution of order quantity for in-house inventory to the drop-shipping model under uniform, exponential, and normal demand distributions. Moreover, Hsu et al. (2003) introduced a discriminating shipping strategy for Internet store operators that varies the optimal shipping cycles for different consumer locations and determined the optimal shipping cycles based on consumer demand and distance to the distribution center. The results show that the discriminating service strategy yields better objective values if the discrepancy of demand pattern is more apparent.

In another line of research, numerous studies have investigated physical distribution problems using analytical approaches (e.g. Burns et al., 1985; Blumenfeld et al., 1985). This research typically considered shipping problems under inelastic demand and focused on operating issues such as scheduling routing, and configuration of physical distribution. However, little research has investigated the influence on logistics costs of time-dependent demand, demand-supply interaction and the 24-h nature of Internet shopping.

Recent studies have investigated carriers or providers issues and their effects on consumer services and operating strategies. Most of these empirical studies dealt with these issues by testing hypotheses. Rabinovich et al. (2003) investigated the impacts on the supply chain efficiency of information exchanges between e-retailers and end consumers. Rabinovich (2004) later examined a Internet retailer’s inventory liquidity and its relationship to the retailer’s ability to fulfill its guarantees, and found that Internet retailers should align inventory liquidity and delivery performance to fulfill economically consumer orders. Rabinovich and Bailey (2004) concluded that Internet retailers usually adopt revenue-maximizing strategies for their physical distribution pricing policies that reflect the physical distribution service quality they provide. Esper et al. (2003) found that allowing consumers to choose a carrier leads to increased levels of anticipated satisfaction with the online experience and an increased willingness to buy.

Boyer et al. (2002) developed preliminary frameworks for analyzing e-services and found that the strategic operations choices regarding fit between delivery processes and products must play an important direct role in the consumer perceptions of delivery services. Chen (2001) investigated the benefits of a segmentation strategy in which price-delay combinations were available for several market segments. In Chen’s model, Poisson process was employed to describe consumer arrival at the selling process and identified that consumers are segmented according their willingness to pay for one unit of a product. Chen found that the benefit of market segmentation is large if more patient consumers are in the market. Table 2.4 summarizes main issues and features and important results in literature on Internet shopping and physical distribution problems.

Table 2.4 Main issues, features and results in literature on Internet shopping and physical distribution problems

Authors	Main issues and features	Important results
Burke (1997)	Empirical study towards Internet shopping	Home-shopping system eliminated drive time and checkout time and enabled shoppers to access distant stores
Olson and Boyer (2003), Heim and Sinha (2001)	Empirical study towards Internet shopping	Short delivery times have a significant influence on customer loyalty
Heim and Sinha (2002)	Develop a taxonomy of service processes and attempted to link electronic service processes with customer ratings of service performance.	A positive and significant correlation between the ordering of the configurations in the taxonomy and consumer satisfaction with Web site aesthetics, production selection and product information
Hsu et al. (2003)	Introduce a discriminating shipping strategy that varies the optimal shipping cycles for different consumer locations based on consumer demand and distance to the distribution center	The discriminating service strategy yields better objective values if the discrepancy of demand pattern is more apparent
Rabinovich et al. (2003), Rabinovich (2004), Rabinovich and Bailey (2004), Esper et al. (2003)	Investigate carriers or providers issues and their effects on consumer services and operating strategies	Retailers usually adopt revenue-maximizing strategies for their physical distribution pricing policies, reflecting the physical distribution service quality they provide. Allowing consumers to choose a carrier leads to increased levels of anticipated satisfaction
Chen (2001)	Investigate benefits of a segmentation strategy where price-delay combinations were available for several market segments	The benefit of market segmentation is large if more patient consumers are in the market

Source: this study

Summary:

Previous empirical studies have investigated the impacts of delivery-related issues on consumer satisfaction with Internet shopping. However, the interaction of time-dependent consumer demand and logistics cost related to different delivery service strategies has seldom been investigated. Furthermore, while consumer demand for goods may increase by employing frequent and short delivery cycles, the extent depends on variations in consumer socioeconomic, temporal and spatial distribution and, furthermore, how Internet store operators set up service cycles during a given operating period of time. Although these issues have been previously addressed, there is currently no mathematical model that can determine an optimal delivery service strategy by integrating all issues.

2.5 MIP formulations

According to Rardin (1998), a mathematical program is a discrete optimization model if it includes any discrete variables at all. Otherwise, it is a continuous optimization model. In other words, if the system contains both discrete and continuous variables, the model is a mixed integer program. Many models have been formulated for the strategic design of supply chains.

Geoffrion and Graves (1974) is the first paper that presented a comprehensive MIP model for the supply chain network design problems. The model formulated in this study represented a production-distribution system with several plants with known capacities, distribution centers (DC), and a number of customer zones. The constraints considered in the model are capacity at plants, customer demand satisfaction, single sourcing by customer zone, bounds on the throughput at DC, and linear configuration constraints on binary variables. The study presented an algorithm based on Bender

Decomposition to solve the problem.

Hodder and Dincer (1986) presented an international plant location model with financial capabilities. The model considers exchange rate fluctuations, market prices, international interest rates, and fixed costs in a stochastic environment. Brown et al. (1987) present a MIP multi-commodity model, where the costs is composed of variable production and shipping costs, fixed costs of equipment assignment and fixed costs of plant operations. Furthermore, Cohen and Moon (1991) presented a mixed integer multi-commodity model to determine inbound raw material flows, assignment of product lines and specification of production volumes, and outbound finished product flows in a production-distribution network. The main contribution of this study is to provide an algorithm to solve some production-distribution models with piecewise linear concave costs of production (Vidal and Goetschalckx, 1997).

Arntzen et al. (1995) considered multiple products, facilities, time periods, and transportation modes. The model aimed at minimizing a composite function of activity days and total production costs, inventory, transportation costs, etc. All the costs considered in the objective function are weighted by a factor α . The objective function represents a weighted combination of time and cost so that either measure or both can be used to derive recommendations (Meixell and Gargeya, 2005).

Jayaraman and Pirkul (2001) formulated a MIP model for locating production and distribution facilities in a multi-echelon environment. The main objective in this formulation is to minimize the total fixed and variable cost associated with the multiple products subject to constraints imposed on the demand, production capacity, warehouse capacity, raw material supply and requirements and the geography of customer zone outlets.

Amiri (2006) addressed the distribution network design problem in a supply chain system that involves locating production plants and distribution warehouses. The goal of this formulation is to select the optimal numbers, locations and capacities of plants and warehouses to open so that all customer demand is satisfied at minimum total costs of the distribution network.

2.6 Summary

There is vast literature conducting supply chain network problems. And the mixed integer programming (MIP) method has been extensively used to investigate the problems. These studies focused mainly on developing approximation procedures and on comparing the efficiency of their proposed heuristics with others in past literature. In addition, though the capacity utilization of different-sized plants will result in various influences on their cost, its extent is seldom discussed. The impacts of high capacity cost, customer demand level and investment conditions on the optimal plant capacity and production among manufacturing plants with different sizes are seldom discussed.

Though optimal flows between demand and supply nodes have been discussed and have been included in the supply chain design problems, the shipping frequency and shipment size between different combinations of suppliers and manufacturing plants have not been discussed yet. Furthermore, production and shipping economies and their tradeoff relationships are seldom discussed when designing a supply chain network. Past literature has demonstrated the importance of logistics functions on the efficiency of a supply chain. However, the shipping frequency and shipment size between different combinations of suppliers and manufacturing plants and of manufacturing plants and customers in different regions have not been discussed yet. Furthermore, shipping economies inhering in the supply chain are seldom discussed when design a supply chain network. The impact of spatial distance on the optimal shipping frequency although having been studied in logistics literature, has not been integrated into the design of supply chain networks.

There are extensive studies addressing the impacts of uncertainty factors on company’s cost and customer service level performance with respect to demand and supply uncertainty. The literature also proposed various strategies to reduce the impacts of uncertainty under different scenarios. Most of these studies focused on the short-term operational issues and constructed analytical models in terms of operation research. In the network planning phase, the performance of the network under abnormal demand fluctuation was seldom evaluated.

Past studies have addressed the importance of logistics function on supply chain management. These studies aimed at investigate relationship between supply chain performance and logistics network using collected empirical data and by conducting hypothesis. However, the interaction of time and spatial dependent customer demand and logistics cost related to delivery service strategy in supply chain network has seldom been investigated. Previous empirical studies have investigated the impacts of delivery-related issues on consumer satisfaction with Internet shopping. The interaction of time-dependent consumer demand and logistics cost related to different delivery service strategies has seldom been investigated. Furthermore, while consumer demand for goods may increase by employing frequent and short delivery cycles, the extent depends on variations in consumer socioeconomic, temporal and spatial distribution and, furthermore, how Internet store operators set up service cycles during a given operating period of time. Although these issues have been previously addressed, there is currently no mathematical model that can determine an optimal delivery service strategy by integrating all issues.

Several important issues in the field of supply chain network design deserve further investigation; however, these issues are rarely emphasized and theoretically formulated in supply chain design literature. This study aims at developing a series models to systematically investigate the supply chain design problems in response to production and shipping economies in an uncertain environment. Furthermore, the delivery service strategies for both the manufacturer and Internet shopping operators are explored by considering time-dependent consumer demand, demand-supply interaction and consumer socioeconomic characteristics.

CHAPTER 3
An integrated plant capacity and production model with economies of scales

This chapter developed a nonlinear mixed integer programming (MIP) model which attempted to minimize the average total cost per unit product subject to constraints such as satisfying customer demand in various geographic regions, relationships between supply flows and demand flows within the physical configuration, and the production limitation of different-sized plants. The impacts of economies of scale on the optimal size of capacity and the production amount are also explored. This chapter also shows that the capacity utilization as well as the production amount in the short run, and the size of capacity of multiple plants in the long run are related, and that those two factors influence the total cost. The research scope of this part is shown as Figure 3.1.

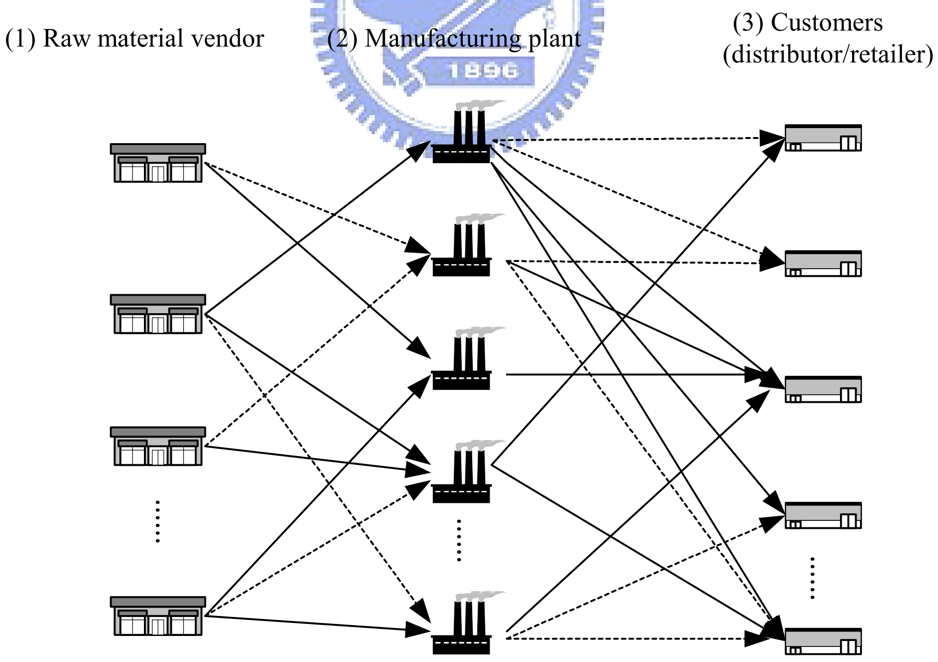

Figure 3.1 The research scope of Chapter 3

3.1 Introduction to the problem

The importance of developing an integrated production-distribution network lies not only in satisfying the demands of customers in the different regions, but also in reducing manufacturers' costs. For high-tech manufacturers the investment in capacity usually involves high capital costs. However, economies of scale allow manufacturers with a large-size capacity to operate more efficiently than those with a small-size capacity. However, it could result in higher production costs if the market demand is insufficient to realize economies of scale, and if the capacity utilization of the manufacturing plant is low. Moreover, for a manufacturer operating multiple plant sites in different regions, additional complicating factors need to be taken into account, such as investment conditions in different regions and physical distribution problems between customers and plant sites. The former involves capital and variable production costs, while the latter affects customers' satisfactions and outbound costs of the product. Therefore, it is important for a high-tech manufacturer operating multiple plant sites with economies of scale to effectively determine the capacity and production volumes for each plant so as to minimize the total cost per unit product while satisfying customer demand.

High-tech products manufacturing firms are characterized as having high capital costs due to the expense of sophisticated equipment, land acquisition, and plant and warehouse construction. For example, semiconductor manufacturers spend almost a billion US dollars to construct an 8-inch wafer fabrication (FAB), and thirty billion US dollars for a 12-inch FAB. In addition, it costs more to produce one piece of 12-inch wafer than it does producing an 8-inch wafer. However, there is an advantage to a 12-inch FAB over an 8-inch FAB in terms of lower per-unit product production costs due the fact that the production is done on a larger scale, which further leads to a larger amount of final products. Nevertheless, the benefit shrinks when the market demand is low and the production is not as much as expected, resulting in a low FAB utilization ratio. In sum, the greater economies of scale advantage for production occurs when the higher the production, the lower its per-unit product cost will be. However, this advantage depends usually on the level of the market demand.

Previous studies in supply chain management focused largely on production, vendor selection and plant location problems (e.g., Min and Melachrinoudis, 1999; Verma and Pullman, 1998; Badri, 1999). However, each of these studies focused on only one single issue. At the same time three levels of planning can be distinguished depending on the time frame used, namely, strategic, tactical and operational. Strategic planning includes the determination of plant sites, the number of manufacturing plants, etc; tactical planning involves the procurement, inventory and transportation systems; and operational planning refers to vehicle routing, scheduling, etc. In practice, short-term operational flexibility is directly related to the strategic decisions.

Due to the fact that large-scale models have proven to be extremely difficult for solving optimality, solution methods and computational experiences are necessary. Brimberg and ReVelle (1998) formulated a bi-objective plant location model for analyzing the trade-off between total cost and the portion of the market to be served. In this study, partial satisfaction of demand is considered rather than serving all demand in the traditional plant location problem. The weighting method approach is investigated for obtaining efficient solutions of the model. Jayaraman and Pirkul (2001) extended the plant location problem to incorporate the tactical production-distribution problem for multiple commodities. In the model, a facility or warehouse is constrained to serve one single customer. Miranda and Garrido (2004) proposed a simultaneous approach to incorporate the inventory control decision with typical facility location models. Crama et al. (2004) constructed a nonlinear MIP model to determine the optimal procurement decisions in the presence of total quantity discounts and alternative product recipes. Cohen and Moon (1991) formulated a MIP model to determine the optimal assignment of product lines and volumes to a set of capacitated plants. In the model, the capacity of plants is given and fixed, and the production cost function exhibits concavity with respect to each product line volume reflecting economies of scale. Moreover, correlation and regression analyses are employed to analyze the relationship between the cost parameters. The results indicate that focused plants arise in situations with high economies of scale. However, although the capacity utilization of different-size plants will result in various influences on their total cost, its extent is seldom discussed. The models constructed are usually large-scale linear or nonlinear MIP formulations, which are difficult to solve. Therefore, these studies focused mainly on developing an approximation procedure and compared the efficiency of their proposed heuristics with others.

Arntzen et al. (1995) developed a global supply chain design model considering multiple products, facilities, time periods, and transportation modes. The model aimed at minimizing a composite function of activity days and total production costs, inventory, transportation costs, etc. However, there are two different terms, such as monetary cost and time, in the objective functions, and it is not clear how the study dealt with a different unit of measure. Nagurney et al. (2002) and Nagurney and Toyasaki (2005) considered many decision-makers and their independent behaviors in the supply chain and developed an equilibrium model of a competitive supply chain network, in which transportation links are associated with different costs. In sum, few previous studies on supply chain design models considered the high capital costs invested in the capacity by high-tech manufacturing firms, and how capacity utilization of different-size plants affects the total average production cost.

This study aims to develop a supply chain design model to determine active suppliers, inbound raw material flows from active suppliers to manufacturing plants, the capacity and production volumes of each plant and the market served by each plant for a high-tech manufacturing firm. The distinguishing features of this study are the comprehensive consideration of economies of scale and capacity utilization in the high-tech manufacturing industry, which are due to the different sizes and locations of the plants deployed by a multiple plant manufacturing firm in the long run and the production volumes assigned to each in the short run. Moreover, the traditional plant location problem, which chooses new facility location from a set of potential sites in order to serve all the demands (Balinski, 1965), is also considered in this study. The model specifically applies MIP formulations and attempts to minimize the average total cost per unit product subject to constraints such as satisfying customer demand in various geographic regions, relationships between supply flows, and demand flows within the physical configuration as well as the production limitation of different size plants.

3.2 Model formulation

This study aims at designing a supply chain network model for a manufacturer who operates multiple plants in different regions. According to Vidal and Goetschalckx (1997), the supply chain design problem in this study can be described as: Given the customer demand, determine the capacity and production volumes for each of the manufacturing plants, and the amount of raw material/final products shipped from vendors/manufacturing plants to manufacturing plants/customers. In other words, the supply chain network design problem is formulated to determine the optimal flows between alternatives from the upper echelons and those of the lower echelons, and the supply flows of all alternatives at different echelons. This study denotes a supply chain network as a directed graph where there are various echelons such as raw material vendors, manufacturing plants and customers and each of them involves different numbers of alternatives, which are located in different regions. In the supply chain network, the relationship between the inbound and outbound flows of an alternative in an echelon, and the relationship between total supply flows among echelons and customer demand are further explored and identified as a non one-to-one problem.

3.2.1 A supply chain network

Consider a supply chain network **G**(***N***, ***A***), where ***N*** and ***A*** represent the set of nodes and the set of links, respectively, in a directed graph **G**. Let *k* denote a specific echelon in a supply chain. From the uppermost echelon to the customer echelon, *k*=0, 1,…,*s*, where *k*=0 represents raw material vendors, *k*=*s* is customers, respectively. Let n_k denote a node at echelon *k*, which can also refer to an alternative at echelon *k*, $n_k \in N$. A specific node can be classified as a demand or a supply node according to the emanation of the link. When the link is outgoing/incoming from/to a node, then the node can be described as a supply/demand node and the outflows/inflows are also called the supply/demand flows of that node.

Let $w_{k-1,k}$ denote the demand flows of a node at echelon *k* from its upper echelon (*k*-1) when the supply flow of that node is one unit and f_{n_k} represents the supply flows of a node at echelon *k*, n_k. Consequently, the demand flows of a node at echelon *k* can be estimated by $w_{k-1,k} f_{n_k}$. Furthermore, the following condition must be satisfied, i.e. the demand flows of a node at the lower echelon are the sum of the flows between the nodes at the upper echelon and that node at the lower echelon. The relationship between the demand flows of a node at the lower echelon *k*, $w_{k-1,k} f_{n_k}$, and the flows between nodes at their upper echelon (*k*-1), n_{k-1}, and a node at the lower echelon *k*, n_k, can be expressed as:

$$w_{k-1,k} f_{n_k} = \sum_{\forall n_{k-1}} f_{n_k}^{n_{k-1}} \delta_{n_k}^{n_{k-1}} \qquad \forall n_k \tag{3.1}$$

where $f_{n_k}^{n_{k-1}}$ represents the flows between a node at the upper echelon, n_{k-1}, and a node at the lower echelon, n_k, and $\delta_{n_k}^{n_{k-1}}$ is an indicator variable representing whether the node at the upper echelon, n_{k-1}, is an active node to the node at the lower echelon, n_k, that is to say, if the node at echelon (*k*-1), n_{k-1}, supplies or transports raw materials/intermediate products/finished goods to the node at its lower echelon, n_k, then $\delta_{n_k}^{n_{k-1}} = 1$ and the amount transported is $f_{n_k}^{n_{k-1}}$, otherwise, $\delta_{n_k}^{n_{k-1}} = 0$. Figure 3.1 illustrates the relationship mentioned above.

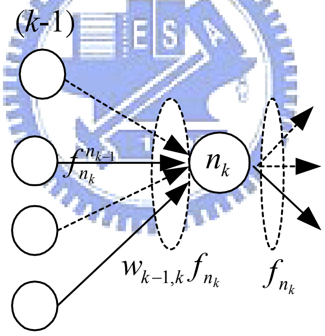

Figure 3.2 The relationship of flows between nodes at the upper echelon and nodes at the lower echelon

The solid lines in Figure 3.2 show that the nodes at the upper and lower echelons are connected; in other words, $\delta_{n_k}^{n_{k-1}}$ is 1, while the dotted lines show that $\delta_{n_k}^{n_{k-1}}$ equals to 0. The supply flows of the node at echelon *k*, f_{n_k}, can also be represented as the sum of the flows between a node at echelon *k*, n_k, and nodes at its lower echelon, n_{k+1}, such as

$$f_{n_k} = \sum_{\forall n_{k+1}} f_{n_{k+1}}^{n_k} \beta_{n_{k+1}}^{n_k} \qquad \forall n_k \tag{3.2}$$

where $\beta_{n_{k+1}}^{n_k}$ is an indicator variable representing whether a node at the lower echelon, n_{k+1}, is a demand node for node at its upper echelon, n_k. If node n_{k+1} demands or orders raw material or products from a node at its upper echelon *k*, n_k, then $\beta_{n_{k+1}}^{n_k} = 1$ and the quantity demanded is $f_{n_{k+1}}^{n_k}$; otherwise, $\beta_{n_{k+1}}^{n_k} = 0$. To sum up, variables $\delta_{n_k}^{n_{k-1}}$ and $\beta_{n_{k+1}}^{n_k}$ can be used to explain, respectively, whether nodes at the upper and lower echelons are active alternatives of the node at echelon *k*, n_k, while variables $f_{n_k}^{n_{k-1}}$ and $f_{n_{k+1}}^{n_k}$ represent flows between n_k and the active nodes at their upper and lower echelons, respectively, in a supply chain. In addition, capacity constraints are imposed on the supply flows of nodes at echelons, that is, $f_{n_k} \le v_{n_k}$, where v_{n_k} represents the capacity of n_k.

The discussion so far has dealt with the relationship and the flows between a node at echelons and nodes at its upper and lower echelons. Next, this study explores and formulates the total supply flows at different echelons and the total customer demand. Similar to the expression of Eq. (3.1), the total customer demand is satisfied only if the supply flows at its upper echelon (*s*-1), $\sum_{\forall n_{s-1}} f_{n_{s-1}}$, equals to $w_{s-1,s} \sum_{\forall n_s} f_{n_s}$, where f_{n_s} represents the customer demand of customer n_s; similarly, the supply flows at the upper echelon (*s*-2) can be estimated by the relationship between the demand flows and the supply flows at echelon (s-2), that is, $\sum_{\forall n_{s-2}} f_{n_{s-2}} = w_{s-2,s-1} w_{s-1,s} \sum_{\forall n_s} f_{n_s}$; and the supply flows at echelon (*s*-3) can be expressed as $\sum_{\forall n_{s-3}} f_{n_{s-3}} = w_{s-3,s-2} w_{s-2,s-1} w_{s-1,s} \sum_{\forall n_s} f_{n_s}$ and so on. Then, the generalized relationship between the total supply flows at echelon *k* and the total customer demand in the supply chain network can be formulated as:

$$\sum_{\forall n_k} f_{n_k} = \prod_{k}^{s} w_{k,k+1} \sum_{\forall n_s} f_{n_s} \qquad \forall k \tag{3.3}$$

where $\prod_{k}^{s} w_{k,k+1}$ represents the total supply flows at echelon k when the customer demand is one unit. Eq. (3.3) shows that the total supply flows at the echelons are different and dependent upon customer demand.

3.2.2 Cost functions

The decision maker in this study is a manufacturer who operates multiple high-tech product manufacturing plants and serves customers in different regions. Therefore, the upper echelon of the manufacturing plants can be defined as the raw material vendors, and the lower echelon as the customers. This study assumes that the firm's procurement and outsourcing decisions are centralized at the corporate headquarter rather than in the individual manufacturing plants. Let $\hat{k}$ be the echelon of manufacturing plants and $n_{\hat{k}}$ represent a manufacturing plant at echelon $\hat{k}$, respectively, while $\hat{k}-1$ is the echelon of raw material vendors and $n_{\hat{k}-1}$ represents a raw material vendor, respectively. Consequently, echelon $\hat{k}+1$ refers to customers, which can also be represented as echelon s.

Let $f_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ and $f_{n_s}^{n_{\hat{k}}}$ represent the amount of raw material shipped from raw material vendor $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$ and the amount of final products produced by manufacturing plant $n_{\hat{k}}$ and transported to customer n_s, respectively. And, let $f_{n_{\hat{k}}}$ be the production amount at manufacturing plant $n_{\hat{k}}$, which is constrained by the plant's capacity, $f_{n_{\hat{k}}} \le v_{n_{\hat{k}}}$. Then, the relationship between the total amount of raw material required by manufacturing plant $n_{\hat{k}}$ and the amount of raw material shipped among raw material vendors can be revised according to Eq. (3.1) as:

$$w_{\hat{k}-1,\hat{k}} f_{n_{\hat{k}}} = \sum_{\forall n_{\hat{k}-1}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} \qquad \forall n_k \tag{3.4}$$

where $\delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} = 1$ represents that raw material is transported from a raw material vendor $n_{\hat{k}-1}$ to a manufacturing plant $n_{\hat{k}}$; otherwise, $\delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} = 0$. Moreover, the relationship between the amount of production produced by manufacturing plant $n_{\hat{k}}$ and the amount of products shipped from manufacturing plant $n_{\hat{k}}$ to customer n_s can be formulated according to Eq. (3.2), as:

$$f_{n_{\hat{k}}} = \sum_{\forall n_s} f_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \qquad \forall n_k \tag{3.5}$$

Since the total customer demand must be satisfied, then the following condition must hold, that is to say, $\sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}} = \sum_{\forall n_{\hat{k}}} \sum_{\forall n_s} f_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}}$. Furthermore, the capacity utilization of manufacturing plant $n_{\hat{k}}$ can be defined as $Y_{n_{\hat{k}}} = {}^{f_{n_{\hat{k}}}}\!\big/_{v_{n_{\hat{k}}}}$, where $f_{n_{\hat{k}}}$ and $v_{n_{\hat{k}}}$ are decision variables in this study.

Costs in this study can be classified as inbound, fixed, production and outbound costs. Inbound costs include raw material purchase and transportation costs, which relates to the movement of the flows from the raw material vendors to the manufacturing plants. The fixed costs represent all expenses required for the manufacturer to contract with active raw material vendors. Production costs incorporate both the capital cost and the variable production costs, where the capital cost includes costs related to the purchasing and installation of related equipments, and plant construction and land rental fee, etc. and differs among manufacturing plants due to different locations and sizes of the manufacturing plants. The variable production cost includes those paid for input factors other than raw materials, such as labor, utility and insurance, etc. Outbound costs refer to the costs related to transporting the final products from the manufacturing plants to the customers.

The production costs of manufacturing plant $n_{\hat{k}}$, $L_{n_{\hat{k}}}$, can be formulated as follows

$$L_{n_{\hat{k}}} = C(v_{n_{\hat{k}}}) + c(v_{n_{\hat{k}}}) f_{n_{\hat{k}}} \qquad \forall n_k \qquad (3.6)$$

where $C(v_{n_{\hat{k}}})$ and $c(v_{n_{\hat{k}}})$ represent, respectively, the capital costs and variable production costs, which depend on capacity, $v_{n_{\hat{k}}}$. Eq. (3.6) shows that the production cost increases with the increase in the production amount, $f_{n_{\hat{k}}}$. Furthermore, the average production cost per unit product of manufacturing plant $n_{\hat{k}}$ can be expressed as

$$\frac{L_{n_{\hat{k}}}}{f_{n_{\hat{k}}}} = \frac{C(v_{n_{\hat{k}}})}{f_{n_{\hat{k}}}} + c(v_{n_{\hat{k}}}) \qquad \forall n_k \qquad (3.7)$$

On the contrary, Eq. (3.7) shows that the average production cost per unit product decreases with the increase in production amount; however, the extent depends upon the capital cost with respect to the capacity. Although a manufacturing plant with large-size capacity could operate efficiently, the manufacturer experiences a high average production cost when the production amount is low, and as a result the high capital cost cannot be absorbed as shown in Eq. (3.7). Figure 3.3 shows the relationship between the average production cost and the production amount for different sizes of capacity, where $v^1_{n_{\hat{k}}}$, $v^2_{n_{\hat{k}}}$, $v^3_{n_{\hat{k}}}$ are three different-size capacities for a manufacturing plant $n_{\hat{k}}$, $v_{n_{\hat{k}}}^{1} > v_{n_{\hat{k}}}^{2} > v_{n_{\hat{k}}}^{3}$ and $C(v_{n_{\hat{k}}}^{1}) > C(v_{n_{\hat{k}}}^{2}) > C(v_{n_{\hat{k}}}^{3})$.

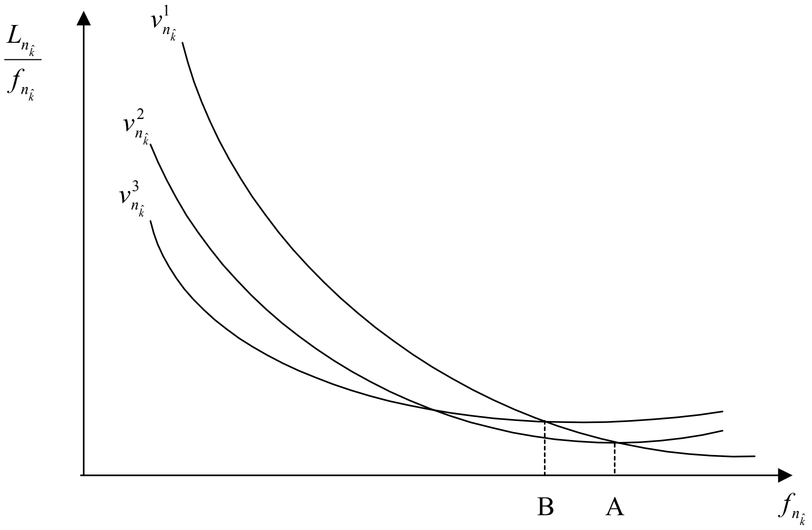

Figure 3.3 The relationship between the average production cost and the production amount

As shown in Figure 3.3, the average production cost per unit product decreases as the production amount for each of the three sizes of capacity increases. And, when the production amount is low, the largest-size capacity $v_{n_{\hat{k}}}^{1}$ yields the highest average production cost among the three different-size capacities. Nevertheless, as the production expands, the average production cost for the largest-size capacity $v_{n_{\hat{k}}}^{1}$ decreases with a maximum decreasing rate. When the production amount exceeds point A in Figure 3.3, the average production cost for the largest-size capacity $v_{n_{\hat{k}}}^{1}$ reaches the lowest among the three different-size capacities, implying that a manufacturing plant with the largest-size capacity $v_{n_{\hat{k}}}^{1}$ is the most advantageous in terms of saving costs. Since the production amount depends on the demand, a large-size capacity is suggested when there is a large demand.

For a manufacturer operating multiple manufacturing plants, the impact of scale economies on the total average production cost depend not only on the total customer demand, but also on the production assignments among manufacturing plants. Furthermore, the total average production cost per unit product for the manufacturer, $H_{\hat{k}}$, can be formulated as

$$H_{\hat{k}} = \frac{\sum\limits_{\forall n_{\hat{k}}} L_{n_{\hat{k}}}}{\sum\limits_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}} = \frac{\sum\limits_{\forall n_{\hat{k}}} C(v_{n_{\hat{k}}}) + c(v_{n_{\hat{k}}}) f_{n_{\hat{k}}}}{\sum\limits_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}} \tag{3.8}$$

The denominator in Eq. (3.8) is fixed and given due to the fact that the total amount of production is constrained in order to satisfy the total customer demand. Eq. (3.8) shows that the total average production cost per unit product for the manufacturer depends on both the capacity and the production volumes of all manufacturing plants.

Let $V_{n_{\hat{k}-1}}$ be the fixed cost of the manufacturer with raw material vendor $n_{\hat{k}-1}$, which is independent as to the amount of raw material procured and the total number of manufacturing plants served since the cost is mainly the results of the manufacturer contracting with the vendor. Then, the total fixed cost for the manufacturer can be expressed as $\sum\limits_{\forall n_{\hat{k}-1}} V_{n_{\hat{k}-1}} \gamma_{n_{\hat{k}-1}}$, where $\gamma_{n_{\hat{k}-1}}$ is an indicator variable representing whether raw material vendor $n_{\hat{k}-1}$ is an active vendor for the manufacturer, and where $\gamma_{n_{\hat{k}-1}}$ can be obtained based on the results of $\delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ for all manufacturing plants, that is, $\gamma_{n_{\hat{k}-1}} = \min\{1, \sum\limits_{\forall n_{\hat{k}}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}\}$. If $\gamma_{n_{\hat{k}-1}}$ is equal to 1, then raw material vendor $n_{\hat{k}-1}$ is an active vendor for the manufacturer; otherwise, $\gamma_{n_{\hat{k}-1}}$ is equal to 0. Then, the average fixed cost per unit raw material for the manufacturer can be formulated as

$$V_{\hat{k}-1} = \frac{\sum\limits_{\forall n_{\hat{k}-1}} V_{n_{\hat{k}-1}} \gamma_{n_{\hat{k}-1}}}{\sum\limits_{\forall n_{\hat{k}-1}} \sum\limits_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}} \tag{3.9}$$

The unit of Eq. (3.9) is measured based on the raw material. To be based on products, Eq. (3.9) can be revised according to Eq. (3.3), and shown as:

$$\overline{V}_{\hat{k}-1} = (\prod_{k-1}^{s} w_{k,k+1}) V_{\hat{k}-1} \tag{3.10}$$

where $\overline{V}_{\hat{k}-1}$ represents the average fixed cost per unit product for the manufacturer.

With regards to the raw material purchase costs, the main influences affecting average raw material purchase cost are unit raw material production cost and a reasonable payment ratio determined by the raw material vendor. Regardless of the reasonable payment ratio, the unit raw material purchase cost is low when the market for that raw material is high due to the fact that there exists economies of scale. To simplify the problem, this study assumes two influences, i.e. unit raw material production cost and payment ratio, are exogenous, and denote unit raw material purchase cost from raw material vendor $n_{\hat{k}-1}$ by $p_{n_{\hat{k}-1}}$. Therefore the purchase cost paid for raw material vendor $n_{\hat{k}-1}$ can be shown as $p_{n_{\hat{k}-1}} \sum\limits_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}$. Summing up all the purchase costs paid to all raw material vendors, the total raw material purchase cost for the manufacturer can be formulated as:

$$\sum_{\forall n_{\hat{k}-1}} p_{n_{\hat{k}-1}} \sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} \tag{3.11}$$

where Eqs. (3.10) and (3.11) are the costs resulting from the raw material procurement.

The transportation costs in this study capture the costs resulting from the spatial distance between two locations. High-tech products are usually characterized as having a high market value and usually depreciate quickly. A nearby raw material vendor is usually selected, since the raw material delivery time is short and as a result the inventory can be kept at a low level. Transportation costs decrease if the manufacturing plant and the raw material vendor are located in the same location because the distance is short and a low-cost transportation mode, i.e. trucks, can be employed. Consequently transportation costs are high if the locations of the manufacturing plant and the raw material vendor are a long distance apart from each other. Let $t_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ represent the average unit-distance transportation cost per unit of raw material between the locations of raw material vendor $n_{\hat{k}-1}$ and manufacturing plant $n_{\hat{k}}$. The transportation cost for transporting raw material from raw material vendor $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$ can be expressed as $d_{n_{\hat{k}}}^{n_{\hat{k}-1}} t_{n_{\hat{k}}}^{n_{\hat{k}-1}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}}$, where $d_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ and $f_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ are the average distance and the amount of raw material shipped from the location of raw material vendor $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$. Then, the total transportation cost of the raw material for the manufacturer can be formulated as

$$\sum_{\forall n_{\hat{k}}} \sum_{\forall n_{\hat{k}-1}} d_{n_{\hat{k}}}^{n_{\hat{k}-1}} t_{n_{\hat{k}}}^{n_{\hat{k}-1}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} \tag{3.12}$$

Eq. (3.12) shows that the transportation costs vary with the different combinations of $(n_{\hat{k}-1}, n_{\hat{k}})$ due to the different distances and average transportation cost per unit of raw material between raw material vendor $n_{\hat{k}-1}$ and manufacturing plant $n_{\hat{k}}$.

Summing up Eqs. (3.11) and (3.12), the inbound cost for the manufacturer can be shown as:

$$\sum_{\forall n_{\hat{k}-1}} p_{n_{\hat{k}-1}} \sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} + \sum_{\forall n_{\hat{k}}} \sum_{\forall n_{\hat{k}-1}} d_{n_{\hat{k}}}^{n_{\hat{k}-1}} t_{n_{\hat{k}}}^{n_{\hat{k}-1}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} \tag{3.13}$$

Dividing Eq. (3.13) by the total amount of raw material supplied by raw material vendors, $\sum_{\forall n_{\hat{k}-1}} f_{n_{\hat{k}-1}}$, the average inbound cost per unit of raw material for the manufacturer, $H_{\hat{k}}^{\hat{k}-1}$, can be formulated as:

$$H_{\hat{k}}^{\hat{k}-1} = \frac{1}{\sum\limits_{\forall n_{\hat{k}-1}} f_{n_{\hat{k}-1}}} \Big(\sum_{\forall n_{\hat{k}-1}} p_{n_{\hat{k}-1}} \sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} + \sum_{\forall n_{\hat{k}}} \sum_{\forall n_{\hat{k}-1}} d_{n_{\hat{k}}}^{n_{\hat{k}-1}} t_{n_{\hat{k}}}^{n_{\hat{k}-1}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} \Big) \tag{3.14}$$

The average inbound cost per unit product for the manufacturer can be obtained as $\overline{H}_{\hat{k}}^{\hat{k}-1} = (\prod_{\hat{k}-1}^{s} w_{\hat{k},\hat{k}+1}) H_{\hat{k}}^{\hat{k}-1}$.

As suggested by Chopra (2003), products with a high value are suitable for a delivery network with direct shipping, that is, products are shipped directly from the manufacturing plant to the customer. In addition, manufacturing plants with a large production can serve many customers, yet this may lead to high transportation costs. To provide better service and reduce transportation costs, manufacturing plants are advised to serve nearby customers. The outbound cost for the manufacturer can be expressed as $\sum_{\forall n_s} \sum_{\forall n_{\hat{k}}} d_{n_s}^{n_{\hat{k}}} t_{n_s}^{n_{\hat{k}}} f_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}}$, where $t_{n_s}^{n_{\hat{k}}}$ represents the average unit-distance transportation cost per unit product between the location of the manufacturing plant $n_{\hat{k}}$ and customer n_s. Moreover, the average outbound cost per unit product for manufacturer, $T_s^{\hat{k}}$, can be shown as:

$$T_s^{\hat{k}} = \frac{1}{\sum\limits_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}} \sum_{\forall n_s} \sum_{\forall n_{\hat{k}}} d_{n_s}^{n_{\hat{k}}} t_{n_s}^{n_{\hat{k}}} f_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \tag{3.15}$$

where $\sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}$ represents the total production amount. Since the total customer demand must be satisfied, $\sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}} = \sum_{\forall n_s} f_{n_s}$.

The total average cost per unit product for the manufacturer is the sum of the average inbound, fixed, production and outbound costs in the entire supply chain, and can be formulated as:

$$(\prod_{\hat{k}-1}^{s} w_{\hat{k},\hat{k}+1})V_{\hat{k}-1} + (\prod_{\hat{k}-1}^{s} w_{\hat{k},\hat{k}+1})H_{\hat{k}}^{\hat{k}-1} + H_{\hat{k}} + T_{s}^{\hat{k}} \tag{3.16}$$

From the discussions above, the nonlinear MIP model for the supply chain network design can be formulated as follows.

$$Min \qquad (\prod_{\hat{k}-1}^{s} w_{\hat{k},\hat{k}+1})V_{\hat{k}-1} + (\prod_{\hat{k}-1}^{s} w_{\hat{k},\hat{k}+1})H_{\hat{k}}^{\hat{k}-1} + H_{\hat{k}} + T_{s}^{\hat{k}}, \tag{3.17a}$$

$s.t.$

$$w_{\hat{k}-1,\hat{k}} f_{n_{\hat{k}}} = \sum_{\forall n_{\hat{k}-1}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}, \qquad \forall n_{\hat{k}} \tag{3.17b}$$

$$f_{n_{\hat{k}}} = \sum_{\forall n_s} f_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}}, \qquad \forall n_{\hat{k}} \tag{3.17c}$$

$$\sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}} = \sum_{\forall n_{\hat{k}}} \sum_{\forall n_s} f_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \tag{3.17d}$$

$$\sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} \le S_{n_{\hat{k}-1}} \qquad \forall n_{\hat{k}-1} \tag{3.17e}$$

$$Y_{n_{\hat{k}}} = f_{n_{\hat{k}}} \Big/ v_{n_{\hat{k}}}, \qquad \forall n_{\hat{k}} \tag{3.17f}$$

$$v_{n_{\hat{k}}}, f_{n_s}^{n_{\hat{k}}}, f_{n_{\hat{k}}}^{n_{\hat{k}-1}} \ge 0 \qquad \forall n_{\hat{k}} \quad \forall n_{\hat{k}-1} \tag{3.17g}$$

$$\delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} = 0 \text{ or } 1 \qquad \forall n_{\hat{k}} \quad \forall n_{\hat{k}-1} \tag{3.17h}$$

$$\beta_{n_s}^{n_{\hat{k}}} = 0 \text{ or } 1 \qquad \forall n_{\hat{k}} \quad \forall n_{\hat{k}-1} \tag{3.17i}$$

Eq. (3.17a) is the objective function that minimizes the total average cost per unit product. Eq. (3.17b) states that the amount of raw material requested by manufacturing plant $n_{\hat{k}}$ is the sum of the amount of raw material provided by its active raw material vendors. Eq. (3.17c) defines that the amount of products shipped from manufacturing plant $n_{\hat{k}}$ to the customers is equal to the amount of production. Eq. (3.17d) constrains the total production amount to meeting the total customer demand. Eq. (3.17e) is the supply limit of raw material vendor $n_{\hat{k}-1}$, where $S_{n_{\hat{k}-1}}$ represents the maximum amount of raw material supplied by vendor $n_{\hat{k}-1}$. Eq. (3.17f) defines the capacity utilization of manufacturing plant $n_{\hat{k}}$. Eq. (3.17g) constrains the decision variables $v_{n_{\hat{k}}}$, $f_{n_s}^{n_{\hat{k}}}$ and $f_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ to be non-negative. Finally, Eqs. (3.17h) and (3.17i) define the decision variables $\delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ and $\beta_{n_s}^{n_{\hat{k}}}$ to be binary. The decision variables are $v_{n_{\hat{k}}}$, $f_{n_{\hat{k}}}$, $f_{n_s}^{n_{\hat{k}}}$, $f_{n_{\hat{k}}}^{n_{\hat{k}-1}}$, $\delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ and $\beta_{n_s}^{n_{\hat{k}}}$. That is, the manufacturer can apply the model to optimally decide the size of the capacity as well as the production volumes for all manufacturing plants, the amount of raw material from the raw material vendors to manufacturing plants, and which manufacturing plants should produce how much production to serve customers in different regions. Furthermore, the optimal capacity utilization of manufacturing plants and the optimal number of active raw material vendors for the manufacturer can also be obtained from the model.

3.3 Algorithm

This chapter formulates a nonlinear MIP model to integrate capacity and production planning problems by considering economies of scale in the supply chain network design. Using the exact algorithm to solve the problem may require a considerable amount of time and can only solve small problems. In this study, we adopt the simulated annealing (SA) heuristic proposed by Kirkpatrick et al. (1983) to solve the optimal problem. The SA algorithm is based on Metropolis et al. (1953), which was originally proposed as a means of finding the equilibrium configuration of a collection of atoms at a given temperature. It has been extensively used in solving very large scale integration (VLSI) layout and graph partitioning problems. The major advantage of the SA algorithm over other local search methods is the ability to avoid becoming trapped in the local optimal. The SA algorithm employs a random search, which not only accepts changes that decrease the objective function, but also accepts some changes that increase it. And, the latter are accepted with a probability of Boltzmann distribution. In this section, we first develop an approach to generate an initial solution, and then use the SA algorithm to develop the heuristic for improving the initial solution.

3.3.1 Initial solution (*INIT*)

Since local improvement methods must start from a feasible solution, this study develops a heuristic to generate good initial solutions. Based on the characteristics of production with economies of scale, the average production cost per unit product may be reduced if there is more production assigned to a manufacturing plant with larger-size capacity. An incremental rule, in which the production volumes are incrementally assigned to manufacturing plants until total customer demands are satisfied, might be used to investigate the relationship between the assigned production volumes among various manufacturing plants and the total average cost per unit product. Besides, the manufacturing echelon is the most value-added echelon for high-tech products, and the production cost is usually high in the high-tech manufacturing supply chain. In other words, the total cost cannot reach a minimization without a well-designed production plan for the various manufacturing plants. The heuristic based on this is developed as follows.

Step 1. Randomly determine the size of capacity for manufacturing plant $v_{n_{\hat{k}}}$, for all $n_{\hat{k}}$, such that the sum of the capacity of all manufacturing plants must exceed the total customer demand, $\sum_{\forall n_{\hat{k}}} v_{n_{\hat{k}}} \geq \sum_{\forall n_s} f_{n_s}$. Set a value, *m*, representing the incremental amount of production that can be assigned to the manufacturing plants at each iteration;

Step 2. Assign the amount of production for the manufacturing plant;

2.1 Calculate the total average production cost per unit product for manufacturer, $H_{\hat{k}}$, when the incremental amount of production, *m*, is assigned to manufacturing plant $n_{\hat{k}}$;

2.2 Find an optimal manufacturing plant $n_{\hat{k}}^*$ with the minimum value of $H_{\hat{k}}$. Assign the incremental amount of production, *m*, to manufacturing plant $n_{\hat{k}}^*$, and update the production amount for manufacturing plant $n_{\hat{k}}^*$, $f_{n_{\hat{k}}^*} = f_{n_{\hat{k}}^*} + m$;

2.3 Calculate the remaining customer demand and the unfulfilled capacity for each of the manufacturing plants;

Step 3. If the demands of all customers are met, then go to Step 4 and output the optimal production amount and the respective amount of raw material requested by the manufacturing plants; else go to Step 2;

Step 4. Determine the active raw material vendors, the amount of raw material from the raw material vendors to the manufacturing plants and the amount of products from the manufacturing plants to the customers;

4.1 Set the values *u* and *v* representing the incremental amount of raw material shipped from the vendors to the manufacturing plants and the incremental amount of products shipped to the customers from the manufacturing plants, respectively;

4.2 Calculate $\overline{H}_{\hat{k}}^{\hat{k}-1} + \overline{V}_{\hat{k}-1}$ and $T_s^{\hat{k}}$ when u and v are, respectively, assigned to links $(n_{\hat{k}-1}, n_{\hat{k}})$ and $(n_{\hat{k}}, n_s)$.

4.3 Find the optimal links $(n_{\hat{k}-1}, n_{\hat{k}})^*$ and $(n_{\hat{k}}, n_s)^*$ with the minimum values of $\overline{H}_{\hat{k}}^{\hat{k}-1} + \overline{V}_{\hat{k}-1}$ and $T_s^{\hat{k}}$, respectively. Assign u to link $(n_{\hat{k}-1}, n_{\hat{k}})^*$ and v to link $(n_{\hat{k}}, n_s)^*$ and update the flows between the links using $f_{n_{\hat{k}}}^{n_{\hat{k}-1}} = f_{n_{\hat{k}}}^{n_{\hat{k}-1}} + u$ and $f_{n_s}^{n_{\hat{k}}} = f_{n_s}^{n_{\hat{k}}} + v$;

4.4 Calculate (1) the unfulfilled amount of raw material of the manufacturing plants and (2) the unsatisfied demand of the customers;

Step 5. If the customer demands and the amount of raw material requested by all manufacturing plants are met, then stop the algorithm; else go to Step 4.

3.3.2 Simulated annealing (SA)

Set up the SA algorithm parameters including (1) down_hill_move ratio≤ 0.5, where down_hill_ move ratio is determined by the number of inferior solutions divided by the number of moves; (2) accept_ratio≤ 0.5, where the accept_ratio is obtained by the number of current accepted solutions divided by the number of moves; (3) Initial temperature $T_0 = 99$, decreasing ratio of temperature is 0.99 and the stop temperature T=0.1; (4) The maximum number of moves at each temperature=100; and (5) The maximum number of down_hill_moves at each temperature=50. Conditions (1), (2) and (3) are the stop criterions for the SA. Conditions (4) and (5) are the stop criterions for the Metropolis algorithm. Referring to Heragu and Alfa (1992) and Yan and Luo (1999), the SA algorithm can be described as follows.

Step 0. Employ *INIT* to find an initial feasible solution, *S*, and calculate its objective value, z(*S*), where $z = (\prod_{\hat{k}-1}^{s} w_{\hat{k},\hat{k}+1})V_{\hat{k}-1} + (\prod_{\hat{k}-1}^{s} w_{\hat{k},\hat{k}+1})H_{\hat{k}}^{\hat{k}-1} + H_{\hat{k}} + T_{s}^{\hat{k}}$.

Step 1. At temperature T_x, implement the Metropolis algorithm;

1.1 Randomly choose a manufacturing plant and alter its capacity from the initial solution. Apply Step 2 to Step 5 in *INIT* to find a good adjacent solution S' and calculate its objective value, z(S');

1.2 Determine whether the new solution is accepted;

1.2.1 Calculate the difference between the objective function of S and S', $\Delta = z(S') - z(S)$.

1.2.2 If $\Delta \leq 0$, then $S = S'$; else randomly generate a variable y~U(0,0.99). If $\exp^{-\frac{\Delta}{T_i}} \geq y$, then $S = S'$; else go to Step 1;

1.2.3 If the stop criterions of the Metropolis algorithm are satisfied, then go to Step 2; else go to Step 1;

Step 2. If the stop criterions of the SA algorithm are satisfied, then go to Step 3; else let $x = x + 1$ and $T_{x+1} = 0.99T_x$, and go to Step 1;

Step 3. Output the optimal sizes of capacity as well as the production amount for all manufacturing plants, i.e. $v_{n_{\hat{k}}}^{*}$ and $f_{n_{\hat{k}}}^{*}$, the active raw material vendors as well as the amount of raw material from the raw material vendors to the manufacturing plants, i.e. $\delta_{n_{\hat{k}}}^{*n_{\hat{k}-1}}$ and $f_{n_{\hat{k}}}^{*n_{\hat{k}-1}}$ and also which manufacturing plants along with their allocated production volumes to serve the customers different regions, i.e. $f_{n_{\hat{k}+1}}^{*n_{\hat{k}}}$, and $\beta_{n_s}^{*n_{\hat{k}}}$, respectively.

3.4 Case study

A numerical example of T-company, which specializes in wafer foundry in the semiconductor industry and has its headquarters in Taiwan, is used herein to demonstrate the application of the proposed models. The final product of T-company are dies, which represents the starting form of an integrated circuit (IC) and can be produced in either 12-inch, 8-inch or 6-inch wafers. Because some of T-company's operating costs and customer demand data are unavailable, the annual report data in Taiwan Semiconductor Manufacturing Company (TSMC) (2004) were employed to estimate them. Regarding customer demand, T-company has customers from six major areas, North America, Taiwan, Europe, Japan, Korea and Hong Kong, and the monthly customer demand for dies for the coming year totals approximately 2×10^{8} dies. The demands from these customers in six areas are 6.4×10^{7}, 5.7×10^{7}, 3.6×10^{7}, 3.2×10^{7}, 8.4×10^{6}, and 7.5×10^{6} dies, respectively. The sizes produced in the manufacturing plants include 12-inch, 8-inch and 6-inch wafer fabrications (FABs), and they produce an average of 40000, 35000 and 30000 pieces per month, respectively. Note that each size of FAB can only produce its particular size of wafers due to the complexity of the technology employed in the manufacturing process of wafers. One piece of 12-inch wafer is 2.25 times the square area of an 8-inch wafer; and 4 times that of a 6-inch wafer. Regardless of the yield, the number of dies produced by one piece of 12-inch, 8-inch and 6-inch wafer are 1233, 514, and 210, respectively, based on the 0.11 μm process technology. To unify, the capacities of 12-inch, 8-inch and 6-inch FABs are revised based on the number of dies produced by one piece of wafer, that is 4.9×10^{7}, 1.8×10^{7} and 6.3×10^{6} dies, respectively. Therefore, constructing a 12-inch FAB is more beneficial for satisfying customer demand in terms of dies as compared with the other two sizes of FABs.

T-company operates five manufacturing plants, which are located at different regions, namely, Taiwan (Hsinchu), Taiwan (Tainan), Shanghai, USA and Singapore. The capital cost per month for different-size FABs can be estimated by the total costs for the FAB construction plus equipment set-up and the maximum usage period of the FAB. The data on the capital cost and the variable production costs for different-size FABs for manufacturing plants in different regions are listed in Table 3.1.

As shown in Table 3.1, the capital and the variable production costs for different-size FABs for some manufacturing plants, i.e. USA and Singapore are higher than in others, because of higher commodity price indexes in these regions. Moreover, the costs for T-company to operate a 12-inch FAB is higher than the other two sizes, due to the high capital and variable production costs as shown in Table 3.1. Considering the final products of T-company are dies, the average production cost per unit product of manufacturing plant $n_{\hat{k}}$ as shown in Eq. (3.7), can be further revised in terms of dies, which yields

$$\frac{L_{n_{\hat{k}}}}{f_{n_{\hat{k}}} u(F_{n_{\hat{k}}})} = \frac{C(v_{n_{\hat{k}}})}{f_{n_{\hat{k}}} u(F_{n_{\hat{k}}})} + \frac{c(v_{n_{\hat{k}}})}{u(F_{n_{\hat{k}}})} \tag{3.18}$$

where $u(F_{n_{\hat{k}}})$ represents the number of dies that one piece of wafer produces when the size FAB for manufacturing plant $n_{\hat{k}}$, are $F_{n_{\hat{k}}}$, and $F_{n_{\hat{k}}}$ =6-inch, 8-inch and 12-inch, respectively. For example, if T-company decides to operate a 12-inch FAB in the USA, then $u(12_{\text{USA}}) = 1{,}233$. Taking the base production parameters of Taiwan (Hsinchu) as an example, the relationship between the average production cost per die and the production amount for different-size FABs can be further explored, and is shown in Figure 3.4.

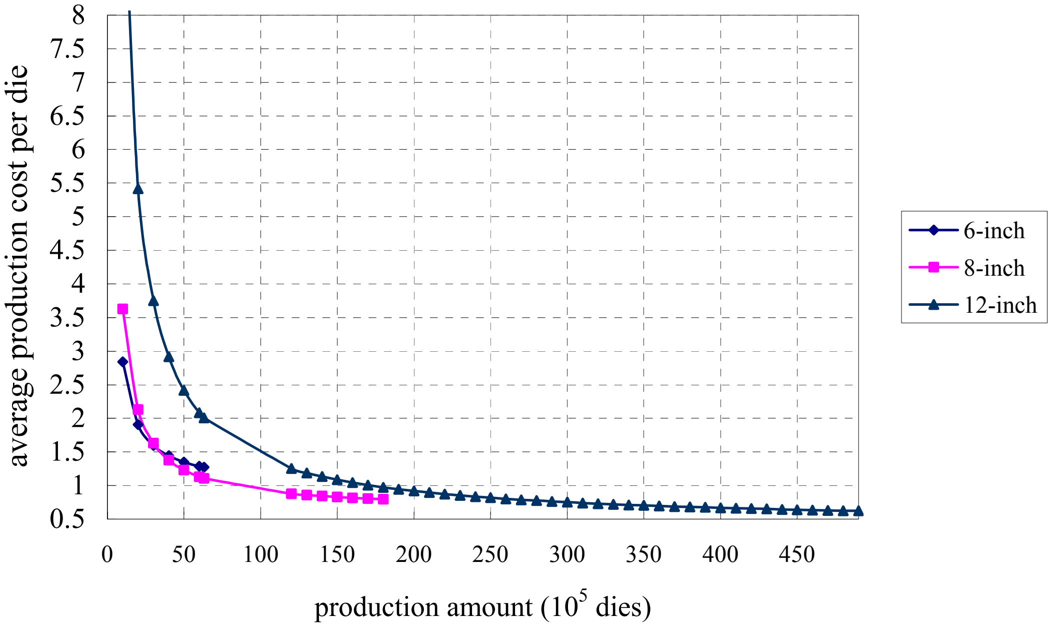

Figure 3.4 Average production cost per die vs. production amount

As shown in Figure 3.4, the average production cost per die for different-size FABs decreases as the production amount increases, but at different rates. The average production cost decreases at an increasing rate when the production amount is rather small; however, as the production becomes larger, the average production cost exhibits a constant number. In addition, all different-size FABs are characterized as having a high production cost due to a low capacity utilization when the production amount is small, such as less than 5×10^6 dies. However, the average production cost per die of a 12-inch FAB is the highest when the least capacity utilization is combined with the most expensive capital cost. Figure 3.4 also shows that there is an advantage of an 8-inch FAB over a 6-inch FAB when the production amount exceeds 3×10^6 dies. Even though the curve representing the average production cost per die of a 12-inch FAB lies above those of the 6-inch and 8-inch FABs as shown in Figure 3.4, the 6-inch and 8-inch FABs cannot satisfy the market due to capacity constraints when the demand exceeds 6.3×10^6 and 1.8×10^7 dies, respectively. Furthermore, as the production amount of a 12-inch FAB approaches its full-capacity, a 12-inch FAB yields the lowest cost among all those with full-capacity production, implying there are economies of scale in the wafer foundry industry.

The main raw materials for producing wafers include silicon wafers, chemical source, photoresist and specialty gases (TSMC, 2004). To simplify the study, chemicals are selected as a raw material in this study. The amount of chemicals required to produce one piece of 6-inch, 8-inch and 12-inch wafers can be estimated as 0.585, 0.475 and 0.450 liters (L), respectively. Considering the difference in the amount of chemical resource required in producing one piece of different size wafers, then the total amount of chemical source required by manufacturing plant $n_{\hat{k}}$ can be further revised as $w_{\hat{k}-1,\hat{k}}(F_{n_{\hat{k}}})f_{n_{\hat{k}}}$, where $w_{\hat{k}-1,\hat{k}}(F_{n_{\hat{k}}})$ represents the amount of chemical source required to produce one piece of wafer when the size FAB for manufacturing plant $n_{\hat{k}}$ is $F_{n_{\hat{k}}}$. There are four chemical source vendors in the market, namely, Merck, Chem Sources (CS), Tai-Young High Tech (TY), and Chemical Sources International (CSI), and both Merck and TY have plant sites in Taiwan, while CS and CSI are located in the USA. Table 3.2 shows the initial values of the base procurement parameters.

Table 3.1 The alternative sizes of FAB and base production parameters for manufacturing plants

	6 inch		8 inch		12 inch	
Manufacturing plant, $n_{\hat{k}}$	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	10000	515
Taiwan (Tainan)	1850	204	2978	321	9900	513
Shanghai	1900	208	3005	327	10032	520
USA	2100	212	3085	335	10090	523
Singapore	2030	215	3078	335	10065	525

Table 3.2 The initial values of base procurement parameters

Chemical source vendor, $n_{\hat{k}-1}$	Fixed cost, $V_{n_{\hat{k}-1}}$ (US$)	Unit chemical source purchase cost, $p_{n_{\hat{k}-1}}$ (US $/L)	Maximum amount supplied, $S_{n_{\hat{k}-1}}$ (L)
Merck	53	5.50	40000
CS	98	5.55	45000
TY	82	5.51	37500
CSI	112	5.49	41000

Table 3.3(a) The transportation cost per kg between chemical source vendors and manufacturing plants

	Chemical sources vendor, $n_{\hat{k}-1}$			
Manufacturing plant, $n_{\hat{k}}$	Merck	CS	TY	CSI
Taiwan (Hsinchu)	2.8	6.1	2.8	4.9
Taiwan (Tainan)	2.9	6.2	3.0	4.4
Shanghai	4.1	6.6	4.5	5.5
USA	3.5	4.3	4.4	4.9
Singapore	5.5	5.1	5.0	5.1

Unit: US$/kg

Table 3.3(b) The transportation cost per kg between manufacturing plants and customers in six areas.

Customer in different areas, n_s	Manufacturing plant, $n_{\hat{k}}$				
	Taiwan (Hsinchu)	Taiwan (Tainan)	Shanghai	USA	Singapore
North America	5.5	5.8	6.4	3.2	6.0
Taiwan	2.6	2.7	2.9	6.2	3.4
Europe	6.1	6.2	6.3	4.5	6.0
Japan	3.3	3.3	3.9	4.8	4.3
Korea	3.2	3.3	4.0	4.7	4.4
Hong Kong	2.9	3.0	2.7	5.0	4.0

Unit: US$/kg

This study further assumes that the transportation cost per unit flow shipped is measured based on the weight and distance. The weight of one die after packaging can be approximately estimated as weighing 300 milligrams (mg), i.e. 3×10^{-4} kilograms (kg). According to the Taiwan Institute of Economic Research (TIER) (2004), the average transportation charges per kg are approximately US$ 2.8 to US$ 4. The transportation cost per kg between two locations can be further estimated by unit-distance transportation cost per kg and the distance between them, and the difference in unit-distance transportation cost between two locations is due to the transportation mode employed. Tables 3.3(a) and (b) show the transportation cost per kg between chemical source vendors and manufacturing plants, and between manufacturing plants and customers in six areas, respectively.

The model is programmed using Visual C++, a computer-modeling program developed by Microsoft, based on the developed heuristic algorithm. Tables 4-6 summarize the initial solution results.

In the case study, since Taiwan's government provided incentives for developing high-tech industry, and since there is a large local customer demand due to economies of agglomeration in the semiconductor industry, T-company chose to construct 12-inch FABs in Taiwan, and they are located in Hsinchu and Tainan. Due to the large demand, the T-company also operates 12-inch FABs in Shanghai and the USA, respectively, as well as an 8-inch FAB in Singapore, as shown in Table 3.4. The capacity utilizations of the four 12-inch FABs are 100%, while that of the 8-inch FAB is 42%. Because of the low capacity of a 6-inch FAB, it is not employed when there is large demand. This can also be explained by the fact that the T-company expanded its capacity to operate more 12-inch FABs rather than 6-inch FABs. Table 3.4 also shows that four 12-inch FABs have the lowest average production cost per die, approximately US$ 0.62, while it is 1.06 US$/die for an 8-inch FAB. In addition, the total average production cost per die for T-company is US$ 0.65. These results imply that because of the high customer demand, the manufacturer can operate its manufacturing plants with large-size capacity, combined with full-capacity production, thereby lowering the production cost. These results also imply that when determining the production amount for multiple manufacturing plants, manufacturing plants with large-size capacity have a high priority over others for filling the capacity, not only due to the high capability of satisfying the customer demand but also because they provide greater cost savings. Finally, Table 3.4 shows the amount of chemical supplies required by each manufacturing plant, with the total amount required being 100642 L.

Table 3.5 shows the initial results of the procurement decisions including the optimal active chemical source vendors, the procured amount of chemicals, and the amount of chemicals shipped from the chemical source vendors to the manufacturing plants. As shown in Table 3.5, the optimal active vendors include Merck, TY and CSI, and each serve different manufacturing plants. This is because the unit chemical source purchase costs offered by these vendors are relatively low. Although there is a high fixed cost with CSI, this high fixed cost per unit chemical source is reduced if the large procurement amount is large. The advantage from this low unit cost outweighs the disadvantage of the high fixed cost. Since the distance between two alternatives can be reflected by the transportation cost, active vendors tend to serve the manufacturing plants nearby. With reference to Table 3.3(a), the distance from vendors Merck and TY to the two manufacturing plants in Taiwan are due to the fact that they are all located in Taiwan; therefore, FABs in Taiwan are mainly served by Merck and TY rather than by CSI. The average inbound cost per die is US$ 4.63×10^{-3}.

Table 3.4 The initial results of manufacturing plants

Manufacturing plant	Taiwan (Hsinchu)	Taiwan (Tainan)	Shanghai	USA	Singapore
Size of wafer, $F_{n_{\hat{k}}}$	12-inch	12-inch	12-inch	12-inch	8-inch
Capacity, $v_{n_{\hat{k}}}$ (wafer)	40000	40000	40000	40000	35000
Production amount, measuring in wafer, $f_{n_{\hat{k}}}$	40000	40000	40000	40000	14825
Production amount, measuring in die, $f_{n_{\hat{k}}}u(F_{n_{\hat{k}}})$	4.9×10^7	4.9×10^7	4.9×10^7	4.9×10^7	7.6×10^6
Chemical sources required, $w_{\hat{k}-1,\hat{k}}(F_{n_{\hat{k}}})f_{n_{\hat{k}}}$ (L)	23400	23400	23400	23400	7042
Capacity utilization ratio, $Y_{n_{\hat{k}}}$	100%	100%	100%	100%	42%
Average production cost per die (US$/ die)	0.62	0.62	0.63	0.63	1.06

Total production amount	2×10^8 (Dies)
Total average production cost per die	0.65 (US$/die)
Total amount of chemical source required	100,642 (L)

Table 3.5 The initial results of the relationship between manufacturing plants and chemical source vendors

Active raw material vendor	Manufacturing plants served	Amounts of chemical sources shipped, $f_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ (L)	Total amount of chemical sources supplied, $\sum_{\forall n_{\hat{k}}} f_{n_{\hat{k}}}^{n_{\hat{k}-1}}\delta_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ (L)
Merck	Taiwan (Tainan)	9300	
	Shanghai	7300	
	USA	23400	40000
TY	Taiwan (Hsinchu)	23400	
	Taiwan (Tainan)	14100	37500
CSI	Shanghai	16100	
	Singapore	7042	23142

The sum of average fixed and inbound cost per die	4.63×10^{-3} (US$/die)

Table 3.6 shows the initial results of the relationship between manufacturing plants and customers in six areas. Since in this study the customer is not constrained to be served by one single manufacturing plant, some customers are served by more than one manufacturing plant, such as customers in North America, Taiwan, Europe and Korea as shown in Table 3.6. For example, customers in North America are served by FABs in Taiwan (Hsinchu) and USA, while customers in Hong Kong is served by the FAB in Shanghai. In Taiwan the majority of customers are served by FABs in Taiwan due to their relative low transportation and production costs. In addition to the amount of customer demand, the main reason that customers are served by different FABs lies in the distance between the customer and the FAB. For example, customers in North America are served by the FAB in the USA, while customers in Taiwan are served by the FAB in Taiwan. These results imply that to reduce the outbound cost, the product should be shipped from a manufacturing plant to a customer with the shortest distance between them. These results also imply that for a wafer foundry company the benefits brought about by centralized production are larger than the increased transportation costs by decentralized production. The manufacturer may adopt a production strategy with centralized production in manufacturing plants with large-size capacity and then ship the product to customers in different regions. Summing up the average production, the inbound and outbound costs per die in Tables 3.4-3.6, the total average cost per die of T-company can be calculated as US$ 0.65579, with the portion of production cost being 99%, the highest of them all. This implies that the wafer foundry industry shows production with economies of scale, and that the production is the most valued-added in the entire supply chain. Therefore, the manufacturer must be aware of the impact on the total cost of capacity utilization of manufacturing plants with different-sizes capacity.

Table 3.6 The initial results of the relationship between manufacturing plants and customers in six areas

Customer in different areas, n_s	Customer demand, f_{n_s} (dies)	Manufacturing plants, $n_{\hat{k}}$	Amount of products shipped, $f_{n_s}^{n_{\hat{k}}}$ (dies)
North America	$6.4\text{x}10^7$	Taiwan (Hsinchu)	$1.5\text{x}10^7$
		USA	$4.9\text{x}10^7$
Taiwan	$5.7\text{x}10^7$	Taiwan (Tainan)	$1.5\text{x}10^7$
		Shanghai	$4.2\text{x}10^7$
Europe	$3.6\text{x}10^7$	Taiwan (Hsinchu)	$2.8\text{x}10^7$
		Singapore	$7.5\text{x}10^6$
Japan	$3.2\text{x}10^7$	Taiwan (Tainan)	$3.2\text{x}10^7$
Korea	$8.4\text{x}10^6$	Taiwan (Hsinchu)	$6.3\text{x}10^6$
		Taiwan (Tainan)	$2.1\text{x}10^6$
Hong Kong	$7.5\text{x}10^6$	Shanghai	$7.5\text{x}10^6$

Average outbound cost per die 1.16×10^{-3} (US\$/die)

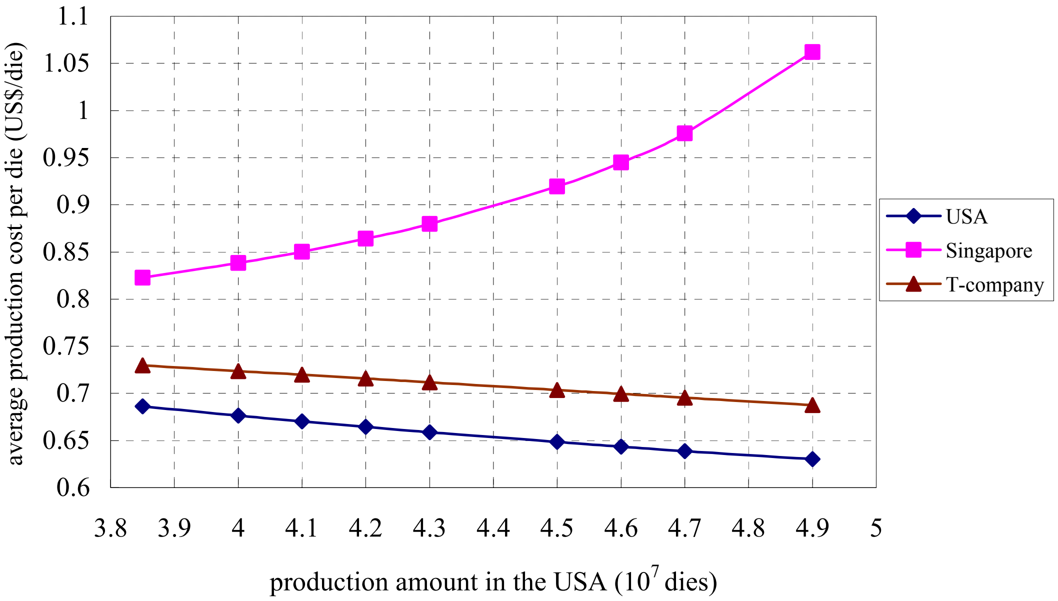

Figure 3.5 Average production cost per die vs. production amount in the USA

So far, this study has conducted a numerical example for T-company specializing in wafer foundry in the semiconductor industry. Next, this study will further explore the influences of changes in key parameters on the average production cost and the optimal capacity and optimal production amount of the manufacturing plants.

In this study, the capacity utilization of different-size FABs significantly influences the total average production cost per die. As Table 4 shows, a minimum cost is yielded for T-company if four 12-inch FABs reach their full-capacity production. This study takes FABs in the USA and Singapore as an example to explore the impact of the production amount of different-size FABs on the total average production cost per die. As shown in Table 4, the total production amount of FABs in the USA and Singapore are 5.66×10^7 dies, with the FABs in the USA and Singapore as 12-inch and 8-inch, respectively. Under the assumption that the size FAB of other manufacturing plants and their production amount remain the same, the number of dies produced by the USA and Singapore are negatively related. Figure 3.5 shows the total average production cost per die vs. the production amount in the USA.

As shown in Figure 3.5, as the production amount produced by the USA increases, the average production cost per die for both USA and T-company decreases, which also includes Singapore for exhibiting increased average production cost. This is because the number of dies produced by one piece of 12-inch wafer exceeds that of an 8-inch wafer. Also, the impact of the increased cost in Singapore on the total cost can be offset by the decreased cost in the USA. In other words, the total production cost can be reduced if there is more production assigned to a manufacturing plant with large-size capacity. This result also implies that with the existence of economies of scale, the mechanism for determining the production amount for manufacturing plants with different-size capacity is to assign the most demands to manufacturing plants with the largest-size capacity, and to assign the remaining ones to those with small-size. However, in addition to the size of capacity, the other important factor affecting the assignments of production is the amount of customer demand. As stated, when the customer demand is small, using manufacturing plants with large-size capacity may lead to high production cost. Consequently, a plant with a large-size capacity is preferred when the demand is large. Table 3.7 shows the optimal sizes of FABs and the capacity utilization of manufacturing plants with different amounts of customer demand.

As shown in Table 3.7, there is a high total average production cost when the amount of customer demand is low. Referring to Table 3.1, the advantages of Hsinchu and Tainan in Taiwan are low capital and variable production costs, which provided T-company with the incentives to construct two 12-inch FABs in those regions, as shown in Table 3.7. The optimal FAB size is 12-inch for Hsinchu and Tainan with full-capacity production regardless of the customer demand. This result implies that the determination of where to operate a manufacturing plant with large-size capacity lies in the labor costs involved as well as the corresponding land rental fee, expenses for equipment installation, etc. This finding also shows that high-tech manufacturers can operate a large-size capacity plant in regions with adequate and low-cost supplies and where low-paid skilled workers are available, or if the governments provide incentives, such as rent or tax free etc. to the high-tech industry. Table 3.7 also shows that not all FABs are being operated until the amount of customer demand exceeds 17.99×10^7 dies. For example, T-company needs only three manufacturing plants when the customer demand is 12.85×10^7 dies. This result implies that when the demand is extremely low, it is not necessary to operate all of the manufacturing plants, and in addition a manufacturing plant with a very high cost is not suggested. As the customer demand increases, in addition to two 12-inch FABs, T-company will start to operate a smaller-size FAB at locations with high capital and variable production costs. For example, when customer demand is 11.82×10^7 dies, then there are three 12-inch FABs, i.e. Hsinchu, Tainan and Shanghai with 100% capacity utilization and one 6-inch FABs in the USA, with a utilization as low as 25%. This implies that a company may incur high costs to operate a large-size capacity at a region with relative high capital and production costs when there is not large demand. As the customer demand increases, the tendency to operate 12-inch FABs increases; even though there is not enough demand to enable full-capacity production for all 12-inch FABs. This implies that rather than using small-size capacity with high capacity utilization, using large-size capacity with a relative low utilization is more cost effective for the manufacturer, as long as the customer demand is sufficiently high to share the high capital cost. Furthermore, the capacity utilization of Singapore has the highest capital and production costs and shows a smaller number, i.e. 38% with a customer demand of 21.59×10^7 dies. This implies that when using the same-size capacity for all manufacturing plants, a manufacturing plant with lower capital and lower production cost should be assigned to produce more products.

Table 3.7 The optimal size FABs and capacity utilization of manufacturing plants with different amounts of customer demand

Customer demand (10^7 dies)	The total average production cost per die (US$/die)	Taiwan (Hsinchu)		Taiwan (Tainan)		Shanghai		USA		Singapore	
		(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
11.57	0.6823	12	100%	12	100%	12	94%	-	-	-	-
11.82	0.6869	12	100%	12	100%	12	100%	6	25%	-	-
12.85	0.6813	12	100%	12	100%	-	-	12	60%	-	-
15.42	0.6549	12	100%	12	100%	12	100%	8	34%	-	-
17.99	0.6530	12	100%	12	100%	12	100%	12	65%	-	-
20.56	0.6386	12	100%	12	100%	12	100%	12	100%	8	46%
20.82	0.6387	12	100%	12	100%	8	60%	12	100%	12	100%
21.07	0.6387	12	100%	12	100%	8	74%	12	100%	12	100%
21.33	0.6386	12	100%	12	100%	8	89%	12	100%	12	100%
21.46	0.6387	12	100%	12	100%	8	96%	12	100%	12	100%
21.59	0.6522	12	100%	12	100%	12	100%	12	100%	12	38%
21.85	0.6036	12	100%	12	100%	12	100%	12	100%	12	43%
22.10	0.5560	12	100%	12	100%	12	100%	12	100%	12	48%
23.13	0.5066	12	100%	12	100%	12	100%	12	100%	12	69%
24.41	0.5024	12	100%	12	100%	12	100%	12	100%	12	95%

(1): size FAB

(2): capacity utilization

3.5 Summary

Past studies have extensively investigated plant location issues. Most of these studies dealt with the problem by constructing MIP models in which the plant is constrained to serve a single warehouse or customer. These studies focused mainly on developing an approximation procedure and on the efficiency of the proposed heuristics. However, the impact of high capital cost on the optimal plant capacity, and the production volumes among manufacturing plants of different size were rarely discussed. This study constructed a nonlinear MIP model which attempted to minimize the average total cost per unit product subject to constraints such as satisfying customer demand in various geographic regions, relationships between supply flows and demand flows within the physical configuration, and the production limitation of different size plants. This study showed how economies of scale can be considered in solving the capacity and production problems. This study also showed that the capacity utilization as well as the production amount in the short run, and the size of capacity of multiple plants in the long run are related, and that those two factors influence the total cost.

A numerical example of T-company in Taiwan, which is the world’s largest dedicated semiconductor foundry, was provided to demonstrate the application of the proposed models. The results show that because of the high customer demand, the manufacturer can operate manufacturing plants with large-size capacity combined with full-capacity production, thereby lowering the production cost. Since the government of Taiwan provided incentives for developing the high-tech industry, and since there is a large local customer demand due to the economies of agglomeration in the semiconductor industry, T-company’ core operations are based in FABs in Taiwan. The results of this study also show that when determining the production volumes for multiple manufacturing plants, those with large-size capacity combined with low capital and variable production costs have a higher priority in filling this capacity, compared to those with small-size capacity combined with relative high capital and variable production costs, not only because of their higher capability to satisfy customer demand but also because they are more cost effective. Although there is a tradeoff between production cost economies and transportation cost diseconomies, the results show that the benefits in terms of cost savings for the wafer foundry company brought by centralized production are larger than the increased transportation cost as a result of decentralization. Therefore, this finding suggests that the manufacturer may adopt a production strategy of centralizing production in manufacturing plants with large-size capacity and then shipping the products to customer in different regions.

As to raw material procurement, the results show that the impact of high fixed costs on the total cost can be absorbed by large-amount procurement, and that the benefits of a low unit purchase cost are larger than the high fixed cost. Also, active vendors tend to serve manufacturing plants that are nearby. In addition, to reduce outbound costs, the product should be shipped from a manufacturing plant to a customer that is located within a short distance. The results also show that the production cost is the highest of all costs involved for a wafer foundry. This finding implies that the wafer foundry industry shows production with economies of scale, and that this production is the most valued-added in the entire supply chain. Therefore, the manufacturer must be aware of the impact on the total cost of capacity utilization by its manufacturing plants with different-size capacity. The results also show that a manufacturing plant with very high capital and variable production costs is not recommended when the demand is extremely low. However, without using small-size capacity combined with high capacity utilization, operating large-size capacity with a relative low utilization is more cost effective for the manufacturer as long as the customer demand is large enough to offset the high capital cost.

In sum, the integrated plant capacity and production model developed in this study provide a highly effective tool that enables high-tech product manufacturers to evaluate the expansion, contraction, or reallocation of their production tasks among various manufacturing plants. This model can be applied to investigate the relationship between the total average production cost and production allocation when deciding whether to operate a new manufacturing plant, or to develop a new technology, such as 0.09 μm process technology, which may lead to larger production. Finally, it is worth noting that the optimal capacity utilization of a manufacturing plant is related to its capacity size, the larger the capacity size the larger the utilization.

CHAPTER 4
Reliability evaluation and adjustment for supply chain network design with demand fluctuations

This chapter focuses on supply chain network design problems by considering economies of scale and further demand fluctuations. The results from the MIP model in the first part, i.e. Chapter 3, are employed as the initial results of the supply chain network, where the optimal locations, capacities and the production amount of manufacturing plants are determined. Moreover, the monthly product/material flows between manufacturing plants/suppliers and customers/manufacturing plants in different locations are also obtained. 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. The research scope of this part is the same as the first part, i.e. Chapter 3, which is shown as Figure 4.1. And the adjustment strategy proposed herein focuses on the production echelon, since the production echelon is the most value-added one for high-tech industries.

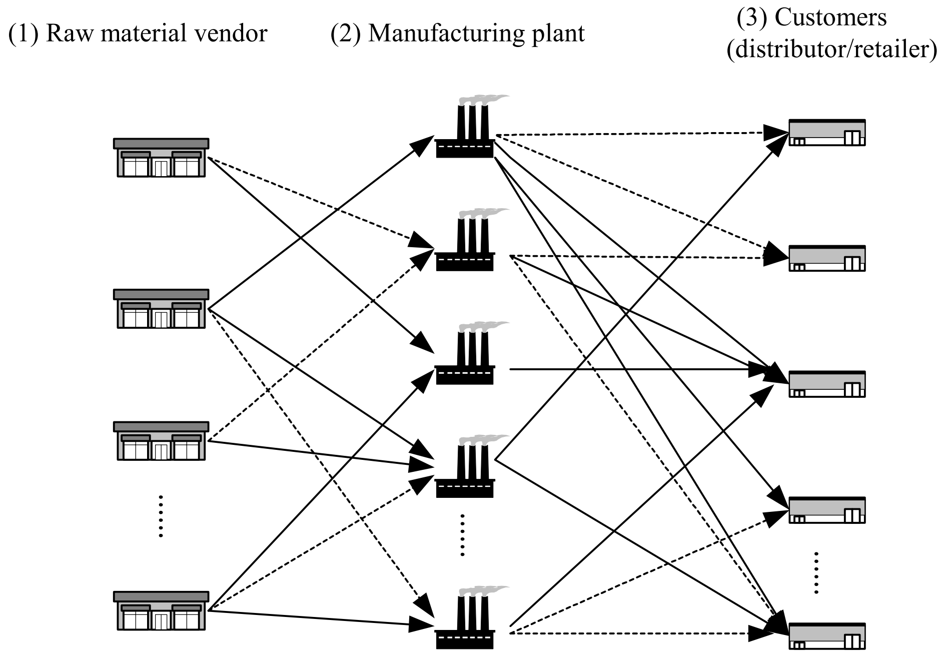

Figure 4.1 The research scope of Chapter 4

4.1 Introduction to the problem

In the strategic supply chain network-planning phase, the problem generally involves deciding the configuration of the network that satisfies customer demand while minimizing manufacturers' costs. Though large-scale capacity is encouraged due to there exist economies of scale following reduced costs, the advantage depends on the level of the market demand. The benefit brought by operating large-scale manufacturing plants shrinks and production costs dramatically increase when the market demand is insufficient to realize scale economies and the capacity utilization is low. On the other hand, revenue loss arises when supply does not match with high market demand. Strategic supply chain network is a key factor influencing efficient tactical operations, and therefore has a long lasting impact on the manufacturers. The majority of supply chain network problems uses average estimated customer demand patterns for the manufacturers over planning years covering peak and off-peak periods. Unfortunately, unexpected abnormal events occur and continue for a period of time, which further influence customer demand and affect network performance. The continued survival and effectiveness lie in manufacturers' ability to respond promptly to environmental turbulence (Lloréns et al., 2005). Since the supply chain network design involves the commitment of meeting customer demand, how to design a flexible supply chain network by considering economies of scale and demand fluctuations is important.

The impacts of uncertainties on manufacturer efficiency have prompted a lot of studies to address stochastic parameters in supply chain planning. At the static and operational levels, there is a great deal of research developing production/inventory models that deal with various uncertain factors in the environment. The attention has been focused mostly on the probabilistic modeling of the customer demand side (e.g. Cachon and Fisher, 2000; Gavirneni et al., 1997; Gavirneni, 2002). Other studies dealt with supply uncertainties, such as machine breakdowns, strikes, shortages in material availability, etc. The majority of this research employed and modified EOQ formulas to include random variables reflecting different uncertainties (e.g. Hariga and Haouari, 1999; Wang and Gerchak, 1996). These studies have shown how the company's performance is affected by uncertain environment and provided tools to tackle these uncertainties and ease these influences. The planning frame of these studies is focused on operational level, rather than strategic design.

Taking another 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 that solve the stochastic integer programming models and presenting computational results on supply chain network involving different number of nodes, arcs or products. However, abnormal states occur unexpectedly, which result in severe demand fluctuations and affect the performance of a well-design network as the abnormal state continues. Instead of reconstructing the whole network, it is important to propose adjustment method for the manufacturer so as to maintain overall global network design objectives. To summarize, few studies have combined supply chain network modeling and economy theory to formulate integrated models, coping with production economies and demand fluctuations.

Reliability engineering is a well-established area of engineering, which has been widely applied to software reliability, mechanical reliability, and transportation network reliability, etc (e.g. Billinton and Allan, 1983; Chen, 1999; 2002). Hsu and Wen (2002) developed a reliability evaluation method for airline network design, evaluating reliability of initial proposed flight frequencies under normal/abnormal demand fluctuations. In the paper, a priori adjustment of flight frequencies is also presented. Lai et al. (2002) developed a measurement instrument for supply chain performance in transport logistics. However, the production of the manufacturing plants is directly affected by market demand, which influences the revenue and further market shares of the operator in the long run. There are few studies in the field of supply chain management paying attention to evaluate the reliability of proposed design of the network under abnormal demand fluctuations. Furthermore, how to determine flexible adjustment strategies by considering related adjusted benefits and costs under different abnormal states are essential for the manufacturer on maintaining competition in the industry. This study attempts to explore above issues by formulating a series of models.

4.2 Reliability evaluation methods

This section investigates how demand fluctuations from different markets influence the production of the manufacturing plants and affect their performance.

Based on Hsu and Wen (2002), this study revises the definition of the reliability as it copes with the characteristics of supply chain networks. The unreliability problem arises from the condition the proposed capacity cannot match customer demand due to abnormal events occur. When abnormal events lead to a shrunk demand, excess supply occurs, following increased production cost due to low capacity utilization. On the other hand, though demand expansion causes decreased production cost, revenue loss follows once proposed capacity cannot meet the excessive demand. Thus, the results of a supply chain network design, i.e., the proposed capacity and production allocation produce reliability for the manufacturer only when the demand fluctuates within ranges that allow the capacity utilization of the manufacturing plants to maintain cost economies and customer service level. This study defines the reliability as the probability that initially proposed capacity of the manufacturing plant will operate effectively under demand fluctuations.

This study assumes that the proposed capacities of the manufacturing plants resulting from supply chain network design in Chapter 3, v_{n_k}, associated with the average monthly customer demand, f_{n_s}, are initially reliable, where the capacity utilization of the plant could maintain a break-even level or/and the production does not exceed the full-capacity production level. Let the capacity utilization be the basic criterion for evaluating the reliability of the manufacturing plant under demand fluctuations. The capacity utilization of manufacturing plant n_k with respect to random production amount $\tilde{f}_{n_k}^{t}$ in month *t*, $Y_{n_k}(\tilde{f}_{n_k})$, is defined as:

$$Y_{n_k}(\tilde{f}_{n_k}^{t}) = \frac{\tilde{f}_{n_k}^{t}}{v_{n_k}^{*}} \tag{4.1}$$

Since the proposed capacity, $v_{n_k}^{*}$, is fixed, $Y_{n_k}(\tilde{f}_{n_k}^{t})$ is directly proportion to the realizations of $\tilde{f}^{t}_{n_k}$ for month *t*. Let $\bar{f}^{t}_{n_k}$ represent a random realization of $\tilde{f}^{t}_{n_k}$ and a potential value of production amount of manufacturing plant n_k under all demand fluctuations over month *t*. If $Y_{n_k}(\bar{f}^{t}_{n_k}) = 0$, it implies that the potential production amount is zero, i.e. $\bar{f}^{t}_{n_k} = 0$; and $Y_{n_k}(\bar{f}^{t}_{n_k}) \geq 1$ reveals that the manufacturing plant is under full-capacity production or the potential production amount exceeds its capacity, which further implies the capacity cannot satisfy the excess demand. This study assumes $\overline{Y}_{n_k} = 1$ to be the maximally acceptable capacity utilization of manufacturing plant n_k, where there exists a lowest unit-product production cost, while let $\underline{Y}_{n_k}$ be the minimally acceptable capacity utilization, at which tolerable minimum revenue for the manufacturer is assumed.

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

$$\begin{aligned} R_{n_k}(\tilde{f}^{t}_{n_k}) &= \Pr[\underline{Y}_{n_k} \leq Y_{n_k}(\tilde{f}^{t}_{n_k}) \leq \overline{Y}_{n_k}] \\ &= \Pr[\underline{Y}_{n_k} v^{*}_{n_k} \leq \tilde{f}^{t}_{n_k} \leq \overline{Y}_{n_k} v^{*}_{n_k}] \qquad (4.2) \end{aligned}$$

The impacts of fluctuating customer demand on the production amount of different manufacturing plants are further analyzed. Let θ_{n_k} be the proportion of the production from manufacturing plant n_k to that from all plants, which is the results of initially proposed production allocation among the manufacturing plants, namely:

$$\theta_{n_k} = \frac{f_{n_k}}{\sum_{\forall n_k} f_{n_k}} \tag{4.3}$$

θ_{n_k} also implies the magnitude of the manufacturing plant to the manufacturer, in a way that the more substantial production a plant is, the more the manufacturer relies on its output to serve customers and $\sum_{\forall n_k} \theta_{n_k} = 1$. Since the total production amount from all manufacturing plants is restricted to meet demands from all customers, $\sum_{\forall n_k} f_{n_k}$ in Eq. (4.3) can be substituted by $\sum_{\forall n_s} f_{n_s}$, yielding $\theta_{n_k} = \frac{f_{n_k}}{\sum_{\forall n_s} f_{n_s}}$. Furthermore, Eq. (4.3) can be rewritten as:

$$\tilde{f}^{t}_{n_k} = \theta_{n_k} \sum_{\forall n_s} \tilde{f}^{t}_{n_s} \tag{4.4}$$

Substituting Eq. (4.4) for $\tilde{f}_{n_k}$ in Eq. (4.2), Eq. (4.2) can be rewritten in terms of customer demand, restated:

$$R_{n_k}(\tilde{f}^{t}_{n_k}) = \Pr[\frac{\underline{Y}_{n_k} v^{*}_{n_k}}{\theta_{n_k}} \le \sum_{\forall n_s} \tilde{f}^{t}_{n_s} \le \frac{\bar{Y}_{n_k} v^{*}_{n_k}}{\theta_{n_k}}] \tag{4.5}$$

Assume that random variable $\tilde{f}^{t}_{n_s}$ follows a normal distribution with parameters $\bar{f}^{t}_{n_s}$ and $\sigma(\tilde{f}^{t}_{n_s})$ and $\tilde{f}^{t}_{n_s}$ for all customers is independent. Total fluctuating demand, $\sum_{\forall n_s} \tilde{f}^{t}_{n_s}$, is also a random variable, distributing with a normal distribution with mean $\sum_{\forall n_s} \bar{f}^{t}_{n_s}$ and standard deviation $\sqrt{\sum_{\forall n_s} \sigma^2(\tilde{f}^{t}_{n_s})}$. The reliability of manufacturing plant n_k can now be evaluated by using the cumulative distribution functions of normal distribution, namely:

$$R_{n_k}(\tilde{f}^t_{n_k}) = \Phi\left(\frac{\dfrac{\overline{Y}_{n_k} v^*_{n_k}}{\theta_{n_k}} - \sum_{\forall n_s} \bar{f}^t_{n_s}}{\sqrt{\sum_{\forall n_s} \sigma^2(\tilde{f}^t_{n_s})}}\right) - \Phi\left(\frac{\dfrac{\underline{Y}_{n_k} v^*_{n_k}}{\theta_{n_k}} - \sum_{\forall n_s} \bar{f}^t_{n_s}}{\sqrt{\sum_{\forall n_s} \sigma^2(\tilde{f}^t_{n_s})}}\right) \tag{4.6}$$

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 finance crisis, war or natural disaster, economy recovery, which further cause demand from that market fluctuating. The network performance is affected in a way that the more fluctuating demand is different from the forecasted for a long period of time, the more accumulated revenue loss the manufacturer will surfer. An abnormal state is one in which monthly customer demand values do not follow the normal demand distributions, estimated from all survey years, due to the occurrence of an abnormal event. For customer n_s, let $\mathbf{K}_{n_s}$ represent the set of all distinct states, which occur on the market during the planning year and let $\mathbf{K}_{n_s} \equiv \{w^0_{n_s}, w^1_{n_s}, .., w^i_{n_s}, .., w^W_{n_s}\}$, where $w^i_{n_s}$ denotes a specific abnormal state and W gives the number of distinct abnormal states, and $w^0_{n_s}$ represents a normal state, in which no abnormal fluctuation occurs, respectively. Let $\Pr(w^i_{n_s})$ be the probability that state $w^i_{n_s}$ occurs during the planning year, where $\Pr(w^i_{n_s}) \geq 0$ and $\sum_{i=0}^{W} \Pr(w^i_{n_s}) = 1$.

Suppose that, during the planning year, an abnormal state $w^i_{n_s}$ occurs at time t^*_i with duration $\tilde{v}^i_{n_s}$, where t^*_i is the time elapsed from the beginning of year, and t^*_i with 1 month as a unit. The duration of $w^i_{n_s}$, $\tilde{v}^i_{n_s}$, is considered to be a random variable. To simplify this study, $\tilde{v}^i_{n_s}$ is supposed to have a finite discrete distribution:

$\{(v_{n_s}^{ij}, p_j), \mathrm{j}=1,2...,V_{n_s}\}$, where $v_{n_s}^{ij}$ is a realization of $\tilde{v}_{n_s}^{i}$ with probability p_j and V_{n_s} is the number of realizations of $\tilde{v}_{n_s}^{i}$. Let I be the set of all months during the planning year and $I_{n_s}^{i,j}$ represent the set of months belonging to the time interval within which an abnormal state $w_{n_s}^{i}$ continues on the location of customer n_s, i.e. $I_{n_s}^{i,j} \equiv \{t \| [t_i^*] \le t < \lceil t_i^* + v_{n_s}^{ij} \rceil \}$ given state duration $v_{n_s}^{ij}$. Moreover, suppose that the monthly demand from customer n_s in abnormal state $w_{n_s}^{i}$ follows another normal distribution with different parametric values. That is, the monthly demand associated with abnormal state $w_{n_s}^{i}$ follows another random variable, $\tilde{f}_{n_s,ij}^{t}$, $\forall t \in I_{n_s}^{i,j}$. Note that the mean and standard deviation of the distribution $\tilde{f}_{n_s,ij}^{t}$ is related to the effect and duration of the event corresponding to state $w_{n_s}^{i}$. Consider different durations of abnormal state $w_{n_s}^{i}$, $v_{n_s}^{ij}$, and their probabilities p_j, the average demand from customer n_s in month t given abnormal state $w_{n_s}^{i}$, $\tilde{f}_{n_s,i}^{t}$, can be expressed as:

$$\tilde{f}_{n_s,i}^{t} = \sum_{j=1}^{V_{n_s}} p_j \times \tilde{f}_{n_s,ij}^{t} \tag{4.7}$$

Furthermore, the expected fluctuating demand from customer n_s in month t, depending on the occurrence of abnormal states, is obtained as: $\tilde{f}_{n_s}^{t} = \sum_{i=1}^{W} \Pr(w_{n_s}^{i}) \tilde{f}_{n_s,i}^{t}$. The reliability of manufacturing plant n_k in month t associated with abnormal demand further can be calculated using Eq. (5.6).

4.3 Supply chain network adjustment model

Some manufacturing plants may be found to have low reliability when initially proposed capacity and production allocation results experience severe demand fluctuations. To prevent the incurred costs, it is worth considering an adjustment of the network. Since the manufacturing echelon is the most value-added for high-tech product industry, this study focuses on the adjustment of the production allocation among the manufacturing plants for the manufacturer. To capture various abnormal states and their impacts on customer demand, this study formulates supply chain network adjustment models with respect to demand expansion and shrinkage, as they cope with different fluctuant demands combined with various durations where the abnormal states continue.

4.3.1 Customer demand expansion

Demand expansion resulting from an abnormal state may lead the potential production amount to exceed the capacity in a manufacturing plant, given customer demand being satisfied. Because there is limited capacity, demand expansion usually accompanies unsatisfied customers. The excessive demand burdens the manufacturer with an even heavy revenue loss if the abnormal state lasts for a long period of time. In accordance with these unreliable situations, this study proposes a production adjustment strategy, where it suggests the reliable manufacturing plants with remaining capacities to produce more or booking the capacity of outsourcing firms. The induced costs and benefits associated with adjustment decisions are also discussed. This study formulates 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 $\mathbf{t} \equiv \{I_{n_s}^{i,j}, \forall n_s, \forall i\}$ represent the set of months belonging to the time interval within which excessive demand 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 manufacturing plants operated by the manufacturer, $\mathbf{J} \equiv \{\dot{n}_k\}$ be the set of the detected unreliable manufacturing plants, and $\bar{n}_k$, $\bar{n}_k \in \mathbf{K} - \mathbf{J}$, represents a reliable manufacturing plant, where $Y_{\dot{n}_k}(\tilde{f}_{\dot{n}_k}) > 1$ and $Y_{\bar{n}_k}(\tilde{f}_{\bar{n}_k}) \leq 1$, respectively. Moreover, let m_k be a specific alternative outsourcing firm, where the product quality is indifferent from the manufacturer. For the sake of simplification, this study averages the total customer demands and denotes $\bar{f}_s$ as average monthly customer demand for the manufacturer during $n(\mathbf{t})$ months, $\bar{f}_s = \frac{1}{n(\mathbf{t})}\sum_{\forall t}\sum_{\forall n_s}\bar{f}^t_{n_s}$, where $\bar{f}^t_{n_s}$ is a realization demand from customer n_s in month t, $t \in \mathbf{t}$. Then, the expected average monthly production amount of manufacturing plant n_k can be estimated as $\bar{f}_{n_k} = \theta_{n_k}\bar{f}_s$.

The allocation cost includes fixed allocation cost and variable allocation cost. The fixed allocation costs are those expenses associated with production schedule change costs, contract cost with outsourcing firms, etc and are incurred if the manufacturer once determines 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, while the latter reflects additional labor costs and extra utilities cost, etc because of over-production than scheduled in a reliable manufacturing plant. Let o_{m_k} be the unit-product outsourcing cost paid for outsourcing firm m_k and $h_{\bar{n}_k}$ be the unit-production compensation cost for manufacturing plant $\bar{n}_k$. The outsourcing cost reflects not only production and material purchase costs borne by the outsourcing firm, but also a premium charged, and thus $o_{m_k} \geq h_{\bar{n}_k}$ can be concluded. The total allocation cost over $n(\mathbf{t})$ months, G, is formulated as:

$$G = O_k + n(\mathbf{t})(\sum_{\forall m_k} o_{m_k} \sum_{\forall \dot{n}_k} q_{\dot{n}_k, m_k} x_{m_k}^{\dot{n}_k} + \sum_{\forall \bar{n}_k} h_{\bar{n}_k} \sum_{\forall \dot{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k}) \tag{4.8}$$

where O_k represents the fixed allocation cost, and $q_{\dot{n}_k, m_k}$ and $\Delta_{\dot{n}_k, \bar{n}_k}$ are the production amounts allocated from manufacturing plant $\dot{n}_k$ to outsourcing firm m_k and to reliable manufacturing plant $\bar{n}_k$, respectively. Indicators $x_{m_k}^{\dot{n}_k}$ and $y_{\bar{n}_k}^{\dot{n}_k}$ represent, respectively, whether there exist production allocation relationships between $\dot{n}_{\hat{k}}$ and m_k and between $\dot{n}_{\hat{k}}$ and $\bar{n}_k$. Moreover, $\sum_{\forall \dot{n}_k} q_{\dot{n}_k, m_k} x_{m_k}^{\dot{n}_k}$ and $\sum_{\forall \dot{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k}$ in Eq. (4.8) indicate the outsourcing amount from outsourcing firm m_k and additional production amount from manufacturing plant $\bar{n}_k$, respectively.

The extra material purchase cost arises due to there could be no sufficient material to support the production, given considerable customer demands. Let $\bar{p}$ be the average unit-material purchase cost and $\bar{p}$ would be high since it is an emergency purchase and also due to there should be large material demanded in the market during high demand period. The extra material purchase cost over $n(\mathbf{t})$ months, R, is given as:

$$R = n(\mathbf{t}) \bar{p} \sum_{\forall \dot{n}_k} \sum_{\forall \bar{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} \tag{4.9}$$

The difference in production cost discussed herein accounts for the benefits brought by production reallocation such that all manufacturing plants reach their full-capacity production. Let $\bar{f}_{\dot{n}_k}$ and $\bar{f}_{\bar{n}_k}$ represent, respectively, the realized average monthly production amount of manufacturing plant $\dot{n}_k$ and $\bar{n}_k$ under demand expansion, i.e. unadjusted amounts, while $f_{\dot{n}_k}^{'}$ and $f_{\bar{n}_k}^{'}$ are the adjusted ones, respectively. Then, the relationship between adjusted and unadjusted production amount can be represented as follows:

$$\sum_{\dot{n}_k} (\bar{f}_{\dot{n}_k} - f_{\dot{n}_k}^{'}) = \sum_{\dot{n}_k} \sum_{m_k} q_{\dot{n}_k, m_k} x_{m_k}^{\dot{n}_k} + \sum_{\dot{n}_k} \sum_{\bar{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} \tag{4.10a}$$

$$f'_{\bar{n}_k} = \bar{f}_{\bar{n}_k} + \sum_{\forall \dot{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} \tag{4.10b}$$

$$f'_{\dot{n}_k} = \bar{f}_{\dot{n}_k} - \sum_{\forall \bar{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} - \sum_{\forall m_k} q_{\dot{n}_k, m_k} x_{m_k}^{\dot{n}_k} \tag{4.10c}$$

Note that the adjusted production amount is restricted by the capacity, $f'_{\dot{n}_k} \le v_{\dot{n}_k}$ and $f'_{\bar{n}_k} \le v_{\bar{n}}$. As shown in Eq. (4.10b), a reliable manufacturing plant produces more after production reallocation, $f'_{\bar{n}_k} \ge \bar{f}_{\bar{n}_k}$, which leads to a lower production cost. Consider all manufacturing plants, which do not reach their full-capacity production before production reallocation, the total difference in production cost over $n(\mathbf{t})$ months, Q, can then be formulated as:

$$Q = n(\mathbf{t}) \sum_{\forall \bar{n}_k} \left(\frac{C(v_{\bar{n}_k}^*) + c(v_{\bar{n}_k}^*) \bar{f}_{\bar{n}_k}}{\bar{f}_{\bar{n}_k}} - \frac{C_{\bar{n}_k}(v_{\bar{n}_k}^*) + c(v_{\bar{n}_k}^*) f'_{\bar{n}_k}}{f'_{\bar{n}_k}} \right) f'_{\bar{n}_k} \tag{4.11}$$

Substituting Eq. (4.10b) for $f'_{\bar{n}_k}$ in Eq. (4.11), Eq. (4.11) can be rewritten as:

$$Q = n(\mathbf{t}) \sum_{\forall \bar{n}_k} \frac{C(v_{\bar{n}_k}^*) \sum_{\forall \dot{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k}}{\bar{f}_{\bar{n}_k}} \tag{4.12}$$

where $Q > 0$ reveals that there is always cost savings due to production reallocation and the total benefits are significant with considerable additional production amount, $\sum_{\forall \dot{n}_k} \Delta_{\dot{n}_k, \bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k}$ and the number of months with excessive demands, $n(\mathbf{t})$.

The manufacturer could also decide to stay in status quo and do nothing such that the production allocation among the manufacturing plants is the same as initially proposed; however, revenue loss or customer service downgraded exist due to unsatisfied demands. The penalty cost is introduced to represent the expected loss. The unit-product penalty cost can be estimated based on the unit-product price, P, and a proportion of penalty cost to price, ϕ. The total penalty cost over $n(\mathbf{t})$ months, T, is given by:

$$T = n(\mathbf{t})\phi P \sum_{\forall \dot{n}_k} (\bar{f}_{\dot{n}_k} - f_{\dot{n}_k}) \tag{4.13}$$

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

$$E = n(\mathbf{t})(\sum_{\forall \bar{n}_k} \bar{t}_{\bar{n}_k} \sum_{\forall \dot{n}_k} \Delta_{\dot{n}_k,\bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} + \sum_{\forall m_k} \bar{t}_{m_k} \sum_{\forall \dot{n}_k} o_{\dot{n}_k,m_k} x_{m_k}^{\dot{n}_k}) \tag{4.14}$$

From the discussion to date, the supply chain network adjustment model in response to customer demand expansion can then be determined by solving the following programming model (P2):

$$\text{P2:} \quad \min \quad G + R + T + E - Q \tag{4.15a}$$

$$s.t. \quad \sum_{\dot{n}_k} (\bar{f}_{\dot{n}_k} - f'_{\dot{n}_k}) = \sum_{\dot{n}_k} \sum_{m_k} q_{\dot{n}_k,m_k} x_{m_k}^{\dot{n}_k} + \sum_{\dot{n}_k} \sum_{\bar{n}_k} \Delta_{\dot{n}_k,\bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} \tag{4.15b}$$

$$f'_{\bar{n}_k} = \bar{f}_{\bar{n}_k} + \sum_{\forall \dot{n}_k} \Delta_{\dot{n}_k,\bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} \qquad \forall \bar{n}_k \tag{4.15c}$$

$$f'_{\dot{n}_k} = \bar{f}_{\dot{n}_k} - \sum_{\forall \bar{n}_k} \Delta_{\dot{n}_k,\bar{n}_k} y_{\bar{n}_k}^{\dot{n}_k} - \sum_{\forall m_k} q_{\dot{n}_k,m_k} x_{m_k}^{\dot{n}_k} \qquad \forall \dot{n}_k \tag{4.15d}$$

$$x_{m_k}^{\dot{n}_k} = 0 \text{ or } 1 \qquad \forall \dot{n}_k \quad \forall m_k \tag{4.15e}$$

$$y_{\bar{n}_k}^{\dot{n}_k} = 0 \text{ or } 1 \qquad \forall \dot{n}_k \ \forall \bar{n}_k \tag{4.15f}$$

$$q_{\dot{n}_k,m_k} \text{ and } \Delta_{\dot{n}_k,\bar{n}_k} \geq 0 \text{ and integer} \qquad \forall \dot{n}_k \ \forall \bar{n}_k \ \forall m_k \tag{4.15g}$$

Eq. (4.15a) is the objective function that minimizes total adjustment cost over $n(\mathbf{t})$

months. Eqs. (4.15b), (4.15c) and (4.15d) express the relationships between adjusted and unadjusted production amount of the manufacturing plants. Eqs. (4.15e) and (4.15f) constrain decision variable $x_{m_k}^{\dot{n}_k}$ and $y_{\bar{n}_k}^{\dot{n}_k}$ to be binary. Finally, Eq. (4.15g) defines decision variables $q_{\dot{n}_k, m_k}$ and $\Delta_{\dot{n}_k, \bar{n}_k}$ to be non-negative integers.

4.3.2 Customer demand shrinkage

The potential production amount of the manufacturing plants is significantly reduced due to a decline in customer demand, thereby resulting in production diseconomies. The production cost will be even higher if most manufacturing plants locate in regions with high commodity price index. On the contrary to demand expansion, this study proposes a production adjustment strategy in response to demand shrinkage such that the production could be focused on a few economical manufacturing plants, instead of dispersed production by all manufacturing plants. This study considers costs and benefits associated with production adjustment and formulates a mathematical programming model for determining the optimal production reallocation among the manufacturing plants by minimizing total adjustment cost during months with shrunk demand, given by the sum of allocation cost, difference in production cost, and transportation cost.

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

$$f'_{\ddot{n}_k} = \bar{f}_{\ddot{n}_k} - \sum_{\forall \hat{n}_k} e_{\ddot{n}_k,\hat{n}_k} q_{\hat{n}_k}^{\ddot{n}_k} \tag{4.16a}$$

$$f'_{\hat{n}_k} = \bar{f}_{\hat{n}_k} + \sum_{\forall \ddot{n}_k} e_{\ddot{n}_k,\hat{n}_k} q_{\hat{n}_k}^{\ddot{n}_k} \tag{4.16b}$$

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

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

$$W_{\ddot{n}_k} = n(\mathbf{y}) w_{\ddot{n}_k} \max\{\sum_{\forall \hat{n}_k} e_{\ddot{n}_k,\hat{n}_k} q_{\hat{n}_k}^{\ddot{n}_k}, 0\} \tag{4.17a}$$

$$W_{\hat{n}_k} = n(\mathbf{y}) w_{\hat{n}_k} \max\{\sum_{\forall \ddot{n}_k} e_{\ddot{n}_k,\hat{n}_k} q_{\hat{n}_k}^{\ddot{n}_k}, 0\} \tag{4.17b}$$

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

$$W = O_k + \sum_{\forall \ddot{n}_k} W_{\ddot{n}_k} + \sum_{\forall \hat{n}_k} W_{\hat{n}_k} \tag{4.18}$$

Though the production cost of a manufacturing plant with additional production amount can be 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 manufacturing plants when it comes to production reallocation in response to demand shrinkage. Let X^1 and X^2 represent, respectively, the total difference in production costs for all unreliable manufacturing plants and for all reliable manufacturing plants over $n(\mathbf{y})$ months, namely:

$$X^1 = n(\mathbf{y})\sum_{\ddot{n}_k}\left(\frac{C(v^*_{\ddot{n}_k}) + c(v^*_{\ddot{n}_k})\bar{f}_{\ddot{n}_k}}{\bar{f}_{\ddot{n}_k}} - \frac{C(v^*_{\ddot{n}_k}) + c(v^*_{\ddot{n}_k})f'_{\ddot{n}_k}}{f'_{\ddot{n}_k}}\right)f'_{\ddot{n}_k} \tag{4.19a}$$

$$X^2 = n(\mathbf{y})\sum_{\hat{n}_k}\left(\frac{C(v^*_{\hat{n}_k}) + c(v^*_{\hat{n}_k})\bar{f}_{\hat{n}_k}}{\bar{f}_{\hat{n}_k}} - \frac{C(v^*_{\hat{n}_k}) + c(v^*_{\hat{n}_k})f'_{\hat{n}_k}}{f'_{\hat{n}_k}}\right)f'_{\hat{n}_k} \tag{4.19b}$$

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

$$\begin{aligned} X &= X^1 + X^2 \\ &= n(\mathbf{y})\left(\sum_{\ddot{n}_k}\frac{C_{\ddot{n}_k}(v^*_{\ddot{n}_k})\sum_{\forall\hat{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k}}{\bar{f}_{\ddot{n}_k}(\bar{f}_{\ddot{n}_k} + \sum_{\forall\hat{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k})} - \sum_{\hat{n}_k}\frac{C_{\hat{n}_k}(v^*_{\hat{n}_k})\sum_{\forall\ddot{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k}}{\bar{f}_{\hat{n}_k}(\bar{f}_{\hat{n}_k} - \sum_{\forall\ddot{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k})}\right) \end{aligned} \tag{4.20}$$

If $X>0$, there is a reduction in production cost; otherwise, the reallocation incurs an increased cost.

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

$$E = n(\mathbf{y})\left(\sum_{\forall\ddot{n}_k}\bar{t}_{\ddot{n}_k}\max\{\sum_{\forall\hat{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k}, 0\} + \sum_{\forall\hat{n}_k}\bar{t}_{\hat{n}_k}\max\{\sum_{\forall\ddot{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k}, 0\}\right) \tag{4.21}$$

From the discussions to date, the supply chain network adjustment model in response to demand shrinkage can then be determined by solving the following programming model (P3):

$$\text{P3:}\quad \min \quad W+E-X \tag{4.22a}$$

$$s.t.\quad f'_{\ddot{n}_k}=\bar{f}_{\ddot{n}_k}-\sum_{\forall \hat{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k} \qquad \forall \ddot{n}_k \tag{4.22b}$$

$$f'_{\hat{n}_k}=\bar{f}_{\hat{n}_k}+\sum_{\forall \ddot{n}_k} e_{\ddot{n}_k,\hat{n}_k} q^{\ddot{n}_k}_{\hat{n}_k} \qquad \forall \hat{n}_k \tag{4.22c}$$

$$e_{\ddot{n}_k,\hat{n}_k}\ \text{integer} \qquad \forall \ddot{n}_k\ \ \forall \hat{n}_k \tag{4.22d}$$

$$q^{\ddot{n}_k}_{\hat{n}_k}=0 \text{ or } 1 \qquad \forall \ddot{n}_k\ \ \forall \hat{n}_k \tag{4.22e}$$

Eq. (4.22a) is the objective function that minimizes total adjustment cost over $n(\mathbf{y})$ months. Eqs. (4.22b) and (4.22c) state the relationships between adjusted and unadjusted production amounts for the manufacturing plants. Eq. (4.22d) constrains decision variable $e_{\ddot{n}_k,\hat{n}_k}$ to be an integer and Eq. (4.22e) defines decision variable $q^{\ddot{n}_k}_{\hat{n}_k}$ to be binary.

4.4 Case study

Following the study object in Chapter 3, a numerical example of T-company is also provided to demonstrate the application of the proposed models in this chapter. Base values for the cost-function relevant parameters are given to solve the problem of T-company's supply chain network; however, some operating costs are unavailable, the annual report data in TSMC (2004) are employed to estimate them. In this chapter, total customers are classified according to the geographic distributions, which result in six major customers, namely North America, Europe, Japan, China and Taiwan.

T-company could operate either 12-inch, 8-inch or 6-inch wafer fabrications[1] (FABs) to serve customers, which produce average monthly capacities of 50000, 70000 and 82000 pieces, respectively. In terms of area, one piece of 12-inch wafer is 2.25 times the size of that of 8-inch wafer; furthermore, it is 4 times of 6-inch wafer. To unify, customer demand, capacity and production amount are measured in terms of pieces of 8-inch equivalent (eq.) wafers. Thus the capacities of 12-inch, 8-inch and 6-inch FABs can be revised as 112500, 70000, 45920 8-inch eq. wafers. Regarding manufacturing plants, there are five available locations for T-company to operate various sizes of FABs, namely, Taiwan (Hsinchu), Taiwan (Tainan), Shanghai, USA and Singapore. The monthly capital cost for different-size FAB can be estimated by total expenses for the FAB construction and equipment set up and the maximum usage period of the FAB. Tables 4.1 and 4.2 show, respectively, the forecast values for each of the 5 major customer demands in year 2007 and base production parameters for different-size FAB in different locations.

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[1] Each size FAB can only produce its particular size of wafers, i.e. 12-inch, 8-inch and 6-inch wafers due to the complexity of technology in the manufacturing process of producing wafers.

Table 4.1 Demand forecasts for five major customers in 2007

Customer in different areas	Annual forecasts*	Monthly forecasts*
North America	6165050	513754
China	207774	17315
Japan	508312	42359
Taiwan	333723	27810
Europe	497992	41499
Total	7712851	642737

Source: TSMC Annual Report

* 8-inch eq. wafers

Table 4.2 The base production parameters for different-size FAB in different locations

	6-inch		8-inch		12-inch	
	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	10032	520
USA	2100	212	3085	335	10090	523
Singapore	2030	215	3078	335	10065	525

Table 4.3 Initial results of manufacturing plants and their relationship with customers in different locations

Locations	FAB	Customer in different locations	Monthly flows (8-inch eq. wafer)
Taiwan (Hsinchu)	12-inch	North America	112500
	12-inch	North America	112500
Taiwan (Tainan)	12-inch	China	17315
		Japan	42359
		Taiwan	27810
		Europe	25016
		Total	112500
Shanghai	12-inch	North America	112500
USA	12-inch	North America	112500
Singapore	12-inch	North America	63755
		Europe	16480
		Total	80235

	Locations					
	Taiwan (Hsinchu)		Taiwan (Tainan)	Shanghai	USA	Singapore
FAB	12-inch	12-inch	12-inch	12-inch	12-inch	12-inch
Capacity utilization (Y_{n_k})	100%	100%	100%	100%	100%	71.32%
Proportion of production to totals (θ_{n_k})	0.175	0.175	0.175	0.175	0.175	0.125

Average production cost per 8-inch eq. wafer (US$) 322.85
Average outbound cost per 8-inch eq. wafer (US$) 8.61

This study determines the capacity of manufacturing plants, i.e. the sizes of 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 (Eqs. 3.17(a)-3.17(h)) in Chapter 3. This study employs the simulated annealing (SA) heuristic proposed by Kirkpatrick et al. (1983) to obtain the solutions. The initial solution results are listed in Table 4.3.

As shown in Table 4.3, T-company will operate six 12-inch FABs in the five locations, where there are two 12-inch FABs constructing and operating in Taiwan (Hsinchu) due to economical incentives provided by Taiwan government. To meet the high demands, all FABs, other than the FAB in Singapore, are planned to reach the full-capacity production, i.e. 100% capacity utilization. Though the production amount could efficiently share the high capital cost of constructing a 12-inch FAB in Singapore, the higher production cost hinders the FAB from a 100% capacity utilization as compared to that in other locations. Similarly, the proportion of output from FAB in Singapore is merely 0.125, while that of other FABs is 0.175. The results show that the production allocation among manufacturing plants depends not only on the capacities but also labor, utility and insurance costs with respect to the locations of the manufacturing plants. The average production cost per 8-inch eq. wafer for 12-inch FAB is US$ 322.85. The result shows that the manufacturer can reduce the impact of employing a large-size capacity plant on the total costs, by determining a full-capacity production for that plant. The results also imply that the wafer foundry production exhibits scale economies and a large-size capacity manufacturing plant combined with the full-capacity production yields a lowest cost. Table 4.3 also shows the relationship between the manufacturing plants and customer in different locations and their monthly product flows. Since demands from customers in North America account for the largest demands for T-company among all, most of the FABs solely serve customers from that area.

A hypothetical scenario involving abnormal states is further considered in this case study. We suppose that an explosion in demand from customers in China occur owing to government policy in promoting the usage of integrated circuit identity card, which is a by-product of wafer foundry, from April to July. The data concerning this abnormal state, including occurrence duration, abnormal demand distribution and duration probabilities, is listed in Table 4.4. The expected demand distribution from the abnormal location, China, is also calculated and shown in Table 4.4. The reliabilities of the FABs, considering abnormal states, are listed in Table 4.5.

Due to the proposed full-capacity production of many FABs, demand expansion occurring in China has led these FABs to low reliability, where there are diverse reliability values as shown in Table 4.5. The acceptable utilization levels often reflect the expectations of T-company towards various FABs in different locations. In this study, the maximally acceptable capacity utilization is set to be 1, where there exists a lowest unit-product production cost, while the minimally acceptable capacity utilization is assumed to realize tolerable minimum revenue at the manufacturing plant. There would be a small chance that capacity utilizations fall within a narrow range of acceptable level due to a high expectation towards a manufacturing plant, thereby low reliability values. The above reason explains why the two FABs in Taiwan (Hsinchu) exhibit the lowest reliability values, as listed in Table 4.5. In addition to the acceptable utilization limits, the reliability value also depends on the production allocation among FABs in different location. Since there exists the surplus capacity of the FAB in Singapore, it maintains a good performance under demand expansion.

Table 4.4 Hypothetical data regarding abnormal state on customers in China

Customers in different locations	State occurrence duration and probability	Abnormal month			
		April	May	June	July
		Abnormal demand distributions: $\tilde{f}^t_{n_s,ij} \sim N(\bar{f}^t_{n_s,ij}, \sigma(\tilde{f}^t_{n_s,ij}))$			
China	v^1=3.2, p_1=0.5	N(46818, 2620)	N (45160, 2392)	N(43646, 2125)	N(18346, 2000)
	v^2=3.5, p_2=0.3	N (46818, 2620)	N(43904, 2436)	N(43304, 2330)	N(44674, 2659)
	v^3=4.0, p_3=0.2	N (46818, 2620)	N(44330, 2330)	N(43648, 2536)	N(44297, 2765)
	Expected demand distribution	N (46818, 1615)	N(44617, 1477)	N(43544, 1369)	N(31435,1394)
		Normal demand distributions: $\tilde{f}^t_{n_s} \sim N(\bar{f}^t_{n_s}, \sigma(\tilde{f}^t_{n_s}))$			
Japan	-	N(42100, 3900)	N(42155, 3856)	N(42578, 3912)	N(42321, 3866)
Taiwan	-	N(26955, 2881)	N(27934, 2540)	N(28142, 2725)	N(28568, 2506)
Europe	-	N(41746, 4264)	N(42078, 4000)	N(42256, 4231)	N(42129, 4303)
North America	-	N(513700, 61330)	N(513650, 63954)	N(514018, 58988)	N(513755, 60418)

Table 4.5 Reliability of the manufacturing plants, given abnormal demand from China

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

Furthermore, the fluctuant demands from customers in Japan, Taiwan, Europe and North America can be classified as normal by a comparison between the data in Tables 4.1 and 4.4. This study focuses on the unreliable situation arising from expanded demand from China and proposes an adjustment strategy by solving P2 (Eqs. 4.15(a)-4.15(g)). Suppose there are two available outsourcing firms in the market, which locate in Japan and Korea with limited outsourcing amounts. The set of adjustment months, **t**, is **t**={4, 5, 6, 7}, totaling 4 months. Table 4.6 lists the initial values of parameters in P2. Table 4.7 shows the results and the optimal objective function values with and without network adjustments.

As shown in Table 4.7, the expected production amounts of most FABs exceed their capacities, which are unattainable situations. In this circumstance, T-company could operate the FABs as initially proposed and bears a huge revenue loss of US$ 39936000 in cases no adjustment is performed, as listed in Table 4.7. T-company could also alter and increase the production amount at a reliable FAB, i.e. the FAB in Singapore; meanwhile, consider an outsourcing so that the high demands are satisfied. As shown in Table 4.7, performing an adjustment yields a reduction in total production cost which offsets the derivative additional costs, such as allocation costs, extra material purchase costs and transportation costs, etc. Furthermore, the high penalty cost is avoided. However, there are still unfulfilled demands due to limited outsourcing amounts, remaining a penalty cost of US$ 4161600. By comparing between total costs with and without an adjustment, the production adjustment is shown to benefit T-company.

Table 4.6 The initial values of parameters in P2

Definition	Initial values
Average unit-material purchase cost ($\overline{p}$)	2.5
Unit-product penalty cost (ϕP)	240
Fixed allocation cost (O_k)	350000

		Outsourcing firms in different locations	
	Singapore	Japan	Korea
Unit-product compensation cost ($h_{\bar{n}_k}$)	67	-	-
Unit-product outsourcing cost (o_{m_k})	-	402	405
Average unit-product transportation cost	2.4	2.28	1.5
Limitation of outsourcing production amounts	-	2000	3000

Table 4.7 Initial proposed, expected and adjusted monthly flows, related costs and the results of adjust/do-nothing judgments in response to demand expansion

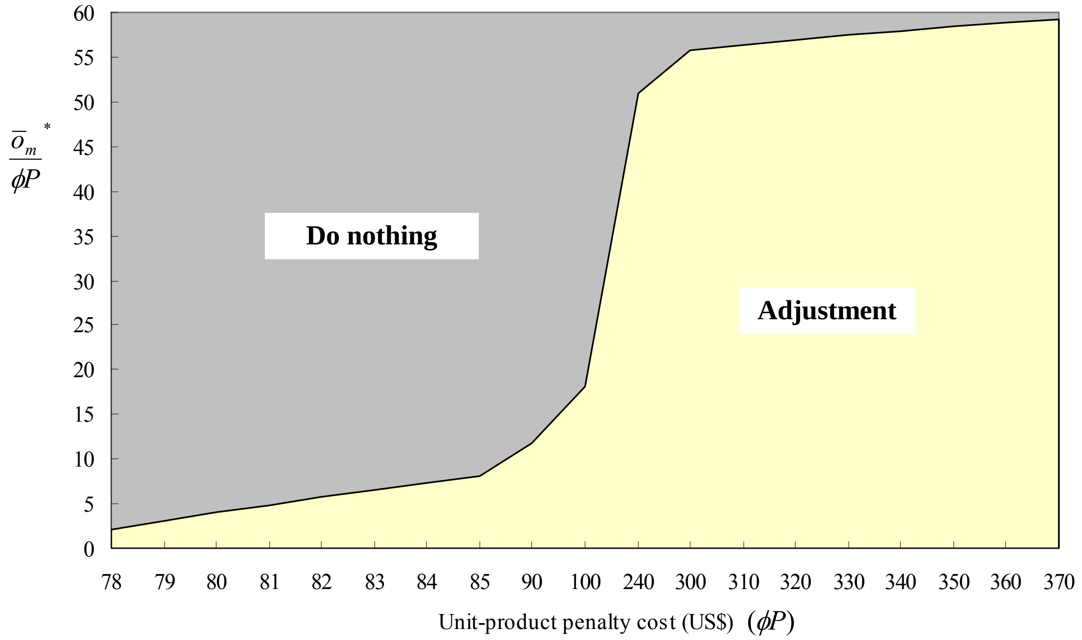
Manufacturing plants			Monthly flows (8-inch eq. wafer)		
				Abnormal months (Apr., May, Jun., Jul.)	
Operated by T-company in different locations	FAB	Customer in different locations	Initial proposed	Expected	Adjusted
Taiwan (Hsinchu)	12-inch	North America	112500	122035	112500
	12-inch	North America	112500	122035	112500
Taiwan (Tainan)	12-inch	China	17315		17315
		Japan	42359		42359
		Taiwan	27810		27810
		Europe	25016		25016
		Total	112500	122035	112500
Shanghai	12-inch	North America	112500	122035	112500
USA	12-inch	North America	112500	122035	112500
Singapore	12-inch	North America	63755		63755
		Europe	16480		16480
		China	-		32265
		Total	80235	87165	112500
Japan*		China	-		2000
Korea*		China	-		3000

Total penalty costs without adjustment (US$)	39936000
Total adjustment costs (US$)	20284256
(+) Allocation costs	17073020
(+) Extra material purchase costs	322652
(−) Differences in production costs	1619000
(+) Penalty costs	4161600
(+) Transportation costs	345984
Judgment	Adjust

*Outsourcing firms

In the case study, T-company gains a high profit margin on wafer foundry; consequently, it will 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 is paid to the outsourcing firms, which include not only production and material purchase costs borne by the outsourcing firm, but also a premium charged. This study further performs sensitivity analysis to investigate how changes in unit-product penalty cost and outsourcing cost affect the judgments of do-nothing and adjustments. Let $\overline{o}_m$ be the average unit-product outsourcing cost and ϕP be the unit-product penalty cost, respectively. Thus, $\frac{\overline{o}_m}{\phi P}$ reflects the ratio of the outsourcing to penalty cost. A large value of $\frac{\overline{o}_m}{\phi P}$ indicates an increased outsourcing cost as compared with the penalty cost, which reflects the situations of product being less value or a high premium charged by outsourcing firms. Figure 4.2 shows the threshold of adjust/do-nothing judgments by comparing between various unit-product outsourcing and penalty costs. The left-hand and right-hand sides of the solid line in Figure 4.2 represent, respectively, the judgments being do-nothing and judgments.

As stated, do-nothing is suggested if the adjustment benefits cannot offset the adjustment cost, where the adjustment benefits are given by the sum of savings in production cost and the exemption from the penalty cost. Given the savings in production cost, a decreased penalty cost leads to a shrunk adjustment benefit; thus, the tendency towards adopting an adjustment is small, as shown in Figure 4.2. Since the penalty cost reflects the market value of the product, the result suggests the manufacturer to stick to the initial proposed decisions and neglect the abnormal demand if the product value is low. On the other hand, it is worth performing an adjustment and continuing to outsource for a high value-added product, even though the payment is expensive, as shown in Figure 4.2.



*Average unit-product outsourcing cost/unit-product penalty cost

Figure 4.2 The threshold of adjust/do-nothing judgments by comparing between unit-product outsourcing and penalty costs

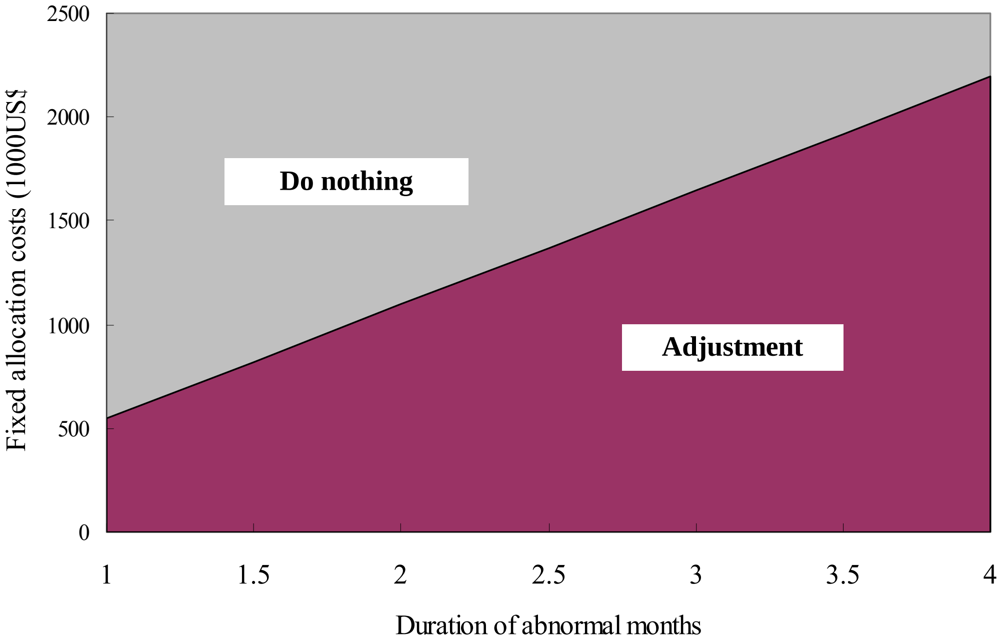


Figure 4.3 The threshold of adjust/do-nothing judgments by comparing between duration of abnormal months and fixed allocation costs

In this study, the fixed allocation cost includes production schedule change costs at the manufacturing plants, contract cost related to outsourcing firms, which is triggered once an adjustments is made. The fixed allocation cost can be also explained as the difficulty in searching qualified outsourcing firms. The fixed allocation cost will be extremely high if there are few available and qualified outsourcing firms, at which the disadvantage may outweigh the advantage of the adjustment. Furthermore, the total adjustment benefits during the execution of an adjustment depend on not only the considerable amounts of abnormal demand but also the duration of the abnormal months. An increased duration of abnormal months accumulates lots of savings in production costs and exempts heavy penalty costs, thereby an adjustment is suggested. The advantage is diminished if the fixed allocation cost is high combined with a short abnormal period. This study further examines how changes in abnormal periods and fixed allocation cost affect the judgments of do-nothing and adjustments. Figure 4.3 shows the threshold of adjust/do-nothing judgments by comparing between the durations of abnormal months and fixed allocation costs, where the left-hand and right-hand sides of the solid line represent, respectively, do-nothing and adjust judgments.

As long as the adjustment benefits outweigh the adjustment costs, the production allocation among the manufacturing plants should be adjusted. In some ways, the adjustment decisions depend on whether the adjusted production amount can effectively share the high fixed allocation cost. As shown in Figure 4.3, the threshold of an adjustment is increased with an increase in the duration of abnormal months, meaning 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 influencing. Furthermore, the results imply the manufacturer could neglect the unreliable situations caused by an abnormal state with a short period, because the accumulated benefits during this short period might not compensate the high allocation costs. The results of the study provide a reference for the manufacturer in the decision making procedures of network planning under demand expansion, as they cope with related benefits, costs and the duration of abnormal months.

Another hypothetical scenario involving abnormal situations, causing demand shrinkage in North America, is considered in the case study. Suppose a sudden declined demand from customers in North America due to the occurrence of finance crisis from January to March. The data concerning this abnormal state, including duration, abnormal demand distributions and duration probabilities, are listed in Table 8. The expected demand distribution from the abnormal location, North America, is calculated and shown in Table 4.8. The reliabilities of the FABs in different locations, considering demand shrinkage, are listed in Table 4.9.

Table 4.8 Hypothetical data regarding abnormal state on customers in North America

Customers in different regions	State occurrence duration and probability	Abnormal month		
		January	February	March
		Abnormal demand distributions: $\tilde{f}^t_{n_s,ij} \sim N(\bar{f}^t_{n_s,ij}, \sigma(\tilde{f}^t_{n_s,ij}))$		
North America	v^1=2.3, p_1=0.2	N(406936, 45631)	N(415972, 41330)	N(459639, 40629)
	v^2=2.6, p_2=0.4	N(417712, 47778)	N(409685, 44852)	N(442366, 38844)
	v^3=3.0, p_3=0.4	N(418964, 45711)	N(409119, 41567)	N(422587, 44753)
	Expected demand distribution	N(416058, 27979)	N(410716, 25820)	N(437909, 25058)
		Normal demand distributions: $\tilde{f}^t_{n_s} \sim N(\bar{f}^t_{n_s}, \sigma(\tilde{f}^t_{n_s}))$		
China	-	N(17189, 2021)	N(17200, 1953)	N(17239, 2563)
Japan	-	N(42366, 2963)	N(42423, 3216)	N(43019, 3623)
Taiwan	-	N(27693, 2896)	N(28131, 2688)	N(27585, 3022)
Europe	-	N(41500, 5626)	N(42015, 6025)	N(42134, 6060)

Table 4.9 Reliability of the manufacturing plants, given abnormal demand from North America

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

Demands from North America account for nearly 80% output of T-company, as shown in Table 4.1. To satisfy the considerable demands, most FABs produce the products to serve customers solely from this location, as shown in Table 4.3. The occurrence of an abnormal event in North America will markedly influence the performance of the FABs in different locations. As shown in Table 4.9, the abnormal demands from North America result in low reliabilities for most FABs, yet the FABs in Shanghai and USA maintain good performance. Though there is no rigid expectation towards the FAB in Singapore, the FAB exhibits a low reliability value as well. This is because the output from the FAB in Singapore merely accounts for a small proportion of total output from T-company, i.e. $\theta_{n_k} = 0.125$, as compared with θ_{n_k} being 0.175 of the others. When total demands declines, the production amount of the FAB in Singapore declines even more than the others. For the sake of simplification, this study focuses on the unreliable situation arising from demand shrinkage in North America and proposes an adjustment strategy by solving P3 (Eqs. 5.22(a)-5.22(e)). The set of adjustment months, **y**, is **y**={1, 2, 3}, totaling 3 months. And the average monthly customer demands during these months is estimated as 513754 8-inch eq. wafers. Table 4.10 shows the initial values of parameters in P3 and Table 4.11 lists the results and the optimal objective function values, respectively.

Table 4.10 The initial values of parameters in P3

Manufacturing plants		Unit-product compensation cost	Average unit-product transportation cost
Location	FAB		
Taiwan (Hsinchu)	12-inch	58	4.9
	12-inch	58	4.9
Taiwan (Tainan)	12-inch	59	5.0
Shanghai	12-inch	64	4.6
USA	12-inch	66	6.3
Singapore	12-inch	67	6.9

Table 4.11 Initial proposed, expected and adjusted monthly flows, related costs and the results of judgments in response to demand shrinkage

Manufacturing plants		Customer in different locations	Monthly flows (8-inch eq. wafer)		
			Initial proposed	Abnormal months (Jan., Feb., Mar.)	
Location	FAB			Expected	Adjusted
Taiwan (Hsinchu)	12-inch	North America	112500		96020
		Europe	-		16480
		Total	112500	96436	112500
	12-inch	North America	112500	96436	112500
Taiwan (Tainan)	12-inch	China	17315		17315
		Japan	42359		42359
		Taiwan	27810		27810
		Europe	25016		25016
		Total	112500	96436	112500
Shanghai	12-inch	North America	112500	96436	112500
USA	12-inch	North America	112500	96436	101060
Singapore	12-inch	North America	63755		-
		Europe	16480		-
		Total	80235	68880	-
Total adjustment costs (US$)				-48978258	
(+) Allocation costs				1588535	
(−) Differences in production costs				50647545	
(+) Transportation costs				80752	
Judgment				Adjust	

We can expect a fall in production amount of all FABs in different locations with demand shrinkage, as shown in Table 4.11, yielding a low capacity utilization and thus high production cost. To avoid the high production cost, an adjustment is considered. As shown in Table 4.11, the adjusted production amounts of the FABs in Taiwan (Hsinchu), Taiwan (Tainan) and Shanghai reach full-capacity production, where these three locations are featured with low capital and variable production costs. And the total production cost of these FABs can be effectively reduced. Though there is an idle FAB locatied in Singapore, which yields a high idle capital cost, savings in total production costs still exists, i.e. US$ 50647545, implying the effects of an idle FAB on total production costs are offset by the reduced production costs. The results imply that centralized production is recommended in response to demand shrinkage and the manufacturing 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 4.11 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. The results imply that partial adjustment is encouraged, rather than a whole network consideration, since the 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 the adjustment benefits T-company in response to the severe fluctuations.

4.5 Summary

This study focuses on reliability evaluation and adjustment of the supply chain network design responding to different demand fluctuations. The reliability evaluation method proposed in this study evaluates the performance of different manufacturing plants on condition that abnormal fluctuations occur. Two mathematical programming models with respect to demand expansion and demand shrinkage are further developed. This study shows how the advantage and disadvantage brought by the adjustment can be carefully considered in advance when solving the network adjustment problems. This study also shows how the duration of an abnormal state and the related allocation costs influence the judgment on whether or not an adjustment should be performed.

This study demonstrates the application of the models by using T-company as an example, which specializes in wafer foundry in semiconductor industry. The result shows that the manufacturer can reduce the impact of employing a large-size capacity plant on the total costs, by realizing economies of scale and determining a full-capacity production for that plant. The results show that when severe demand fluctuations occur, the performance of different manufacturing plants depends on production allocation among and various expectations towards these plants. A full-capacity production plant combined with high expectation often follows a low reliability value under demand expansion, while other plants with surplus capacities maintain a good performance. On the other hand, demand shrinkage will cause a further reduction in a manufacturing 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 in way that total production cost can be reduced and revenue loss is avoided, which outweigh the derivate additional costs. The results also suggest the manufacturers to stick to the initial proposed decisions and neglect the abnormal demand if the product value is low combined with high extra allocation cost. On the other hand, it is worth performing an adjustment and continuing to outsource for a high value-added product, even though the payment is pricey. Furthermore, the threshold of an adjustment is increased with an increased duration of abnormal months, meaning 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 the manufacturer could neglect an abnormal state with a short period, because the accumulated benefits during this short period might not compensate the high allocation costs. The results show that severe demand shrinkage from customers with significance may result in low capacity utilizations for most manufacturing plants, resulting in an overall high production cost. In the circumstance, the result implies a centralized production is necessary, where the determinations of least economical plants being idle and the rests being full-capacity production are suggested. The results also imply that a partial adjustment is always encouraged, rather than a whole network consideration, since the whole network reconstruction will incur extra costs. In sum, the results of the study provide a reference for the manufacturer in the decision making procedures of network planning under demand fluctuations, as they cope with related benefits, costs and the duration of abnormal months.

This study can be extended in several ways. In this study, the demand from different customer is not correlated and is independent from each other. Some abnormal event may occur and even have impacts 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 global financial crisis. Second, the fixed allocation cost reflects the difficulty in searching 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 outsourcing firm selection decisions. Finally, the case study is based on a wafer foundry company in the semiconductor industry, which is characterized with extremely high capital cost. Future study may apply the model to different industry. Such studies would need to examine the impact of capital cost and customer demand on production allocation among manufacturing plants and how the revenue is affected when the demand is not satisfied.

CHAPTER 5
Incorporating dispatching decisions into supply chain network design with production and shipping economies

Chapter 3 focuses on investigating how production economies of scale, customer demand and investment conditions of different locations influence the supply chain network design. This chapter further investigates supply chain network design problems when incorporating inbound and outbound dispatching decisions by considering both production and shipping economies. A nonlinear mixed integer programming (MIP) model is formulated to determine not only decisions as per Chopra and Meindle (2004) but also to determine the optimal shipment size and frequency between supply and demand by minimizing the sum of the average inbound, production and outbound costs. The research scope of this part of study is shown as Figure 5.1.

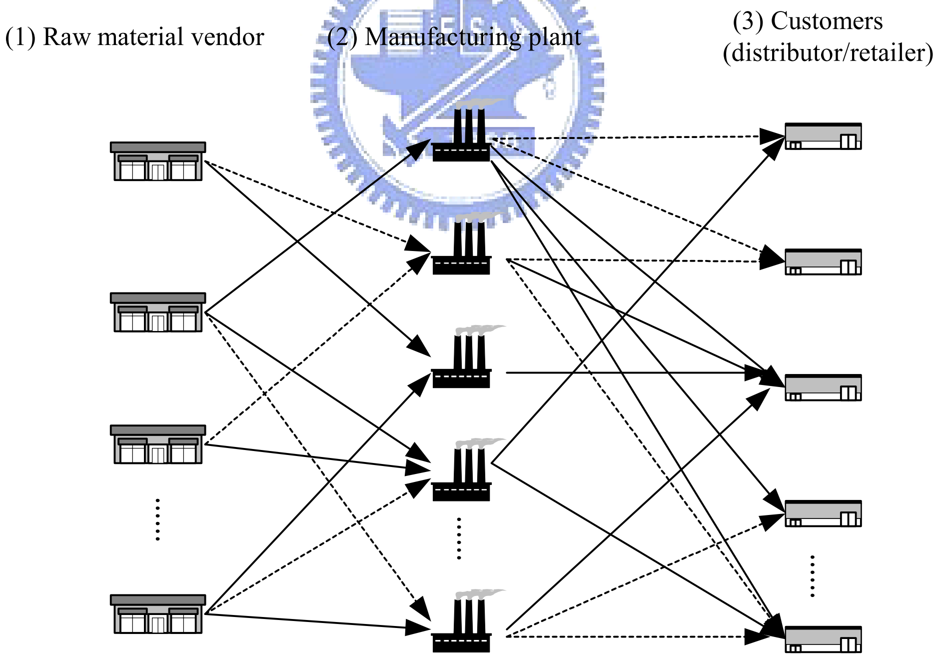


Figure 5.1 The research scope of Chapter 5

5.1 Introduction to the problem

Manufacturing industries are usually characterized with high capital cost. Their economies of scale occur due to specialization. However, increased specialization also requires increased transportation. As a result, the profits may shrink due to the geographical spread of their suppliers and customers, leading to a higher transportation cost. In response to the increased transportation cost, a nearby supplier is usually chosen and assigned to serve manufacturing plants that are close by. However, conflicts arise when the manufacturer aims to pursue a minimized cost rather than a least transportation cost. Manufacturers usually maintain their long-term contractual basis with particular suppliers, in which the total procurement meets the annual or monthly demands. To remain adaptable, the manufacturer has the flexibility of scheduling dispatching decisions, i.e. shipping frequency and shipment size to satisfy their contracted annual or monthly demands. To avoid large inventories on hand, the manufacturer may determine a more frequent shipment; however, this results in a higher shipping cost due to shipping diseconomies. On the other hand, to take advantage of shipping economies, larger shipment sizes are encouraged. This may result in less frequent shipments for an equal total shipment amount, and consequently resulting in a high inventory cost. These inbound and outbound dispatching decisions involve the trade-off between inventory and shipping costs as a result of variations in the total amount of flows between two locations and their spatial distance.

International manufacturing advantages, such as low labor cost and capital subsidies, have provided manufacturers the incentives to operate manufacturing plants in foreign areas. Benefits accrue due to the improved reliability based on the close proximity to suppliers and customers in different regions, which have been investigated and strategically planned. The strategic results of location decisions have a remarkable influence on tactical and operational aspects (Miranda and Garrido, 2004). For example, it is expensive to meet the demand of a key-component for a distant manufacturing plant with a large production amount. That is to say, the inbound and outbound decisions are bound by the capacity and production planning of the manufacturing plants and the demands of customers in different geographical areas.

This chapter aims at designing a supply chain network to incorporate the inbound and outbound dispatching decisions by considering both production economies and shipping economies. This study extends the supply chain design problems from a two-echelon to a multi-echelon problem, with multiple suppliers, manufacturing plant sites and markets, which are not necessarily in the same geographical regions. Specifically, the proposed model applies mixed integer programming (MIP) methods and attempts to minimize the sum of the average inbound, production and outbound costs per unit product, subject to constraints such as satisfying monthly customer demand in various geographical regions, the relationships between supply flows and demand flows within the physical configuration and the monthly production limitation of different size plants. The decision variables are made up of: (1) the capacity and the monthly production amounts at each manufacturing plant, (2) the supplier selection for different manufacturing plants, and the monthly procurement amount from active suppliers to the manufacturing plants, (3) the assignment of each customer market to the manufacturing plants, and (4) inbound and outbound dispatching decisions, i.e. the shipping frequency and shipment size between two locations.

5.2 Model formulation

The formulations in Section 3.1 dealt with the general relationship between the supply flows of all alternatives at different echelons and flows between those alternatives and the alternatives of the lower echelons. In this section, the relationships between the shipping frequency and shipment size and the total monthly amount of flows between two locations are further investigated. Let $z_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ be the average shipment size from key-component supplier $n_{\hat{k}-1}$ to manufacturer plant $n_{\hat{k}}$ during one month. To meet the monthly key-component requirements of a certain manufacturing plant, $n_{\hat{k}}$, the following equation must be satisfied:

$$w_{\hat{k}-1,\hat{k}}\, g(v_{n_{\hat{k}}}) = \sum_{\forall n_{\hat{k}-1}} h_{n_{\hat{k}}}^{n_{\hat{k}-1}} z_{n_{\hat{k}}}^{n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{n_{\hat{k}-1}} \qquad \forall n_{\hat{k}} \qquad (5.1)$$

where $h_{n_{\hat{k}}}^{n_{\hat{k}-1}}$ and $g(v_{n_{\hat{k}}})$ represent the monthly shipping frequency of the key-component from supplier $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$, and the monthly production amount at manufacturing plant $n_{\hat{k}}$, respectively.

In reality, some cost components may not be paid by the manufacturer, e.g. the key-component shipping fee and the inventory cost of the final products at the customers. However, an optimization without these costs tends to transfer the burden of the operation from the manufacturer to the customers and the suppliers, since their costs are not being considered. In other words, the customers and suppliers may be less willing to participate in the operation (Daganzo, 1991). That is to say, a well-coordinated supply chain should integrate their decisions across the supply chain. In this study, the cost components can be defined as including inbound, production and outbound costs. Among these costs, the production cost incorporates both the capital cost and variable production cost. The capital cost includes costs related to the purchasing and installation of related equipments, plant construction, land rent, etc. as well as differences among manufacturing plants due to different locations and size. The variable production cost includes those paid for input factors other than key-component, such as labor, utility and insurance, etc. The production cost of manufacturing plant $n_{\hat{k}}$, $L_{n_{\hat{k}}}$, can be formulated as follows:

$$L_{n_{\hat{k}}} = C(v_{n_{\hat{k}}}) + c(v_{n_{\hat{k}}})g(v_{n_{\hat{k}}}) \qquad \forall n_{\hat{k}} \tag{5.2}$$

where $C(v_{n_{\hat{k}}})$ and $c(v_{n_{\hat{k}}})$ represent, respectively, the capital and variable production costs, depending on capacity $v_{n_{\hat{k}}}$, and the production cost is increasing with an increased monthly production amount; conversely, the average production cost per unit product, $l_{n_{\hat{k}}}$, decreases with it, $l_{n_{\hat{k}}} = \dfrac{C(v_{n_{\hat{k}}})}{g(v_{n_{\hat{k}}})} + c(v_{n_{\hat{k}}})$. The total average production cost per unit product for the manufacturer is obtained as:

$$H_{\hat{k}} = \frac{\sum_{\forall n_{\hat{k}}} l_{n_{\hat{k}}} g(v_{n_{\hat{k}}})}{\sum_{\forall n_{\hat{k}}} g(v_{n_{\hat{k}}})} \tag{5.3}$$

Eq. (5.3) shows that the total average production cost per unit product for the manufacturer depends on the monthly production assignment among multiple manufacturing plants, where the total monthly production amount by all manufacturing plants is restricted to meet the total monthly customer demand.

The inbound cost comprises the key-component purchase cost at the origin prior to shipping and logistics cost and fixed cost. The first two costs, i.e. purchase cost and logistics cost, relate to the movement of the flows from the supplier to the manufacturing plant, and the fixed cost represents all expenses required for the manufacturer to contract with active suppliers. Let's assume that it requires *J* different kinds of key-components to produce and assemble one unit product, and let *j* denote a specific key-component, *j*=1, 2,.., *J* and each supplier produces a specific key-component due to the complexity and specification of production. A specific key-component may be supplied by different suppliers. For the sake of simplicity in this study, the problem regarding the bill of material (BOM) is not discussed. The total fixed cost for the manufacturer depends mainly on the active suppliers and the category of key-components. Let $V_{n_{\hat{k}-1}}$ be the fixed cost for the manufacturer contracting with supplier $n_{\hat{k}-1}$, and let $\gamma^{j}_{n_{\hat{k}-1}}$ be an indicator variable representing whether supplier $n_{\hat{k}-1}$ supplies key-component j. The average fixed cost per unit product is then expressed as:

$$\overline{V}_{\hat{k}-1} = \frac{\sum_{\forall j} \sum_{\forall n_{\hat{k}-1}} V_{n_{\hat{k}-1}} \gamma^{j}_{n_{\hat{k}-1}} I_{n_{\hat{k}-1}}}{\sum_{\forall n_{\hat{k}}} g(v_{n_{\hat{k}}})} \tag{5.4}$$

where $I_{n_{\hat{k}-1}}$ is an indicator representing whether supplier $n_{\hat{k}-1}$ is active for the manufacturer. Regarding the key-component purchase cost at the origin before shipping, the main influences affecting average purchase cost are unit key-component production cost and a reasonable payment ratio determined by the suppliers. The unit purchase cost is low when the monthly purchase amount for that key-component is large. In addition, the shipping frequency may also affect the unit purchase cost. The storage space at the suppliers can be reduced by shipping a large amount at a time, i.e. a less shipping frequency under an equal basis of monthly procurement amount, resulting in a decreased inventory cost for the suppliers. Therefore, the suppliers may encourage large shipment size by offering a price discount. However, this strategy results in an increased inventory level at the manufacturing plants. The total purchase cost of all key-components can be formulated as:

$$\sum_{\forall j} \sum_{\forall n_{\hat{k}-1}} c^{j}_{n_{\hat{k}-1}} (1 - u^{j}_{n_{\hat{k}-1}} (\bar{z}^{j}_{n_{\hat{k}-1}})) \sum_{\forall n_{\hat{k}}} h^{j,n_{\hat{k}-1}}_{n_{\hat{k}}} z^{j,n_{\hat{k}-1}}_{n_{\hat{k}}} \delta^{j,n_{\hat{k}-1}}_{n_{\hat{k}}} \tag{5.5}$$

where $c^{j}_{n_{\hat{k}-1}}$ denotes the basic purchase cost of key-component j without any discount,

$u^j_{n_{\hat{k}-1}}(\bar{z}^j_{n_{\hat{k}-1}})$ is the discount when the average shipment size is $\bar{z}^j_{n_{\hat{k}-1}}$, and $h^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}$ and $z^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}$ represent the average shipping frequency and shipment size of key-component *j* from supplier $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$ for the period of one month, respectively. The average shipment size of key-component *j* from supplier $n_{\hat{k}-1}$ to all manufacturing plants is estimated using the weighting average method based on shipping frequency and shipment size, such as:

$$\bar{z}^j_{n_{\hat{k}-1}} = \frac{\sum_{\forall n_{\hat{k}}} h^{j,n_{\hat{k}-1}}_{n_{\hat{k}}} z^{j,n_{\hat{k}-1}}_{n_{\hat{k}}} \delta^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}}{\sum_{\forall n_{\hat{k}}} h^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}} \qquad \forall n_{\hat{k}-1} \qquad \forall j \tag{5.6}$$

Eq. (5.6) shows that the average shipment size from a specific supplier is increased with an increase in the procurement size and a decrease in the shipping frequency. Furthermore, a large value of average shipping size, $\bar{z}^j_{n_{\hat{k}-1}}$, results in a high discount.

The cost of logistics in this study includes shipping cost and inventory cost. According to Daganzo (1991), shipping costs arise when transporting goods from their origin to their destination, and the total cost is the sum of the costs of each individual shipment. The shipping cost per shipment comprises fixed shipping cost and variable shipping cost. The fixed shipping cost includes things such as driver wages, depreciation cost of the shipping mode, and variable shipping costs include things such as the fuel and handling fees, among others. The shipping cost per shipment for transporting $z^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}$ units of key-component *j* from supplier $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$, i.e. ($n_{\hat{k}-1}, n_{\hat{k}}$), can be shown as $G^{j,n_{\hat{k}-1}}_{n_{\hat{k}}} + t^{j,n_{\hat{k}-1}}_{n_{\hat{k}}} z^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}$, where $t^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}$ represents the variable shipping cost per unit key-component *j* for ($n_{\hat{k}-1}, n_{\hat{k}}$), and $G^{j,n_{\hat{k}-1}}_{n_{\hat{k}}}$ is the fixed shipping cost, respectively. Note that $G_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$ and $t_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$ are different for different combinations of $(n_{\hat{k}-1}, n_{\hat{k}})$ due to the fact that these variables depend on distance. The average shipping cost per unit key-component j for $(n_{\hat{k}-1}, n_{\hat{k}})$ can be computed as $\frac{G_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}}{z_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}} + t_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$, which decreases with the shipment size, $z_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$, in which shipping economies occur because all key-components in a shipment share the fixed shipping cost, $G_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$; however, the extent still depends on the value of $G_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$. The total shipping cost for transporting all the key-components procured from the suppliers to the manufacturing plants by different frequency of shipments can thus be formulated as:

$$\sum_{\forall j}\sum_{\forall n_{\hat{k}}}\sum_{\forall n_{\hat{k}-1}}(G_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} + t_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} z_{n_{\hat{k}}}^{j,n_{\hat{k}-1}})h_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}\delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} \tag{5.7}$$

Eq. (5.7) shows that a frequent shipment may incur high fixed shipping cost, thereby resulting in an increased total shipping cost.

The inventory cost, also called waiting cost or opportunity cost, is the cost associated with the delay of the goods, including the opportunity cost of the capital tied up in storage, any value lost while waiting, etc. The average waiting time can be measured by one half of the headway between two consecutive shipments under a continuous production. The total inventory cost for transporting all key-components procured from the suppliers to the manufacturing plants can be formulated as:

$$\sum_{\forall j}\sum_{\forall n_{\hat{k}}}\sum_{\forall n_{\hat{k}-1}}(\frac{c^j}{2h_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}} z_{n_{\hat{k}}}^{j,n_{\hat{k}-1}})h_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}\delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} \tag{5.8}$$

where c^j represents the inventory cost per unit key-component j per month. Eq. (5.8) shows that a frequent shipment incurs a reduced average waiting time and a small storage space at the manufacturing plants, thereby yielding a decreased total inventory cost. From Eqs. (5.5), (5.7) and (5.8), the sum of the average purchase cost and logistics cost per unit product can be formulated as:

$$\overline{IC} = \frac{1}{\sum_{\forall n_{\hat{k}}} g(v_{n_k})} \sum_{\forall j} \sum_{\forall n_{\hat{k}}} \sum_{\forall n_{\hat{k}-1}} \left(G_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} + \left(c_{n_{\hat{k}-1}}^{j} (1 - u_{n_{\hat{k}-1}}^{j} (\bar{z}_{n_{\hat{k}-1}}^{j}) + t_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} + \frac{c^{j}}{2h_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}} \right) z_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} \right) h_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} \tag{5.9}$$

Eq. (5.9) shows relationships between purchase cost, shipping cost and inventory cost with respect to shipment size and shipping frequency. The purchase cost will be low if the manufacturer adopts a large average shipment size from a certain supplier to multiple manufacturing plants. However, the shipping cost may be affected two ways. The shipping costs may be high since it involves a few suppliers and multiple manufacturing plants, which are spatially dispersed; on the other hand, it may result in a low shipping cost due to shipping a large amount of goods at one time. But, there will be a high inventory cost at the manufacturing plants. Summing up Eqs. (5.4) and (5.9), the average inbound cost per unit product is thus:

$$\overline{IC} + \overline{V} \tag{5.10}$$

The outbound cost reflects the costs incurred from the manufacturing plants to the customers in different regions. As suggested by Chopra (2003), products with a high value are suitable for a delivery network with direct shipping, meaning products that are shipped directly from the manufacturing plant to the customers. Therefore, the outbound cost indicates the logistics cost resulting from distributing the products from the manufacturing plant to the customers in different regions. The formulations of the logistics cost from an outbound point of view are similar to those from the inbound.

Let $z_{n_s}^{n_{\hat{k}}}$ be shipment size of the final product from manufacturing plant $n_{\hat{k}}$ to customer n_s, and let $h_{n_s}^{n_{\hat{k}}}$ be the shipping frequency, respectively. The relationship between the shipment size, shipping frequency and monthly customer demand can be formulated as:

$$g_{n_s} = \sum_{\forall n_{\hat{k}}} h_{n_s}^{n_{\hat{k}}} z_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \qquad \forall n_s \tag{5.11}$$

The total shipping cost for transporting all products from manufacturing plants to customers in different regions can thus be formulated as:

$$\sum_{\forall n_{\hat{k}}} \sum_{\forall n_s} (G_{n_s}^{n_{\hat{k}}} + t_{n_s}^{n_{\hat{k}}} z_{n_s}^{n_{\hat{k}}}) h_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \tag{5.12}$$

Eq. (5.12) shows that the total shipping cost increases with the shipping frequency and thus it is expensive to serve customers who are located far from the manufacturing plants, with frequent shipments and without an economical shipment size. Furthermore, the total inventory cost for transporting all the products from the manufacturing plants to the customers in different regions is:

$$\sum_{\forall n_{\hat{k}}} \sum_{\forall n_s} (\frac{c_s}{2h_{n_s}^{n_{\hat{k}}}} z_{n_s}^{n_{\hat{k}}}) h_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \tag{5.13}$$

where c_s represents the inventory cost per unit product per month. Since the market value for the final product is usually higher than that for all the key-components, $c_s > c^j$. Therefore the total outbound cost can be shown as $\sum_{\forall n_{\hat{k}}} \sum_{\forall n_s} \left(G_{n_s}^{n_{\hat{k}}} + (t_{n_s}^{n_{\hat{k}}} + \frac{c_s}{2h_{n_s}^{n_{\hat{k}}}}) z_{n_s}^{n_{\hat{k}}} \right) h_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}}$. When dividing the total outbound cost by the total monthly amount of the final product between the manufacturing plants and the customers in different regions, the average outbound cost per unit product is obtained as:

$$\overline{OC} = \frac{1}{\sum_{\forall n_{\hat{k}}}\sum_{\forall n_s} h_{n_s}^{n_{\hat{k}}} z_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}}} \sum_{\forall n_{\hat{k}}}\sum_{\forall n_s} \left(G_{n_s}^{n_{\hat{k}}} + (t_{n_s}^{n_{\hat{k}}} + \frac{c_s}{2h_{n_s}^{n_{\hat{k}}}}) z_{n_s}^{n_{\hat{k}}} \right) h_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \tag{5.14}$$

The objective function in this study aims at minimizing the total average cost per unit product of the supply chain. This includes the average inbound cost from the suppliers to the manufacturing plants, the average fixed cost, the average production cost at the manufacturing plants and the average outbound cost from the manufacturing plants to the customers in different regions, which can be shown as:

$$\overline{IC} + \overline{V} + H_{\hat{k}} + \overline{OC} \tag{5.15}$$

From the discussions above, the nonlinear MIP model for the supply chain network design can be formulated as follows.

$$\min \ \overline{IC} + \overline{V} + H_{\hat{k}} + \overline{OC} \tag{5.16a}$$

s.t.

$$w_{\hat{k}-1,\hat{k}}^{j} g(v_{n_{\hat{k}}}) = \sum_{\forall n_{\hat{k}-1}} h_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} z_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} \delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} \qquad \forall n_{\hat{k}} \ \forall j \tag{5.16b}$$

$$g_{n_s} = \sum_{\forall n_{\hat{k}}} h_{n_s}^{n_{\hat{k}}} z_{n_s}^{n_{\hat{k}}} \beta_{n_s}^{n_{\hat{k}}} \qquad \forall n_s \tag{5.16c}$$

$$\sum_{\forall n_{\hat{k}}} g(v_{n_{\hat{k}}}) = \sum_{\forall n_s} g_{n_s} \tag{5.16d}$$

$$g(v_{n_{\hat{k}}}), v_{n_{\hat{k}}} \geq 0 \qquad \forall n_{\hat{k}} \tag{5.16e}$$

$$z_{n_{\hat{k}-1}}^{j,n_{\hat{k}}}, h_{n_{\hat{k}-1}}^{j,n_{\hat{k}}} \geq 0 \qquad \forall n_{\hat{k}} \ \forall n_{\hat{k}-1} \ \forall j \tag{5.16f}$$

$$z_{n_s}^{n_{\hat{k}}}, h_{n_{\hat{k}-1}}^{n_{\hat{k}}} \geq 0 \qquad \forall n_{\hat{k}} \ \forall n_s \tag{5.16g}$$

$$\delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}} = 0 \text{ or } 1 \qquad \forall n_{\hat{k}}\ \forall n_{\hat{k}-1}\ \forall j \qquad (5.16h)$$

$$\beta_{n_s}^{n_{\hat{k}}} = 0 \text{ or } 1 \qquad \forall n_{\hat{k}}\ \ \forall n_s \qquad (5.16i)$$

Eq. (5.16a) is the objective function that minimizes the total average cost per unit product. Eq. (5.16b) states that the combinations of the shipping frequency and shipment size between manufacturing plant $n_{\hat{k}}$ and the suppliers must satisfy the monthly amount of key-component j demanded by manufacturing plant $n_{\hat{k}}$. Eq. (5.16c) constrains that the combinations of the shipping frequency and shipment size from the manufacturing plants to customer n_s must meet the monthly demand of customer n_s. Eq. (5.16d) defines that the total monthly production amount at all manufacturing plants must meet the total monthly customer demand. Eqs. (5.16e), (5.16f) and (5.16g) constrain the decision variables $g(v_{n_{\hat{k}}})$, $v_{n_{\hat{k}}}$, $z_{n_{\hat{k}-1}}^{n_{\hat{k}}}$, $z_{n_s}^{n_{\hat{k}}}$, $h_{n_{\hat{k}-1}}^{n_{\hat{k}}}$ and $h_{n_s}^{n_{\hat{k}}}$ to be nonnegative. Finally, Eqs. (5.16h) and (5.16i) define the decision variable $\delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$ and $\beta_{n_s}^{n_{\hat{k}}}$ to be binary. The decision variables are $g(v_{n_{\hat{k}}})$, $v_{n_{\hat{k}}}$, $z_{n_{\hat{k}-1}}^{j,n_{\hat{k}}}$, $z_{n_s}^{n_{\hat{k}}}$, $h_{n_{\hat{k}-1}}^{j,n_{\hat{k}}}$, $h_{n_s}^{n_{\hat{k}}}$, $\delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$ and $\beta_{n_s}^{n_{\hat{k}}}$. That is, the manufacturer can apply the model to optimally decide the capacity as well as the monthly production amount for all manufacturing plants, the monthly procurement amount of key-component j from suppliers to manufacturing plants, as well as which manufacturing plants should produce how much of the production to serve customers in different regions. In addition, the average shipping frequency and shipment size between different combinations of suppliers to manufacturing plants and between those of manufacturing plants to customers can also be determined. Furthermore, the optimal suppliers can be obtained based on the results of $\delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$ for all manufacturing plants, that is,

$I_{n_{\hat{k}-1}} = \min\{1, \sum_{\forall n_{\hat{k}}} \delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}\}$, where $\delta_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$ represents whether supplier $n_{\hat{k}-1}$ supplies key-component j for manufacturing plant $n_{\hat{k}}$.

5.3 Algorithm

The mathematical programming model in this chapter belongs to the non-linear mixed integer programming models, where the objective function is non-linear. Using the exact algorithm to solve the problem may require a considerable amount of time and can only solve small problems. This study adopted the simulated annealing (SA) heuristic proposed by Kirkpatrick et al. (1983) to solve the optimal problem. In this section, we first develop an approach to generate an initial solution, and then use the SA algorithm to develop the heuristic for improving the initial solution.

5.3.1 Initial solution (*INIT*)

The local improvement methods start from a feasible solution. As for the production, the average production cost per unit product may be reduced if there is a larger amount of production assigned to a manufacturing plant with larger size capacity based on production economies. An incremental rule, in which the production amount is incrementally assigned to manufacturing plants until the total customer demands are satisfied, may be used to investigate the relationship between the assigned production amounts among various manufacturing plants and the total average production cost per unit product. Furthermore, the location problems and the production assignments can be referred to as a long-term strategy in supply chain management. In view of this, the heuristic procedures can be further divided into two phases. In phase one, the optimal capacity and the monthly production amount for the manufacturing plants are determined based on production economies. The solutions obtained in phase one are regarded as inputs in phase two. Then, the optimal suppliers, total amount procured and shipped from the suppliers to the manufacturing plants as well as the optimal shipping frequency are determined by considering the key-components purchase price offered by different suppliers, and the spatial distance between two locations. The optimal decisions for the manufacturing plants and the customers in different regions can be determined in a similar manner. The heuristic based on these data is developed as follows.

Step 1. Randomly determine the capacity size $v_{n_{\hat{k}}}$ for all $n_{\hat{k}}$, where the sum of the capacity of all manufacturing plants must exceed the monthly demand from all customers, $\sum_{\forall n_k} v_{n_k} \ge \sum_{\forall n_s} g_{n_s}$. Set a value, *m*, representing the incremental production amount that can be assigned to the manufacturing plants at each iteration;

Step 2. Assign the monthly production amount for the manufacturing plants;

2.1 Calculate the total average production cost per unit product, $H_{\hat{k}}$, when the incremental production amount, *m*, is assigned to manufacturing plant $n_{\hat{k}}$. Find an optimal manufacturing plant $n_{\hat{k}}^{*}$ with the minimum value of $H_{\hat{k}}$. Assign *m* to manufacturing plant $n_{\hat{k}}^{*}$, and update the monthly production amount for $n_{\hat{k}}^{*}$, $g_{n_{\hat{k}}^{*}} = g_{n_{\hat{k}}^{*}} + m$;

2.2 Calculate the remaining customer demand and the unfulfilled capacity for each of the manufacturing plants. If the demands of all the customers are satisfied, then go to Step 3; else go to Step 2;

Step 3. Employ SA-1 in Section 4.3.2 to obtain the optimal capacity size and the monthly production amount for all the manufacturing plants, i.e. $v_{n_{\hat{k}}}^{*}$ and $g^{*}(v_{n_{\hat{k}}})$ for all $n_{\hat{k}}$;

Step 4. Randomly select q suppliers from all the alternative suppliers;

4.1 Assign suppliers to serve the manufacturing plants as well as the total monthly procurement amount between them according to their spatial distance and their purchase prices offered.

4.2 For each combination of supplier and manufacturing plant, $(n_{\hat{k}-1}, n_{\hat{k}})$ for all $n_{\hat{k}}$ and $n_{\hat{k}-1}$, find the optimal shipping frequency, $h_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$, and shipment size, $z_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$, with a minimum value of $C^j + T^j$, where C^j and T^j represent, respectively, the average inventory cost and average shipping cost per unit key-component j;

Step 5. Employ SA-2 in Section 4.3.2 to obtain the optimal shipping frequency and shipment size between suppliers and manufacturing plants;

Step 6. Assign the manufacturing plants to serve customers in the different regions as well as the monthly product amount between them according to the spatial distance.

6.1 For each combination of the manufacturing plant and customer, $(n_{\hat{k}},\ n_s)$ for all $n_{\hat{k}}$ and n_s, find the optimal shipping frequency, $h_{n_s}^{n_{\hat{k}}}$, and shipment size, $z_{n_s}^{n_{\hat{k}}}$, with a minimum value of $C' + T'$, where C' and T' represent, respectively, the average inventory cost and average shipping cost per unit product and $C' + T'$ can be calculated based on Eq. (17).

Note that since the number of suppliers, q, in Step 4 will influence the final results and this study tests a variety of q to verify a good feasible solution.

5.3.2 Simulated annealing (SA)

Set up the SA algorithm parameters and the stop criteria for the SA and Metropolis algorithms. Then, referring to Heragu and Alfa (1992) and Yan and Luo (1999), the SA algorithms can be described as follows.

SA-1

Step 0. Employ Step 1 to Step 2 in *INIT* to find an initial feasible solution, *S*, and calculate its objective value, z(*S*), where $z = H_{\hat{k}}$.

Step 1. At temperature T_x, implement the Metropolis algorithm;

1.1 Randomly choose a manufacturing plant and alter its capacity from the initial solution. Again apply Step 1 to Step 2 in *INIT* to find a good adjacent solution S' and calculate its objective value, z(S');

1.2 Determine whether the new solution is accepted;

1.2.1 $\Delta = z(S') - z(S)$;

1.2.2 If $\Delta \le 0$, then $S = S'$; else randomly generate a variable y~U(0,0.99). If $\exp^{-\frac{\Delta}{T_x}} \ge y$, then $S = S'$; else go to Step 1;

1.2.3 If the stop criteria of the Metropolis algorithm are satisfied, then go to Step 2; else go to Step 1;

Step 2. If the stop criteria of the SA algorithm are satisfied, then stop; else let $x = x + 1$ and $T_{x+1} = 0.99T_x$, and go to Step 1;

SA-2

Step 0. Employ Step 4 in *INIT* to find an initial feasible solution, *Y*, and calculate its objective value, $z'(Y)$, where $z' = \overline{IC} + \overline{V}$.

Step 1. At temperature T_x, implement the Metropolis algorithm;

1.1 Randomly choose an active supplier and rescind the contract with it and choose another inactive supplier as an active supplier at the current iteration. Apply Step 4 in *INIT* to find a good adjacent solution Y' and calculate its objective value, $z^{'}(Y')$;

1.2 Determine whether the new solution is accepted;

Step 2. If the stop criteria of the SA algorithm are satisfied, then stop; else let $x = x + 1$ and $T_{x+1} = 0.99T_x$, and go to Step 1;

5.4 Case study

This section presents an application of the proposed models, using a numerical example. The object manufacturer is D-company of the USA, and the proposed models are applied to a simplified version of D-company's supply chain network. The aim of the example is to design D-company's supply chain network for one of its specific products, i.e. notebook. For the sake of simplicity, three manufacturing plants were selected as being operated by D-company, a manufacturing plant located in the USA (Texas), one in Malaysia (Penang) and one in China (Xiamen). To serve customers in different regions and gain advantage through outsourcing, a substantial amount of notebooks are manufactured by the original equipment manufacturers (OEM), but are tagged as being D-company's product. Those OEMs include manufacturers in Taiwan and Korea. Regarding customer demand, there are five major customers of D-company around the world, the USA, West Europe, Japan, China and Taiwan. The monthly demands from these customers are 236500, 148500, 110000, 27500 and 27500 notebooks, respectively.

To simplify the study, the thin screen is selected as a key-component because it is more standardized than any of the other components. The basic prices of one unit screen offered by suppliers in Japan, Korea and Taiwan are US$ 240, US$ 234 and US$ 230, respectively. The screen suppliers in Japan, Korea and Taiwan account for the major screen suppliers in the market. The inventory costs per month for one unit screen and notebook are US$ 1.2 and US$ 8, respectively. The base values for the parameters in shipping and production cost functions are shown in Tables 5.1 and 5.2, respectively. The model is programmed using Visual C++, a computer-modeling program developed by Microsoft, based on the developed heuristic algorithm. Table 5.3 summarizes initial solution values.

Table 5.1 Initial values of base shipping parameters.

	Shipping cost			Shipping cost	
Screen	Fixed	Variable	Notebook computer	Fixed	Variable
Japan-USA (Texas)	3500	7.9	USA (Texas)-USA	3500	7.2
Japan-Malaysia (Penang)	3100	3.1	USA (Texas)- West Europe	4000	13.6
Japan- China (Xiamen)	2400	2.4	USA (Texas)-Japan	4000	19.9
Japan- Korea	1000	1.2	USA (Texas)- China	4000	27.1
Japan-Taiwan	2400	2.1	USA (Texas)- Taiwan	4000	30.7
Korea – USA (Texas)	4000	12.4	Malaysia (Penang)- USA	4000	30.2
Korea – Malaysia (Penang)	3100	4.0	Malaysia (Penang)-West Europe	4000	21.7
Korea – China (Xiamen)	1700	1.6	Malaysia (Penang) Japan	3500	7.8
Korea – Korea	500	0.2	Malaysia (Penang)- China	3500	9.1
Korea – Taiwan	1000	1.4	Malaysia (Penang)- Taiwan	3500	7.8
Taiwan – USA (Texas)	4000	12.3	China (Xiamen)- USA	4000	26.7
Taiwan – Malaysia (Penang)	3100	3.1	China (Xiamen)- West Europe	4000	22.5
Taiwan – China (Xiamen)	1000	1.3	China (Xiamen)- Japan	3500	5.9
Taiwan- Korea	1000	1.4	China (Xiamen)- China	1000	1.5
Taiwan – Taiwan	500	0.07	China (Xiamen)- Taiwan	3100	3.3
			Taiwan – USA	4000	30.2
			Taiwan – West Europe	4000	24.3
			Taiwan – Japan	3500	5.2
			Taiwan –China	3500	4.3
			Taiwan – Taiwan	500	0.17
			Korea – USA	4000	23.1
			Korea – West Europe	4000	21.9
			Korea –Japan	3100	2.9
			Korea –China	2400	2.2
			Korea – Taiwan	3100	3.6

Note: Variable shipping cost per unit goods is estimated by the distance between two locations and shipping fee per goods.

Table 5.2 Alternative sizes and base production parameters for manufacturing plants

	USA (Texas)			Malaysia (Penang)			China (Xiamen)			Korea			Taiwan		
Alt.	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
1	63	408	112	62	364	112	130	392	96	100	-	120	150	-	120
2	95	612	112	95	546	112	165	490	96	200	-	112	200	-	104
3	126	816	112	130	728	112	-	-	-	-	-	-	-	-	-

Note: (1) Capacity (10^3 Notebook/month)

(2) Capital cost (10^2 US$)

(3) Variable production cost (US$/notebook)

Table 5.3 Initial results and optimal objective function values

From	To	Frequency[c]	Average shipment size	Monthly flow
Screen supplier	Manufacturing plant			
Japan	Korea	5.5	9091	50000
Korea	USA (Texas)	3	21000	63000
	Malaysia (Penang)	3.5	17714	62000
	China (Xiamen)	6.5	17692	115000
	Korea	3.5	2857	10000
	Total	16.5	15152	250000
Taiwan	China (Xiamen)	5.5	9091	50000
	Taiwan	15.5	12903	200000
	Total	21	11905	250000
Manufacturing plant	Customer			
USA (Texas)	USA	8.5	7412	63000[a, b]
Malaysia (Penang)	West Europe	8	7750	62000[a, b]
China (Xiamen)	West Europe	7.5	8000	60000
	Japan	11	9545	105000
	Total	18.5	8919	165000[a, b]
Korea	Japan	2.5	2000	5000
	China	7	3929	27500
	Taiwan	6	4583	27500
	Total	15.5	3871	60000[a]
Taiwan	USA	13	13346	173500
	West Europe	5	5300	26500
	Total	18	11111	200000[a]

Average production cost per unit note book (US$/notebook)	105.39				
Average cost per unit notebook (US$/notebook)		Inventory	Shipping		Total outbound
		0.45	18.31		18.76
Average cost per unit screen (US$/screen)	Fixed	Purchase	Inventory	Shipping	Total inbound
	0.006	232.72	0.10	2.56	235.39

[a] Monthly production amount of manufacturing plants

[b] Monthly capacity

[b] Shipment/month

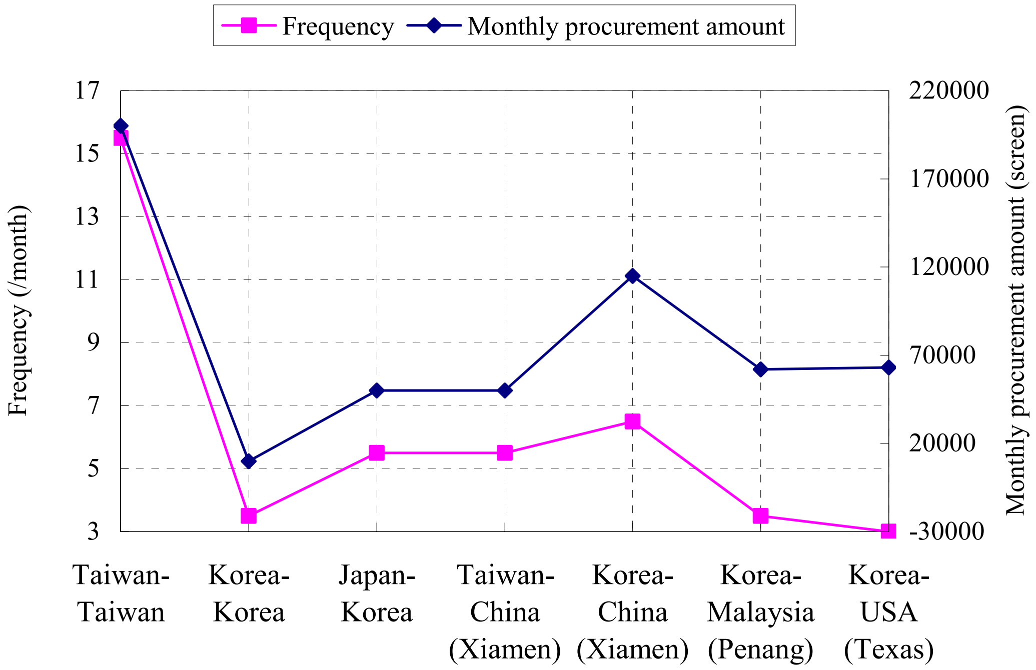
Table 5.3 shows that D-company chooses to operate the largest-size of manufacturing plant capacity in China (Xiamen) among all of its own plants due to its low capital cost and plentiful labor force at a low labor costs. To realize production economies, the monthly production amount for different manufacturing plants operated by D-company reaches full-capacity production, resulting in low production cost, i.e. US$105.39 /notebook. Also shown in Table 5.3, the monthly production amount of the manufacturing plants in Taiwan is the largest among all OEMs and its own manufacturing plants. The results are in accordance with the fact that Taiwan is currently the largest OEM for D-company due not only to its production capability but also its close proximity to the suppliers and customers. The large monthly production amount of the manufacturing plants in both Taiwan and China indicates that the two manufacturing plants require a substantial amount of screens.

The active suppliers for D-company include suppliers in Japan, Korea and Taiwan. That is, D-company procures screens from all suppliers in the market to meet the high demand from all its customers in different regions. Because the price offered by the suppliers in Japan is the highest among all suppliers, to further reduce costs, D-company assigns the suppliers in Japan to serve the manufacturing plants in Korea whose distance are relative short compared to that from manufacturing plants in other regions. Table 5.3 also shows that the suppliers in Korea also serve the manufacturing plants in the same region, but with only a small amount and that the larger amount of screens from Korea are shipped to manufacturing plants in different regions. The results show that as long as the reduced purchase cost can offset the increased shipping cost, the manufacturer can procure a large amount of key-components from a supplier at a low purchase cost and serve many manufacturing plants in different regions. The results also show that the manufacturer aims at pursuing a minimized total cost rather than a minimized logistics cost. Therefore, the assignment of a supplier to serve the closest manufacturing plant is not always applied. The results show that there is a low fixed cost, i.e. US$ 0.006 /screen, because a large amount of procurement shares the high fixed cost. The results imply that the impact of the fixed cost on the optimal suppliers is not significant. The most important factors influencing the optimal suppliers and their procurement size are the purchase prices offered by the different suppliers and their average spatial distance. After determining the optimal suppliers and the procurement assignments of different suppliers to multiple plants, D-company adjusted and determined the optimal shipment size and frequency in its procurement network. The minimized logistics cost is US$ 2.66 /screen, and the shipping cost and the inventory cost are US$ 2.56 /screen and US$ 0.10 /screen, respectively, as shown in Table 5.3.

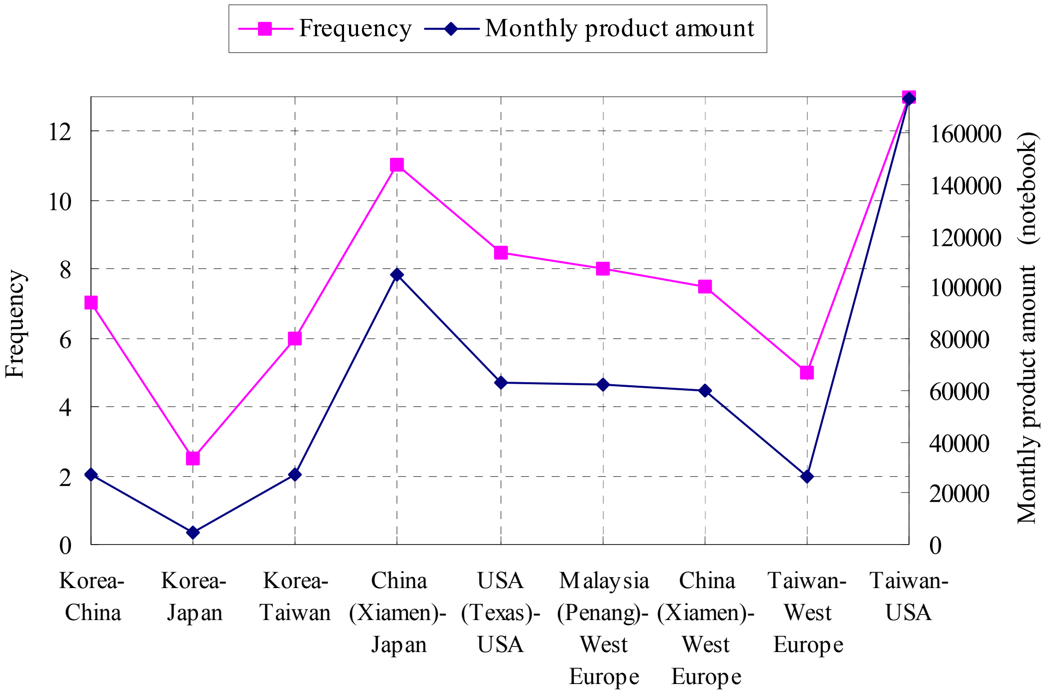
The dispatching decisions are bounded by the monthly production amount of the manufacturing plants and the monthly demands of all customers as well as their locations. As shown in Table 5.3, the customers in Taiwan are served by the manufacturing plants in Korea rather than those in Taiwan. It is likely that assigning the manufacturing plants in Taiwan to serve the distant customers, i.e. USA and West Europe, is more cost effective than assigning other plants to serve these customers, despite the fact that they are so far apart. The results imply that the optimal assignments are determined from an entire network perspective, not from an individual node-to-node basis.

From Table 5.3, the outbound logistics cost is higher than the inbound logistics cost due to a higher inventory and a higher variable shipping costs for notebooks than those for screens. With reference to Table 5.2, there are wide spreads among the manufacturing plants and the customers in different regions. Because of the production economies combined with transportation diseconomies, there is a higher outbound logistics cost. In order to further reduce shipping costs and take advantage of shipping economies, D-company determines various shipping frequency for different combinations of the manufacturing plants and the customers. For example, since the manufacturing plants in Taiwan and customers in West Europe are far apart, the economic shipment size should be as many as 5300 notebooks, while the economic shipment size for two close locations, i.e. Korea and Japan is only 2000 notebooks. Furthermore, since there are only a small amount of notebooks shipped between the manufacturing plant in Taiwan and customers in West Europe, there should be less frequent shipments to maintain the economic shipment size. In other words, only by using a low shipping frequency for two distant locations with a small total monthly amount can the economical shipment size be realized. On the other hand, the monthly demand of customers in the USA is quite large, and there would be a high inventory cost if D-company determines a low service frequency for customers in this region. Since there is a substantial amount of product produced by the manufacturing plants in Taiwan and there is also a manufacturing plant in the USA, D-company assigns manufacturing plants in the USA and Taiwan to serve customers in the USA with high shipping frequencies, i.e. average 8.5 and 13 times per month, as shown in Table 5.3. Furthermore, the average outbound cost per unit notebook is US$ 18.76.

To further investigate impacts of spatial distances and monthly flow between two locations on the optimal shipping frequency as well as the economical shipment size, Figures 5.1(a) and (b) illustrate relationships between the shipping frequency and monthly flow between different combinations of suppliers and manufacturing plants and between those of manufacturing plants and customers in different regions, respectively.



(a) Supplier-manufacturing plant



(b) Manufacturing plant-customer

Figure 5.2 Shipping frequency vs. monthly flow between two locations

From left to right, the X-axis in Figure 5.2 shows that the distances between two locations are increased. As shown in Figure 5.2, there is a similar pattern and a positive relationship between total monthly amount and the shipping frequency between two locations. Also shown in Figure 5.2(a), D-company tends to ship more frequent between Korea and China (Xiamen) than within Korea, where the former has a larger monthly procurement amount, and a longer distance than the latter. Furthermore, the average shipping frequency and monthly procurement amount for the combinations of Taiwan and China (Xiamen) and for those of Japan and Korea are the same, although it is slightly more distant from Taiwan to China (Xiamen) than from Japan to Korea, yet its difference is not as much as the others. These results imply that the total monthly procurement amount between two locations impacts more than their distance does on the optimal shipping frequency. As a result, reducing shipping costs by lowering shipping frequency cannot compensate for the increased inventory cost. As shown in Figure 5.2(a), the shipping frequencies within the same region, Korea and between Korea and Malaysia (Penang) are the same, i.e. average 3.5 times per month, yet there is less monthly procurement amount for the former than that for the latter. Moreover, the relative difference between the monthly procurement amount and the shipping frequency for different combinations of suppliers and manufacturing plants in Figure 5.2(a) is increasing from left to right. These results show that only a small amount of procurement is required for two close locations to maintain the same shipping frequency with that for two distant locations. To realize shipping economies, the more distant two locations are from each other, the larger the monthly procurement amount should be. Furthermore, this study compares the model results with considerations of spatial distance and total monthly product and procurement amount between two locations and the results with an average identical shipping frequency and summarizes the results as Table 5.4.

Table 5.4 Comparisons of results from models with and without considerations of distances and total monthly flow between two locations

	With considerations of distance and total monthly amount	With an average identical shipping frequency[1]
Average inbound cost per unit screen[2]	235.39	235.45
Fixed cost	0.006	0.006
Purchase cost	232.72	232.72
Inventory cost	0.10	0.12
Shipping cost	2.56	2.60
Average outbound cost per unit notebook[2]	18.76	18.83
Inventory cost	0.45	0.50
Shipping cost	18.31	18.33

[1] The optimal shipping frequency between suppliers and manufacturing plants and between manufacturing plants and customers are five and eight times a month, respectively

[2] US$/goods

Table 5.5 Results for supplier-manufacturing plant under a low price strategy of suppliers in Japan

Screen supplier	Manufacturing plant	Frequency*	Average shipment size	Monthly flow
Japan	USA (Texas)	3.5	18000	63000
	Malaysia (Penang)	3.5	17714	62000
	China (Xiamen)	5.5	20909	115000
	Korea	6	10000	60000
	Total	18.5	16216	300000
Taiwan	China (Xiamen)	5.5	9091	50000
	Taiwan	15.5	12903	200000
	Total	21	11905	250000

Average cost per unit screen (US$/screen)	Fixed	Purchase	Inventory	Shipping	Total inbound
	0.004	231.09	0.10	2.23	233.42

*Shipment/month

D-company could alter the combinations of shipping frequency and shipment size according to the spatial distance between two locations to meet the monthly production and monthly customer demand. Table 5.4 shows that there are variations in inbound and outbound logistics costs between model results when considering the spatial distance and monthly amount between two locations and model results without considerations. Because shipping economies are taken into account, the model taking into account spatial distance and total monthly amount has advantages in low logistics cost over the model without considerations, as shown in Table 5.4.

A reduction in purchase price offered by a supplier may influence the total procurement amount from the supplier and how much monthly amount of screens to procure from that supplier for different manufacturing plants, which can further affect the shipping frequency and shipment size for different combinations of the suppliers and the manufacturing plants. This study assumes that the suppliers in Japan offer a further reduction in purchase price, i.e. US$ 232 /screen, if the average shipment size from the suppliers in Japan to multiple manufacturing plants exceeds 100000 screens. Table 5.5 shows results for different combinations of suppliers and manufacturing plants under a price cut by the suppliers in Japan.

To minimize the total average cost in the supply chain, D-company may alter its active suppliers, to meet the same monthly requirements of screens for different manufacturing plants. Under a low price offered by suppliers in Japan, D-company chooses to procure a large amount of screens from these suppliers instead from suppliers in Korea as shown in Table 5.5. In other words, the procurement amount is entirely shifted from suppliers in Korea to suppliers in Japan with a low screen price, but more distant. Although the average distance from suppliers in Japan to the plants is more distant than those from suppliers in Korea to the plants, the logistics cost is not increased. This is because there is a smaller number of combinations of the suppliers and the manufacturing plants in the procurement network and there is also a large monthly procurement amount, which realizes shipping economies and results in a low logistics cost. Table 5.5 also shows that the average inbound cost is US$ 233.42 /screen which is lower than that in Table 5.3.

5.5 Summary

The goal of this study has been to explore the supply chain design network in previous studies from different perspectives. Those studies focused mainly on developing an approximation procedure and compared the efficiency of the proposed heuristic. This study constructed a MIP model to incorporate the inbound and outbound dispatching decisions into a supply chain network design problem. This study explored the impact of different flow values, total amount of flows between two locations as well as their spatial distance on the optimal shipping frequency and size. Moreover, the impacts of the key-component price by suppliers, which are located at different distance to the manufacturing plants, on the optimal supplier selection were also investigated.

The results show that the manufacturer can reduce the production cost by operating a large-scale plant at an area with low capital cost and skilled employees. And to further achieve production economies, the monthly production amount of a large-size capacity manufacturing plant should be characterized with full-capacity production. If there are large demands in the market and the customers are wide spread, the results imply that the manufacturer may corporate with OEM whose production cost is low and is in close proximity to the suppliers and customers.

Regarding the final products from the manufacturing plants to customers in different regions, the results show that there might be a chance for a manufacturing plant to be assigned to serve distant customers, instead of serving customers in the same area, as long as this assignment leads to a minimized total cost for the entire supply chain network. The results imply that optimal assignments are determined from a network perspective, not from an individual node-to-node basis. The results also show that as long as the decreased purchase cost can offset the increased shipping cost, the manufacturer can procure a large amount of key-components from a supplier who offers a low purchase price, and then assign that supplier to serve multiple manufacturing plants in different regions. These results show that the total monthly procurement amount between two locations has a greater impact than their distance on the optimal shipping frequency. The results show that it requires a smaller procurement amount for two close locations than for two distant locations to maintain the same shipping frequency and to realize shipping economies. The more distant two locations are, the larger the monthly procurement amount should be. The results also show the inventory costs for different goods flowing in a supply chain significantly influence the optimal shipping frequency. The results imply that the final product must be shipped with a high frequent shipment strategy, not only to reduce the inventory cost but also to attain a better service by shortening the waiting time. The results also imply that the procurement network ought to be rescheduled if it leads to cost beneficial results. Finally, it was demonstrated that the model results with considerations of spatial distance and total monthly product amount and monthly procurement amount have a better performance in cost savings than the model results with an average identical shipping frequency strategy.

The results of this study may provide a reference for manufacturers when making decisions not only for production allocation, supplier selection for different plants and the assignment of customer markets to plants, but also for the inbound and outbound dispatching decisions, as they cope with spatially and temporal costs. And the participants of the supply chain at different tiers could be better coordinated and more willing to participate in the operation if all costs incurred by the operation are taken into account.

This study can be extended in several ways. Regarding supplier selections, the key-component quality of different suppliers is not considered, and the effects of taxes and duties on the supply chain network design are not discussed in this study. Future studies may incorporate these issues and investigate the impacts of these influences on the optimal supply chain network design. Second, to simplify the study, we only selected the thin screen as the key-component in the case study. Also, the problem of manufacturing requirements planning (MRP), which relies on the bill of material (BOM) of the product, was ignored. Future studies may expand this study's model and address this issue by determining the optimal shipping frequency and shipment size for different key-components. Such studies would need to investigate the relationship between different key-components and the construction and installation phase of the final product, and examine the impact of the manufacturing or assembly procedure of the products on the optimal shipping frequency and shipment size for different key-components.

CHAPTER 6

Optimal delivery service strategy for high-tech product manufacturers with time and spatial dependent demand

This chapter investigates physical distribution problems in the supply chain and attempts to optimize a delivery service strategy for high-tech product manufacturer by considering time-dependent demand, demand-supply interaction and geographical spreads of plants and customers. A mathematical programming model is formulated to solve the optimal number and duration of customers' service cycles and their plant assignments by maximizing profit subject to demand-supply interaction. The research scope of this part of study is shown as Figure 6.1.

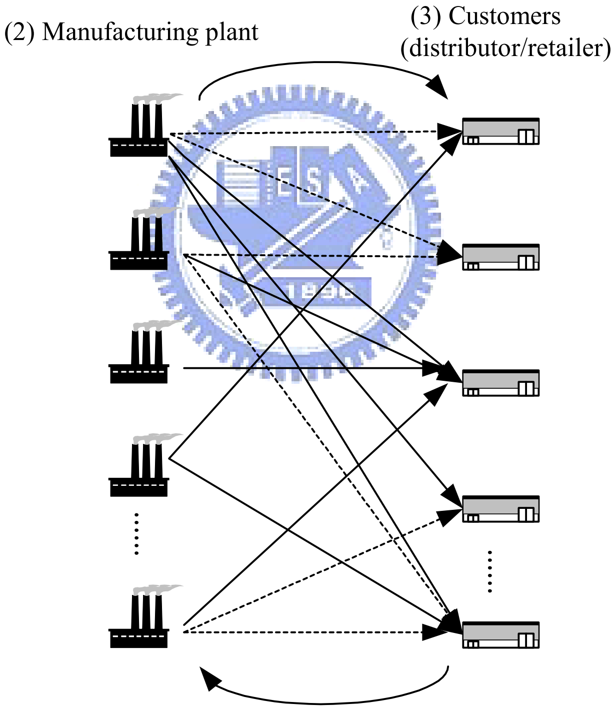


Figure 6.1 The research scope of Chapter 6

6.1 Introduction to the problem

In some ways, high-tech product demands are featured with time-dependent distribution. For example, customer demand for notebooks is increased with the coming of school open seasons and Christmas holidays. To prevent profit loss resulting from stockout, retailers often increase their inventory level, which leads to a high inventory cost. To solve this problem and improve customer service performance, transporting parts in frequent shipments of small lots are encouraged for the manufacturer. However, this strategy makes it expensive to serve and deliver product to customers whose distance are far away and the shipment size is not sufficient to achieve transportation cost economies. Serving all customers via the same service delivery strategy without considering variations in cumulative product amount during each service cycle and geographical spread among plants and customers causes high logistics cost under time-dependent customer demand. In addition, the service delivery strategy has a dramatic influence on customer intention to purchase the manufacturer product, since it determines delay in receiving products. A trade-off relationship exists between logistics cost and customer demand for the manufacturer product. A low average logistics cost could be realized by a least delivery cycle but customer intention to purchase is reduced due to consumers have to wait a long time in receiving their ordered goods. Moreover, the amount of customer demand directly influences the decisions on the capacity and production among of the manufacturing plants. An inferior delivery service strategy may result in high production cost since there is insufficient demand to realize production cost economies. In summary, how to determine an optimal delivery service strategy for high-tech product manufacturer by considering demand-supply interaction, time-dependent demand and wide spread among plants and customers in different regions has become important.

The major issues related to supply chain network design have been extensively examined in numerous studies, including facility location selection, production/shipment quantities, etc (e.g. Arntzen, 1995; Melachrinoudis et al., 2005). Most of studies focused mainly on developing an approximation procedure and compared the efficiency of their proposed heuristics with others. Some studies have addressed the importance of logistics function on supply chain management. These studies aimed at investigating relationships between supply chain performance and logistics network using collected empirical data and by conducting hypothesis (e.g. Leung et al., 2000; Morash and Clinton, 1997; Chopra, 2003). Ambrosino and Scutellà (2005) studied complex distribution network design problems, which involve facility location, warehousing, transportation and inventory decisions. The main contribution of this study is the statement of two kinds of mathematical programming formulations: some formulations aimed at warehouse location-routing problems and other formulations are based on flow variables and constraints. Eskigun et al. (2005) formulated an integer linear programming (ILP) model, which considered the design of an outbound supply chain network for vehicle distribution centers, considering lead times, location of distribution facilities and choice of transportation mode. A Lagrangian heuristic was developed to solve this large-scale integer linear programming model. Results of the scenario analyses indicate that as the lead-time gains importance, the use of trucks increases significantly to deliver the vehicle directly from plants to demand areas in shorter lead-time. The interaction of time and spatial dependent customer demand, logistics cost and production cost related to the delivery service strategy in supply chain network has seldom been investigated.

In another line of research, numerous studies have investigated physical distribution problems using analytical approaches (e.g. Burns et al., 1985; Blumenfeld et al. 1985). This research typically considered shipping problems under inelastic demand and focused on operating issues such as scheduling, routing and configuration of physical distribution. Little research has investigated the influence on logistics and production of time-dependent customer demand, demand-supply interaction and geographical combinations of plants and customers. Hsu and Li (2005) optimized a delivery service strategy for Internet shopping by considering time-dependent demand, demand-supply interaction and consumer socioeconomic characteristics. In their paper, all customers in the market are served by the same fleet and the transportation cost incurred due to spatial distances between plants and customers is neglected.

This study explores how to optimize delivery service strategy for the high-tech product manufacturer in terms of service cycle frequency and duration for different customers in various regions as well as their corresponding plant assignments. In the study, the impacts of time-dependent customer demand and spatial distribution of customers and plants on logistics cost are investigated. Moreover, the impacts of demand-supply interaction on the optimal capacity and production amount of the manufacturing plants are also analyzed. The model applies mathematical programming methods and attempts to maximize the manufacturer profit during the study period subject to demand-supply equality.

6.2 Model formulations

In this section, this study formulates customers demand function and manufacturer total cost when adopting discriminating and uniform service strategies. Specifically, this study employs the analytical method to formulate the supply cost function by considering the time-dependent demand of various customers in different regions. Then, this study formulates and incorporates disaggregate choice models to estimate customer demand for firm’s product. Furthermore, this study develops a mathematical programming model for determining the optimal delivery service cycles for customers in different regions and the assignment of plants to customers during the study period, taking into account time-dependent customer demand, demand-supply interactions. This study further compares the objective value between discriminating and uniform service strategies and suggests that with the higher value for adopting by high-tech product manufacturer.

6.2.1 Discriminating service strategy

The decision maker in this study is a manufacturer who operates multiple high-tech product manufacturing plants around the world and serves customers in different regions. This study proposes discriminating service strategy, which differs from the traditional and typical uniform service strategy where customers at different regions are served according to the same delivery cycle. Periods with considerable demands suggest that frequent and short service cycles are suitable and may stimulate customer demand for products and reduce logistics cost due to shipping economies. Consequently, long service cycles are suggested when demand is very low. In addition, delay in receiving products is determined here as time span between customer purchasing and receiving products, and depends on service cycles and average distances between plants and customers.

Let s and k denote a specific customer and a manufacturing plant, respectively. And let i_s and $T(i_s)$ be a specific service cycle and duration of service cycle i_s for customer s under discriminating service strategy during the study period, $T(i_s) = (t_0(i_s), t_m(i_s))$, i_s=1,2,.., I_s, where I_s is the total service cycle for customer s during the study period and $t_0(i_s)$ and $t_m(i_s)$ represent the start and end times of service cycle i_s, respectively. Note that the unit of $T(i_s)$ is day and $\sum_{i_s=1}^{I_s} T(i_s) = T$, where T denotes the study period. At each $t_m(i_s)$, i_s=1,2,.., I_s, the operator begins to deliver products to customer s accumulated during service cycle i_s. Figure 6.2 illustrates the profile of service cycles, where f_{i_s} represents total demand of customer

s for the manufacturer during service cycle i_s.

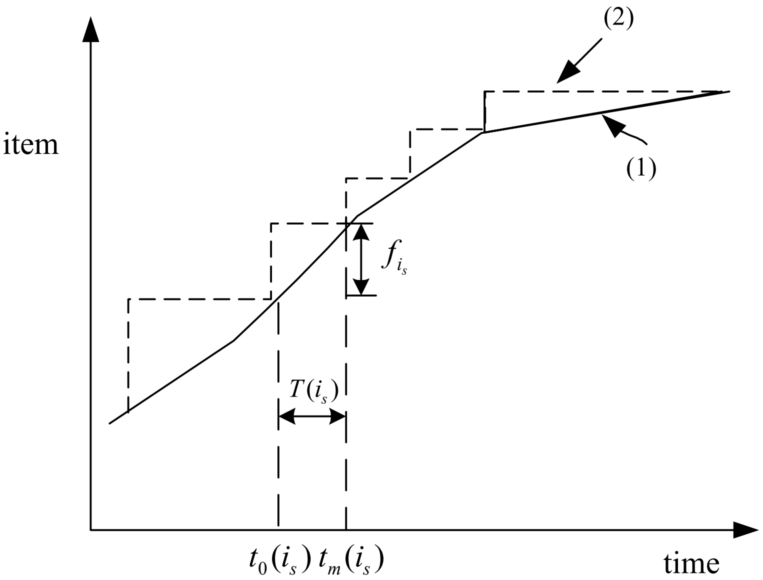


Figure 6.2 The profile of service cycles

Consider two curves in Figure 6.2 representing cumulative number of products, which have been: (1) purchased by customer s; (2) delivered by the manufacture. To satisfy customer demand accumulated during service cycles, the manufacturer must assign which manufacturing plants as well as their production to serve customers in different regions. Let $f_k(i_s)$ represent product amount produced by plant k and deliver to customer s for service cycle i_s. To meet customer demand during service cycle i_s, the following equation must be satisfied:

$$f_{i_s} = \sum_{\forall k} f_k(i_s)\beta_k(i_s) \qquad \forall i_s \quad \forall s \tag{6.1}$$

where $\beta_k(i_s)$ is an indicator variable, if plant k serves and delivers products to customer s for service cycle i_s, then $\beta_k(i_s) = 1$ and the delivered product amount is $f_k(i_s)$; otherwise, $\beta_k(i_s) = 0$. Total product demand of customer s for the manufacturer can then be formulated as:

$$\sum_{i_s=1}^{I_s} f_{i_s} = \sum_{i_s=1}^{I_s}\sum_{\forall k} f_k(i_s)\beta_k(i_s) \qquad \forall s \qquad (6.2)$$

Regarding products delivery, total amount of products delivered by plant *k* during the study period can be obtained by summing up total amount delivering to different customers at various service cycles. Let f_k represent total amount delivered by plant *k* during the study period and f_k can be formulated as:

$$f_k = \sum_{\forall s}\sum_{\forall i_s} f_k(i_s)\beta_k(i_s) \qquad \forall k \qquad (6.3)$$

In this study, the cost components incurring to serve customers in different regions is defined as including production cost and logistics cost. The production cost incorporates both capital and variable production cost. The capital cost includes costs related to the purchasing and installation of related equipments, plant construction, land rents, etc. as well as differences among manufacturing plants due to different locations and size. The variable production cost includes those paid for input factors other than key-component, such as labor, utility and insurance, etc. The monthly production cost of plant *k*, L_k, can be formulated as follows:

$$L_k = C(v_k) + c(v_k)g(v_k) \qquad \forall k \qquad (6.4)$$

where $C(v_k)$ and $c(v_k)$ represent, respectively, the monthly capital and variable production costs of plant *k*, depending on capacity v_k; and $g(v_k)$ denotes monthly production amount of plant *k* and $g(v_k) \le v_k$. Though the monthly production cost is increasing with the increase in monthly production amount, the average production cost per unit product at plant *k* decreases with it, $\frac{L_k}{g(v_k)} = \frac{C(v_k)}{g(v_k)} + c(v_k)$. The total average production cost per unit product for the manufacturer is obtained as:

$$\bar{h} = \frac{\sum_{\forall k} L_k}{\sum_{\forall k} g(v_k)} = \frac{\sum_{\forall k} (C(v_k) + c(v_k) g(v_k))}{\sum_{\forall k} g(v_k)} \tag{6.5}$$

Due to production restriction, some plants will not be assigned to serve customers with large demands where demands might exceed production amount. Let t_k^j be a specific delivery time of plant *k* during the study period, *j*=1, 2,..,m_k, where m_k represents delivery frequency of plant *k*. The duration of a specific delivery cycle of plant *k* is (t_k^{j-1}, t_k^j), *j*=2, 3,..,m_k, which is composed of two consecutive delivery times, and $\sum_{j=2}^{m_k} (t_k^j - t_k^{j-1}) = T$. Assume a continuous production, the relationship between product delivered and production amount can be formulated as:

$$(t_k^{j+1} - t_k^j) \frac{g(v_k)}{30} \geq f_k(i_s) \beta_k(i_s) \tag{6.6}$$

where $\frac{g(v_k)}{30}$ represents daily production amount of plant *k*. The left hand side of Eq. (6.6) express total production amount of plant *k* accumulated during delivery cycle (t_k^j, t_k^{j+1}) and the right hand side is product amount delivered at time t_k^{j+1}. Eq. (6.6) implies that it requires a considerable amount of time for a plant with small capacity producing sufficient products so as to serve customer with large demand, resulting in a long duration of service cycle. A relationship exits among delivery times of a plant, customers the plant served and the service cycles of those customers. For $\beta_k(i_s) = 1$, plant *k* is assigned to serve and satisfy the demand accumulated during service cycle i_s; consequently, the delivery time coincides with the end time of service cycle, $t_k^{j+1} = t_m(i_s)$.

The logistics cost includes transportation cost and inventory cost. The transportation cost involves both fixed and variable transportation costs. Fixed transportation costs are costs attributable to each shipment regardless of shipment volume, while variable transportation costs involve things such as the fuel and handling fees, among others. The transportation cost per shipment for delivering $f_k(i_s)$ units of product from plant k to customer s can be shown as $G_s^k + t_s^k f_k(i_s)$, where G_s^k and t_s^k represent, respectively, the fixed transportation cost and the variable transportation cost, both depending on distance between plant k and customer s. The transportation cost resulting from serving customer s with service cycle i_s can be formulated as:

$$\sum_{\forall k}(G_s^k + t_s^k f_k(i_s))\beta_k(i_s) \qquad \forall s\ \forall i_s \qquad (6.7)$$

Eq. (6.7) shows that assigning more plants to serve a specific customer, i.e. more shipment incurred, leads to a high transportation cost and the cost will be higher if two locations are distant apart. The average transportation cost per unit product during the study period can be shown as:

$$\bar{r} = \frac{1}{\sum_{\forall s}\sum_{i_s=1}^{I_s} f_{i_s}} \sum_{\forall s}\sum_{i_s=1}^{I_s}\sum_{\forall k}(G_s^k + t_s^k f_k(i_s))\beta_k(i_s) \qquad (6.8)$$

Eq. (6.8) shows that the average transportation cost depends not only the assignment of plants to serve customers but also service cycles for customers during the study period. A frequent shipment may incur high fixed transportation cost, thereby leading to an increased transportation cost.

The inventory cost, also called waiting cost or opportunity cost, is the cost associated with delay of goods, including the opportunity cost tied up in storage, any value lost while waiting, etc. The delivery and service cycles influence inventory level of both customers and the manufacturer. A frequent delivery strategy may lead to a reduced inventory cost for the manufacturer since it involves a small storage space at plants. In addition, this strategy may serve customer with a reduced waiting time for products, thereby a high satisfaction for the manufacturer. However, the benefits brought by frequent delivery in inventory cost will be offset by the increased transportation cost if product amount delivered per shipment fall short of economical shipment size. Since the goal of delivery and service strategies is to reduce logistics cost and satisfy customer needs, the number and duration of service cycles should be determined in accordance with the time-dependent demand of customers in various regions. To avoid double counting, inventory cost discussed here reflects the relationship between the production and delivery cycles of plants. The average waiting time can be measured by one half of the headway between two consecutive shipments under a continuous production. The inventory cost of plant k during the study period can then be formulated as follows:

$$\sum_{j=1}^{m_k}\frac{1}{2}(t_k^j - t_k^{j-1})gf_k(i_s)\beta_k(i_s) \qquad \forall k \tag{6.9}$$

where g represents the inventory cost per unit product per month. Eq. (6.9) shows that a frequent shipment, short duration of service cycles, leads to a decreased inventory cost. The average inventory cost per unit product during the study period can be shown as:

$$\bar{d} = \frac{1}{\sum_{\forall s}\sum_{i_s=1}^{I_s} f_{i_s}} \sum_{j=1}^{m_k}\frac{1}{2}(t_k^j - t_k^{j-1})gf_k(i_s)\beta_k(i_s) \tag{6.10}$$

Eqs. (6.8) and (6.10) show the relationship between transportation cost and inventory cost with respect to shipment size, delivery frequency and the assignment of plants to customers during the study period. There are two sided effects on transportation cost if the manufacturer assigns frequent delivery cycles to serve customers whose periods are featured with large demand. The average transportation cost would be low only if large shipment could be accumulated and shipping economies exists. Otherwise, frequent shipment leads to high transportation cost because of large fixed transportation cost. The transportation cost will be even higher if customers are served by multiple plants whose distance are far apart. The above perspective also implies that long service cycles are suitable when demand is very low. From Eqs. (6.5), (6.8) and (6.10), the total average cost per unit product are:

$$\bar{h} + \bar{r} + \bar{d} \tag{6.11}$$

The discussions so far demonstrate how service cycles and the assignments of plants to customers influence manufacturer's cost. This study further deals with dynamic and time-sensitive customer demand, and investigate how service cycle durations affects customer demand for manufacturer products. This study applies a binary logit model to determine customer choice probabilities for manufacturer products. Let o be the objective manufacturer and r be a representative of other manufacturers in the market. Let $U_x(s,t)$ represent the total utility of customer *s* who purchase products from manufacturer *x* at time *t*, $U_x(s,t) = V_x(s,t) + \varepsilon_x$, *x*=*o*, *r*, where $V_x(s,t)$ and ε_x represent, respectively, the deterministic component and unobservable or immeasurable factors of $U_x(s,t)$. Supposing that all ε_x are independent and identically distributed as a Gumbel distribution, then customer choice probability of purchasing products from manufacturer *o* at time *t*, $\Pr_o(s,t)$, can be estimated as:

$$\Pr_o(s,t) = \frac{e^{U_o(s,t)-U_r(s,t)}}{1+e^{U_o(s,t)-U_r(s,t)}} \tag{6.12}$$

The difference in utility values of customer purchasing from manufacturer *o* and *r*, $v(s,t) = U_o(s,t) - U_r(s,t)$, determines the choice probability, which can be rewritten as $\Pr_o(s,t) = \dfrac{e^{v(s,t)}}{1+e^{v(s,t)}}$. The utility function $v(s,t)$ discussed here has the following specifications:

$$v(s,t) = \beta_0 + \beta_1 p_o + \beta_2 T_o^{s,t} - \beta_1 p_r - \beta_2 T_r^{s,t} \tag{6.13}$$

where p_o and p_r denote product prices of manufacturer *o* and *r* ; $T_o^{s,t}$ and $T_r^{s,t}$ represent delay in receiving products from manufacturer *o* and *r* at time *t*, respectively. β_0 reflects alternative specific constant and β_1 and β_2 are parameters, respectively.

Delay in receiving products depends on service cycles and average transportation time to customers in different regions. The demand of products during a specific service cycle may be received separately since it may involve various plants serve a specific customer, thereby resulting in an inconsistent product receiving time. Let H_{i_s} be the average transportation time from plants to customer *s*, and H_{i_s} can be represented as:

$$H_{i_s} = \frac{\sum_{\forall k} T_s^k \beta_k(i_s)}{\sum_{\forall k} \beta_k(i_s)} \tag{6.14}$$

where T_s^k represents average transportation time from locations of plant *k* to customer *s*, depending on their spatial distance and shipping mode and $\sum_{\forall k} \beta_k(i_s)$ reflects plant number. Eq. (6.14) shows that a close proximity of customers and plants results in less transportation time. Consequently, delay in receiving products when customer *s* purchases products from manufacturer *o* at time *t* can then be given by:

$$T_o^{s,t} = t_m(i_s) + H_{i_s} - t \qquad t \in (t_0(i_s), t_m(i_s)) \tag{6.15}$$

From Eq. (6.15), delay in receiving products depends not only on transportation time, but also on customer purchasing time. As customer purchasing time approaches dispatching date, the customer perceives a decreased delay in receiving products.

Normally, total customer demand for manufacturer product can be estimated by multiplying customer demand for products and the choice probability of purchasing products from the manufacturer. Assume total demand for products of customer *s* at time *t* is exogenous and denoted as q_s^t, then the time-dependent demand for manufacturer product of customer *s* at time *t* can be expressed as $q_s^t \Pr_o(s,t)$. Furthermore, total demand for manufacturer product of customer *s* during service cycle

i_s, f_{i_s}, can be represented as:

$$f_{i_s} = \sum_{t=t_0(i_s)}^{t_m(i_s)} q_s^t \Pr_o(s,t) \qquad \forall s \ \forall i_s \qquad (6.16)$$

Eq. (6.16) shows that total demand for manufacturer product increases with increasing value of choice probability of purchasing products from the manufacturer, $\Pr_o(s,t)$. In addition to the choice probability, total demand accumulated during service cycle i_s will be large if the service cycle is periods with numerous demands for products. Total customer demand for manufacturer product during the study period can be expressed as $\sum_{\forall s}\sum_{\forall i_s} f_{i_s}$.

Profit throughout the entire study period can be calculated based on the product price, average cost per unit product, average key-component purchase cost per item and total customer demand for manufacturer product, such as

$$\tau = (p_o - \bar{l} - (\bar{h} + \bar{r} + \bar{d}))\sum_{\forall s}\sum_{\forall i_s} f_{i_s} \qquad (6.17)$$

where $\bar{l}$ and τ represent the average key-component purchase cost per item and profit throughout the study period, respectively. A increased profit can be realized be an increased customer demand and a decreased cost per unit product.

However, interactive relationships exist among profit, average cost per unit product and total customer demand for manufacturer product. Customer demand will increase with a frequent service cycle since it involves a less delay in receiving products, which further results in a reduced production cost; conversely, logistics cost might increase due to frequent shipments without transportation cost economies. On the other hand, the cost saving by assigning least service cycles will be offset if customer demand is little and customer intention to purchase manufacturer product shrinks combined. The above least service cycle strategy also yields a high production cost since there is insufficient demand to realize the production cost economies. Only if a delivery and service strategy with considerations of time-dependent customer demand, demand-supply interaction and spatial spreads of plants and customers, will maximized profit be realized.

A nonlinear mixed integer programming model is formulated here for determining the optimal number and duration of service cycles for different customers and their plant assignment by maximizing profit subject to demand-supply equality. From Eqs. (6.11), (6.16) and (6.17) and the discussions above, the nonlinear MIP problem is as follows:

$$\max \quad \tau = (p_o - \bar{l} - (\bar{h} + \bar{r} + \bar{d}))\sum_{\forall s}\sum_{\forall i_s} f_{i_s} \tag{6.18a}$$

s.t.

$$f_{i_s} = \sum_{\forall k} f_k(i_s)\beta_k(i_s) \qquad \forall s \ \ \forall i_s \tag{6.18b}$$

$$f_{i_s} = \sum_{t=t_0(i_s)}^{t_m(i_s)} q_s^t \Pr_o(s,t) \qquad \forall s \ \ \forall i_s \tag{6.18c}$$

$$(t_k^{j+1} - t_k^j)\frac{g(v_k)}{30} \geq f_k(i_s)\beta_k(i_s) \qquad \forall k \tag{6.18d}$$

$$\sum_{i_s=1}^{I_s}(t_m(i_s) - t_0(i_s)) = T \qquad \forall s \tag{6.18e}$$

$$g(v_k), v_k \geq 0 \qquad \forall k \tag{6.18f}$$

$$t_m(i_s), t_0(i_s) \geq 0 \qquad \forall i_s \ \ \forall s \tag{6.18g}$$

$$f_k(i_s) \geq 0 \qquad \forall k \ \ \forall i_s \ \ \forall i_s \tag{6.18h}$$

$$\beta_k(i_s) = 0 \text{ or } 1 \qquad \forall k \ \ \forall i_s \ \ \forall i_s \tag{6.18i}$$

Eq. (6.18a) represents the objective function that maximizes profit throughout the study period. Eq. (6.18b) states relationships among customer demand, product delivered by plants and plant assignment with respective to delivery cycles. Eq. (6.18c) defines customer demand for manufacturer product during service cycles. Eq. (6.18d) constrains the relationship between product delivered and production amount by plants. Eq. (6.18e) constrains that the summation of the duration of all service cycle for a customer must be equal to the study period. Eqs. (6.18f), (6.18g) and (6.18h) define the decision variables $g(v_k), v_k$, $t_m(i_s), t_0(i_s)$ and $f_k(i_s)$ to be nonnegative. Eq. (6.18i) defines the decision variable $\beta_k(i_s)$ to be binary. The decision variables are $g(v_k), v_k$, $t_m(i_s), t_0(i_s)$, $f_k(i_s)$ and $\beta_k(i_s)$. That is, the high-tech product manufacturer can apply the model to optimally decide the capacity as well as the monthly production amount for all manufacturing plants, which manufacturing plants should produce and deliver how much of the production to serve customer in different regions. Moreover, the optimal duration and service cycles for different combinations of the manufacturing plants and customers can also be determined.

6.2.2 Uniform service strategy

Regarding uniform service strategy, customers from the same region are served according to the same delivery cycles. Let $I_s^{'}$ represent the service cycle for customer s during the study periods with uniform service strategy. The duration of each service cycle is $\frac{T}{I_s^{'}}$ and a specific service cycle is denoted using $T(i_s^{'})$, namely, $T(i_s^{'}) = (t_0(i_s^{'}), t_0(i_s^{'}) + \frac{T}{I_s^{'}})$, $i_s^{'}$=1, 2,…, $I_s^{'}$, where $t_0(i_s^{'})$ and $t_0(i_s^{'}) + \frac{T}{I_s^{'}}$ represent the start and end times of service cycle $i_s^{'}$ assuming a uniform service strategy, respectively. And the total average cost per unit product is formulated in a manner similar to that for discriminating service strategy, as mentioned in Section 6.2.1, namely:

$$\bar{h}' + \bar{r}' + \bar{d}'$$

$$= \frac{\sum_{\forall k}(C(v_k') + c(v_k')g(v_k'))}{\sum_{\forall k} g(v_k')} + \frac{1}{\sum_{\forall s}\sum_{i_s'=1}^{I_s'} f_{i_s'}} \sum_{\forall s}\sum_{i_s'=1}^{I_s'}\sum_{\forall k}(G_s^k + t_s^k f_k(i_s'))\beta_k(i_s')$$

$$+ \frac{1}{\sum_{\forall s}\sum_{i_s'=1}^{I_s'} f_{i_s'}} \sum_{j'=1}^{m_k'} \frac{1}{2}(t_k^{j'} - t_k^{j'-1}) g f_k(i_s')\beta_k(i_s') \tag{6.19}$$

Total demand for manufacturer product of customer s during service cycle i_s' for uniform service strategy, $f_{i_s'}$, can be represented as:

$$f_{i_s'} = \sum_{t=t_0(i_s')}^{t_0(i_s')+\frac{T}{I's}} q_s^t \Pr_o(s,t) \qquad \forall s\ \forall i_s' \tag{6.20}$$

Additionally, profit throughout the entire study period for uniform service strategy, τ', can be formulated as:

$$\tau' = (p_o - \bar{l} - (\bar{h}' + \bar{r}' + \bar{d}')) \sum_{\forall s}\sum_{\forall i_s'} f_{i_s'} \tag{6.21}$$

The mathematical programming problem for determining the optimal number of service cycles for different customers assuming a uniform service strategy can be formulated in a manner similar to that assuming a discriminating service strategy ((6.18a)-(6.18i)). Furthermore, this study compares the values of profit obtained by the manufacturer from discriminating and uniform service strategies using $\frac{\tau - \tau'}{\tau} \times 100\%$, where τ and τ' represent profit using discriminating and uniform service strategies, respectively. If $\frac{\tau - \tau'}{\tau} \times 100\%$ is positive, discriminating service strategy is suggested; otherwise, uniform service strategy is recommended.

6.3 Case study

This section presents an application of the proposed models, using a numerical example. The object manufacturer is D-company of the USA who manufactures and assembles different key-components into notebooks as the product and delivers the final product to the customers in different regions. Total customers are classified according to the geographic distributions, which result in five major customers, such as USA, West Europe, Japan, China and Taiwan. This study assumes three months, from September to November, as the study period, with the unit of time for study being one day. For the sake of simplicity, three locations are available for D-company in operating the manufacturing plants, that is, the USA (Texas), Malaysia (Penang) and China (Xiamen). The capacity cost and variable production cost of these locations are different due to the various commodity indexes in different regions. In addition, to satisfy the substantial demand and gain advantage through outsourcing, the original equipment manufacturers (OEMs) in Taiwan and Korea are also available and the notebooks from these OEMs are tagged as being D-company's product. The average price and key-component purchase cost per unit notebook are US$ 1330 and US$ 1150, respectively. The base values for the parameters in production and transportation cost functions are shown in Tables 6.1, 6.2 and 6.3, respectively. Table 6.1 lists the initial transportation parameters with respect to different combinations of the manufacturing plants and customers, including fixed transportation cost and variable transportation cost, while Table 6.2 lists the average transportation time from locations of the manufacturing plants to customers. Table 6.3 shows the alternative sizes of capacity and base production parameters for manufacturing plants in different regions. As shown in Table 6.3, there are three different alternative sizes of capacity for the manufacturing plants in the USA (Texas) and Malaysia (Penang) and two alternatives for the manufacturing plant in China (Xiamen). The unit-product production costs paid for the outsourcing manufacturers are different with the outsourcing amount, in a way that the outsourcing manufacturers encourage large size outsourcing with preferential price. Figure 6.3 illustrates time-dependent demand from the five major customers during the study period.

Table 6.1 The initial values of base transportation parameters

	Customers									
	USA		West Europe		Japan		China		Taiwan	
Plants	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
USA (Texas)	6600	7.2	8000	13.6	8000	19.9	8000	27.1	8000	30.7
Malaysia	8000	30.2	8000	21.7	7000	7.8	7000	9.1	7000	7.8
China (Xiamen)	8000	26.7	8000	22.5	7000	5.9	2000	1.5	6200	3.3
Taiwan	8000	30.2	8000	24.3	7000	5.2	7000	4.3	1000	0.17
Korea	8000	23.1	8000	21.9	6200	2.9	4800	2.2	6200	3.6

Note: (1): fixed transportation cost; (2): variable transportation cost

Table 6.2 The initial transportation time between locations of the manufacturing plants and customers

	Customers				
Plants	USA	West Europe	Japan	China	Taiwan
USA (Texas)	3.17	11.17	14.67	16.42	17.17
Malaysia	9.50	12.58	7.17	5.33	4.75
China (Xiamen)	15.50	16.00	4.00	1.33	4.00
Taiwan	13.00	15.00	3.17	4.83	0.30
Korea	18.00	14.00	2.17	1.58	2.42

Unit: hour

Table 6.3 The alternative sizes and base production parameters for the manufacturing plants

	USA (Texas)			Malaysia (Penang)			China (Xiamen)			Taiwan			Korea		
Alt.	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
1	63	408	112	62	364	112	130	392	96	150	-	114	100	-	115
2	95	612	112	93	546	112	165	490	96	200	-	110	200	-	113
3	126	816	112	124	728	112	-	-	-	-	-	-	-	-	-

Note: (1) Capacity (10^3 Notebook/month)
(2) Capital cost (10^3 US\$)
(3) Variable production cost (US\$/notebook)

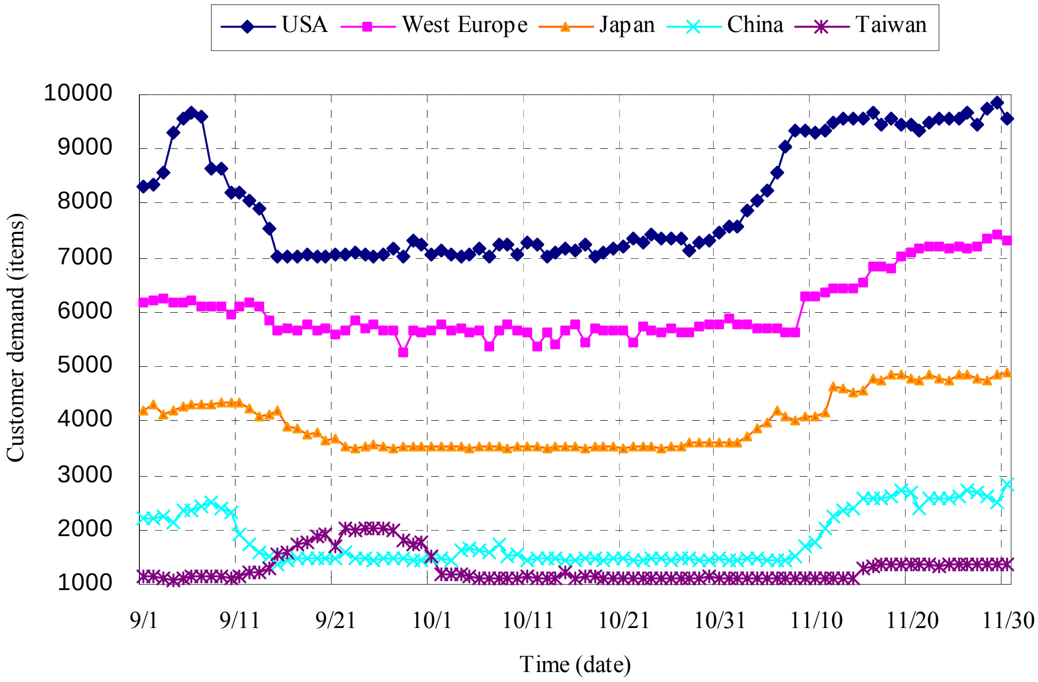


Figure 6.3 Time-dependent customer demands for notebooks from the five major customers during the study period

From Figure 6.3, demands from the customers exhibit various time-dependent patterns and demands from the customers in the USA and in Taiwan are featured with the highest and lowest. And the demand for notebooks during the study period totals 1927983 notebooks, averaging 642661 per month. Generally, customer demands for notebooks are relatively low in October and peak during September and November due to the school open season and the coming of Christmas holidays. Assume D-company ignores the impact of demand-supply interaction on the decisions in the capacity and production allocation among the manufacturing plants. Table 6.4 shows the initial results from models without considering the impact of demand-supply interaction on production decisions.

Table 6.4 The initial results from models without considering the impact of demand-supply interaction on production decisions

Plant	Customer	Average frequency[a] Sep.	Oct.	Nov.	Total product flow	Average monthly flow
USA (Texas)	USA	11	11	15	195401	65134[b]
Malaysia (Penang)	Europe	8	6	7	162318	54106
	Japan	4	3	5	20651	6884
	Total	12	9	12	182969	60990[b]
China (Xiamen)	USA	2	2	3	107929	35976
	Europe	6	5	6	108110	36037
	Total	8	7	9	216039	72013[b]
Korea	USA	2	2	2	32036	10679[b]
Taiwan	Japan	13	10	14	162839	54280
	China	10	7	9	84120	28040
	Taiwan	24	31	18	62150	20717
	Total	47	48	41	309109	103037[b]

Total Profit (US$)	53148823
Total customer demand (item)	935554
Average logistics cost (US$/item)	15.04
Average inventory cost (US$/item)	0.49
Average transportation cost (US$/item)	14.55
Average production cost (US$/item)	108.33

[a] Shipment/month

[b] Average monthly production amount

As shown in Table 6.4, D-company will operate three manufacturing plants in different locations and the meet the high customer demands, there are considerable amounts of notebooks being manufactured by the OEMs. Among the manufacturing plants, the OEM in Taiwan produces the most notebooks for D-company, while the plant in China (Xiamen) also produce considerable product due to its low capital cost and plentiful labor force at a low labor costs. The optimal delivery service frequency from the customers and the corresponding manufacturing plants are also shown in Table 4. This study considers the capacity limitation of the plants and relaxes the constraints on one customer being served by only one plant. For example, the large amount of demands from the USA is satisfied by the manufacturing plants in three locations, namely, USA (Texas), China (Xiamen) and Korea. Also shown in Table 6.4, the outsourcing strategy with the OEM in Taiwan brings the most demands among all the plants. And the corresponding customers of the OEM in Taiwan, i.e. the customers in Japan, China and Taiwan are all served with frequent delivery cycles. Due to these alternatives locate in the same area, namely Asia, the transportation cost will not increase significantly from frequent service cycles. On the contrary, the demand for these customers can be boosted, yielding an increased profit.

Moreover, the average delivery service frequency differs significantly between months and between the combinations of the customers and the manufacturing plants. A high density of service cycles exists during September and November with high customer demand, thus further simulating customer demand for D-company's notebooks. The average logistics cost per item can also be reduced by employing short service cycles during periods with considerable demands and long service cycles during months with sparse demand to realize transportation economies. Frequent delivery service cycles also exist for the manufacturing plants and customers whose distance is short with large product flows. However, as shown in Table 6.4, some customers are served by distant manufacturing plants rather than a near plant. It is likely that assigning these plants to serve the distant customers is more cost effective than assigning other plants to serve these customers. The results imply that the optimal assignments are determined from an entire network perspective, not from an individual node-to-node basis. Moreover, this study proposes a discriminating delivery service strategy in response to time-dependent customer demand. And the optimal dispatching date of the manufacturing plants for the customers can be obtained from the models. Table 6.5 shows the optimal dispatching dates of plants in serving the customers.

Table 6.5 The optimal dispatching dates of plants in serving different customers

		Dispatching date		
Customer	Plant	Sep.	Oct.	Nov.
USA	USA (Texas)	1st, 3rd, 5th, 7th, 10th, 14th, 16th, 18th, 21st, 24th, 27th, 29th	3rd, 5th, 7th, 10th, 13th, 15th, 18th, 21st, 24th, 27th, 31st	1st, 3rd, 5th, 8th, 10th, 12th, 14th, 16th, 18th, 20th, 22nd, 23rd, 25th, 27th, 29th
	China (Xiamen)	14th, 15th	6th, 31st	1st, 8th, 25th
	Korea	9th, 29th	10th, 29th	1st, 20th
Europe	Malaysia (Penang)	2nd, 6th, 10th, 15th, 17th, 21st, 25th, 29th	3rd, 7th, 13th, 20th, 24th, 28th	5th, 12th, 13th, 17th, 21st, 25th, 31st
	China (Xiamen)	3rd, 8th, 16th, 17th, 22nd, 27th	3rd, 12th, 18th, 24th, 29th	3rd, 10th, 13th, 18th, 23rd, 30th
Japan	Malaysia (Penang)	5th, 12th, 21st, 26th	3rd, 21st, 31st	1st, 8th, 14th, 19th, 25th
	Taiwan	1st, 4th, 6th, 8th, 10th, 12th, 14th, 17th, 21st, 22nd, 23rd, 25th, 28th	1st, 4th, 7th, 10th, 13th, 16th, 22nd, 25th, 28th, 31st	1st, 3rd, 5th, 7th, 10th, 12th, 14th, 16th, 18th, 20th, 22nd, 24th, 26th, 29th
China	Taiwan	1st, 4th, 9th, 10th, 11th, 14th, 18th, 22nd, 26th, 30th	4th, 8th, 11th, 15th, 19th, 23rd, 28th	1st, 6th, 11th, 14th, 17th, 20th, 23rd, 26th, 30th
Taiwan	Taiwan	1st, 3rd, 5th, 7th, 9th, 11th, 13th, 14th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 22nd, 23rd, 24th, 25th, 26th, 27th, 28th, 29th, 30th	Everyday	1st, 3rd, 5th, 7th, 9th, 11th, 13th, 15th, 17th, 18th, 20th, 21st, 23rd, 24th, 25th, 26th, 28th, 29th

The results shown in Table 6.4 are obtained from models without considering the impacts of demand-supply interactions on the production decisions. The optimal capacity of the manufacturing plants is determined when the customer demand is exogenous. Though customer intention to purchase notebooks from D-company could be increased by serving them with frequent delivery service cycles, the total profit might be low if the production cost is high. With reference to Table 6.3, D-company tends to operate large-size capacity plants to meet the demands. However, the capacity utilizations of these manufacturing plants are low, i.e. the utilizations of the plants in USA (Texas), Malaysia (Penang) and China being 51.69%, 49.19% and 43.64%. These low utilization values result in an increased production cost for D-company, thus a decreased profit. This study further assumes all customers are served with the same delivery service cycles as Table 6.4 shows, thus the changes in customer demand can be neglected. Eqs. (6.18a) and (6.18f) are applied to optimize the capacity and production amount for the manufacturing plants, where data on customer demand is given and shown as Table 4. The revised results are shown as Table 6.6.

Table 6.6 The revised results with considering the impact of demand-supply interaction on production decisions

Plant	Customer	Average frequency	Average monthly flow
China (Xiamen)	USA	14	111789
	Europe	6	53211
	Total	20	165000
Taiwan	Europe	7	36932
	Japan	16	61164
	China	9	28040
	Taiwan	24	20717
	Total	56	146853

Total Profit (US$)	53869199
Total customer demand (item)	935554
Average logistics cost (US$/item)	19.68
Average inventory cost (US$/item)	0.50
Average transportation cost (US$/item)	19.18
Average production cost (US$/item)	102.75

As shown in Table 6.6, instead of all plants, D-company adopts merely two manufacturing plants, China (Xiamen) and Taiwan, to serve the customers, where there is full capacity production in China and surplus output from the OEM in Taiwan. The average production cost is US$102.75 per notebook, which is lower as compared with that in Table 6.5. The results show the impacts of customer demand for the manufacturer product on profit lie not only on the logistics cost, but also on the production cost, therefore, profit. The decisions on capacity and production amount may not lead to profitable results if the demand-supply interaction is not considered. However, increased specialization requires increased transportation and an increased logistics cost exists in Table 6.6. The results show there is a tradeoff between production cost economies and transportation cost diseconomies. However, the large profit implies that the benefits brought by centralized production outweigh the increased transportation cost by decentralized for D-company. This finding also suggests that the manufacturer may adopt a strategy with centralized production and deliver the products to customers in different regions with frequent delivery service cycles.

Delivery service strategies must not only realize transportation cost economies, but also satisfy customer needs. Previous studies have considered physical distribution problems other than demand-supply interaction by assuming exogenous customer demand. This study compares the results from models with and with demand-supply interaction, where the combinations of the manufacturing plants and customers are the same as Table 6.6. A mathematical programming model without demand-supply interaction, namely Eqs. (6.18a), (6.18b) and (6.18e), is applied to optimize the average delivery service frequency and average shipment size. For comparison, D-company is assumed to adopt an identical market share that in models with demand-supply interaction, namely 49%. Table 6.7 compares the results from models with and without demand-supply interaction in delivery service strategy.

Table 6.7 Comparisons of results from models with and without demand-supply interaction

Plant	Customer	Average frequency	Average shipment size	Average monthly flow	Revised average monthly flow
China (Xiamen)	USA	2.5	44716	111789	41362
	Europe	5	10642	53211	27138
	Total	7.5	22000	165000	68500
Taiwan	Europe	4.5	8207	36932	18835
	Japan	6	10194	61164	33640
	China	4	7010	28040	13459
	Taiwan	9	2302	20717	12016
	Total	23.5	6429	146853	77950

	Model results without demand-supply interaction	Revised results
Total Profit (US$)	54028244	25227477
Total customer demand (item)	935554	439350
Average logistics cost (US$/item)	19.50	18.79
Average inventory cost (US$/item)	1.23	1.16
Average transportation cost (US$/item)	18.27	17.63
Average production cost (US$/item)	102.75	103.79

Table 6.7 shows that the average delivery service frequency using models without demand-supply interaction is less than that in Table 6.6. Comparing the results from Tables 6.6 and 6.7, the logistics cost without considerations of demand-supply interaction is lower than that with consideration. This finding implies that without considering demand-supply interaction, the manufacturer seems to pursue the largest transportation cost economies by assuming inelastic demand and applying a less delivery service frequency than models with demand-supply interaction. However, further applying the proposed model to calculate the revised results, namely Eq. (6.17), yields lower customer demands because of higher delay in receiving ordered goods with those service cycles. The results show that the manufacturer overestimates the customer demand. As for models dealing with demand-supply interaction, the influence of service frequency on customer demand is examined in a way that demands increase with reduced delay in receiving ordered goods. Furthermore, customer demand influences logistics cost and production cost. Finally, the delivery service frequency from models with demand-supply interaction leads to higher profit as shown in Table 6.7.

6.4 Summary

Recent studies have investigated logistics issues in supply chain management fields. Most of these empirical studies dealt with these issues by collecting empirical data and testing hypothesis. This study develops a mathematical programming model that determines the optimal delivery service strategy for high-tech product manufacturers by exploring demand-supply interaction and time and spatial dependent customer demand. This study also investigates how the production decisions can be influenced by demand-supply interaction.

This study demonstrates the applications of the models by using D-company as an example. The study periods are assumed to be three months where the peaks of demand differ among customers in different regions. The results show the average delivery service frequency differs between months and between different combinations of the customers and manufacturing plants. A high density of service cycle strategy is suggested for periods with considerable customer demand and combinations of the customers and plants whose distance is short. Regarding the assignment of which manufacturing plants to serve customers in different regions, the results show the assignment of a distant manufacturing plant in serving customers exists. The results imply that the optimal assignments are determined from an entire network perspective, not from an individual node-to-node basis.

The results show the impacts of customer demand for the manufacturer product on profit lie not only on the logistics cost, but also on the production cost; therefore, profit. The manufacturer tends to employ large-size capacity for all manufacturing plants when the impacts of demand-supply interaction on production are not considered. The results show the decisions on capacity and production amount may not lead to profitable results if the demand-supply interaction is not considered. The results also show there is a tradeoff relationship between production cost economies and transportation cost diseconomies. However, the result also implies that the benefits brought by centralized production outweigh the increased transportation cost by decentralized, thus a higher profit. This finding suggests the manufacturer to adopt a strategy with centralized production and deliver the products to customers in different regions with frequent delivery service cycles.

This study shows that without considering demand-supply interaction, the manufacturer typically pursues transportation cost economies and minimized logistics cost by assuming inelastic customer demand and applying less delivery service cycles. However, this strategy overestimates customer demand and yields higher production cost, leading to a reduced profit than strategies that consider demand-supply interaction. The finding in this study also implies that the delivery service strategy may not only affect customer demand for the manufacturer product and logistics cost, but also production cost.

CHAPTER 7

Optimal delivery service strategy for Internet shopping with time-dependent consumer demand

Previous chapters focus on designing a supply chain network from global logistics viewpoints. Customers can be referred to retailers, wholesalers or end-users and is classified in accordance with areas and regions. In this chapter, we further discuss the impacts of time-dependent demand and socioeconomic characteristics of end-consumers on delivery service strategy. Specifically, in this chapter, we attempt to optimize a delivery service strategy for Internet shopping by considering time-dependent consumer demand, demand-supply interaction and consumer socioeconomic characteristics. A nonlinear mathematical programming model is formulated for solving the optimal number and duration of service cycles for discriminating strategy by maximizing profit subject to demand-supply interaction. The research scope of this part of study is shown as Figure 7.1.

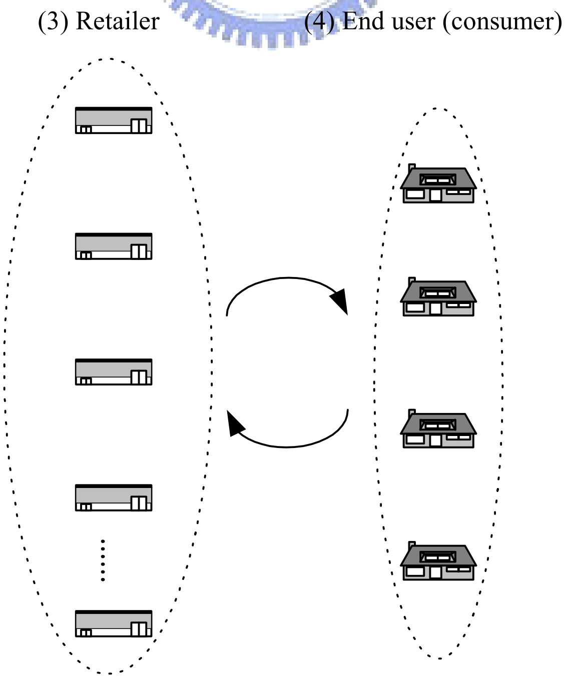


Figure 7.1 The research scope of Chapter 7

7.1 Introduction to the problem

Electronic Data Interchange (EDI) and related technologies have made it more efficient to transmit information to suppliers. At the same time, information flow-based Internet shopping has markedly improved consumer service by reducing order processing time and providing delivery information. Since real-time consumer demand is processed via the Internet, operator inventory costs are reduced by ordering goods from wholesalers or manufactures and shipping them directly to consumers. However, high order frequency and small order quantity that characterize consumer Internet shopping behavior make it expensive to deliver goods to individual consumers (Huppertz, 1999). With fixed transportation costs for each shipment, the average logistics cost per item decreases with increasing shipment size. Therefore, a larger quantity of goods will accumulate with longer shipping cycles, which also results in an increased delay in receiving ordered goods, thus reducing consumer intention to shop via the Internet. The above process involves a trade-off between consumer demands and operator logistics costs.

The goal of delivery strategies is to reduce logistics costs and satisfy consumer needs. A crucial factor in optimizing a delivery service strategy is consumer demand. The assumption of constant demand is highly controversial, since in reality demand varies with time, space, and consumer socioeconomic characteristics. For example, peak demand for food products is likely to occur at lunchtime. Serving consumers via uniform shipping cycles without considering variations in cumulative quantities ordered during each shipping cycle may result in high logistics costs under time-dependent consumer demand. Conversely, shipping cycle has a dramatic influence on consumer intention to shop via the Internet because it determines delay in receiving ordered goods. When a consumer orders goods from an Internet store, they typically receive delivery information with respect to each service cycle, which is posted on the Internet. Upon the completion of the service cycle, the goods ordered during that cycle are shipped to consumers. Thus, service cycles coincide with shipping cycles for Internet store operators. In addition to time-dependent consumer demand, consumer demand for Internet shopping is also characterized by socioeconomic characteristics, and temporal and spatial variations. Even when served by the same service cycles, consumers with different characteristics perceive Internet shopping differently, which may further influence consumer demand for Internet store goods and, thus, profit. In summary, how to determine an optimal delivery service strategy for Internet shopping by considering demand-supply interaction, time-dependent consumer demand and consumer characteristics has become important.

Discriminating service strategy proposed in this study differs significantly from the traditional and typical uniform service strategy in which all consumers are served according to the same delivery cycle. Periods with considerable consumer demand suggest that frequent and short service cycles are suitable and may stimulate consumer demand for Internet store goods because of reduced delay in receiving ordered goods; this perspective also implies that long service cycles are suitable when demand is very low. Such an approach would reduce logistics costs and boost profit. The Internet store in this study is assumed to operate as a retailer, ordering a batch of goods from wholesalers or manufactures and distributing these goods to consumers. Delay in receiving ordered goods is determined here as the time between consumers ordering and receiving goods, and depends on delivery cycles which include lead time for processing and handling.

This chapter explores how to optimize a delivery service strategy for Internet shopping in terms of service cycle frequency and duration by considering time-dependent consumer demand and demand-supply interaction. The model applies mathematical programming methods and compares profit between using discriminating and uniform service strategies thereby identifying the optimal strategy for Internet store operators. This study uses R-company selling flowers via the Internet in Taiwan, as an example to demonstrate the application of the model.

7.2 Consumer demand for Internet store goods

Three key groups of factors influence shopping behavior, namely goods characteristics, shopping mode attributes, and consumer characteristics (Salomon and Koppelman, 1988). Generally, goods that require detailed examination before purchase are considered inappropriate for Internet markets (Liang and Huang, 1998). Thus, the goods discussed here are those that are appropriate for Internet markets. This study designs a consumer choice probability model for choosing between Internet and conventional shopping modes. To capture dynamic and time-sensitive consumer demand, this study considers issues such as differences in consumer socioeconomic characteristics, temporal variations in ordering time of consumer goods, and spatial variations in consumer locations and competitions between Internet stores and retail stores in urban and non-urban areas.

7.2.1 Individual characteristics

Previous empirical studies have developed logit models to investigate the effects of shopping mode attributes, characteristics of consumer shopping behavior on Internet shopping (Koppelman et. al., 1991; Koyuncu and Bhattacharya, 2004; Bhatnagar and Ghose, 2004). Following the formulation of logit models in literature, this study applies a binary logit model to determine consumer choice probabilities for both Internet and conventional shopping. Let $U_{x,k}(t,j)$ represent the total utility of consumer x who orders goods in zone j at time t via shopping mode k. Furthermore, $U_{x,k}(t,j) = V_{x,k}(t,j) + \varepsilon_{x,k}$, where $V_{x,k}(t,j)$ denotes the deterministic component, and $\varepsilon_{x,k}$ denotes a random utility component representing the unobservable or immeasurable factors of $U_{x,k}(t,j)$. Supposing that all $\varepsilon_{x,k}$ are independent and identically distributed as a Gumbel distribution[2], then the probability of choosing shopping mode k can be estimated using the binary logit model (Ben-Akiva and Lerman, 1985). Let subscripts *TS* and *R* denote Internet shopping and conventional shopping, respectively, and the choice probability of choosing Internet stores for consumer x in zone j at time t, $P_{x,TS}(t,j)$, can then be estimated as:

$$P_{x,TS}(t,j) = \frac{e^{U_{x,TS}(t,j)}}{e^{U_{x,TS}(t,j)} + e^{U_{x,R}(t,j)}} \tag{7.1}$$

For simplicity, this study omits subscript x in the following disaggregate choice model in which formulations of the model are also discussed based on individual consumers. The difference in the utility value of consumer shopping via Internet stores and conventional retail stores determines the probability of choosing Internet shopping, which can be rewritten as:

$$P_{TS}(t,j) = \frac{e^{v(t,j)}}{1 + e^{v(t,j)}} \tag{7.2}$$

This study assumes technological advances and well-organized facilities in Internet shopping environments enable consumers to access Internet stores with little effort; therefore, search time for goods via the Internet can be ignored. Assume the quality of a good is the same regardless of whether it is purchased via Internet shopping or conventional shopping. Let v_1 and v_2 be the utility functions when the consumers

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[2] To arrive at the standard logit formulation, it is necessary to assume that the random utility component is independently and identically distributed as a Gumbel distribution (Ben-Akiva and Lerman, 1985).

purchase goods via Internet shopping and conventional shopping, respectively, namely:

$$v_1 = \beta_0 - \beta_1 \frac{p_R}{I} - \beta_2 T_{TS,t} \tag{7.3a}$$

$$v_2 = -\beta_1 \frac{p_{TS}}{I} - \beta_3 T_{t,R,j} \tag{7.3b}$$

The utility function $v(t, j)$ discussed here then has the following specifications:

$$v(t, j) = \beta_0 + \beta_1 \frac{p_{TS}}{I} + \beta_2 T_{TS,t} - \beta_1 \frac{p_R}{I} - \beta_3 T_{t,R,j} \tag{7.3c}$$

where p_{TS} and p_R denote the prices of goods via Internet shopping and conventional shopping, respectively; $T_{TS,t}$ represents delay in receiving ordered goods for consumers ordering goods via Internet at time t, and includes the goods handling/processing time and transportation time, while $T_{t,R,j}$ denotes access time for consumers purchasing goods via retail stores in zone j at time t. Furthermore, I represents consumer average income per unit time; β_1, β_2, β_3 are parameters that express the tastes of consumers; and β_0 reflects alternative specific constant for Internet shopping. The average value of time for delay in receiving ordered goods, VOT, then can be estimated using Eq. (7.3). Restated,

$$VOT = \frac{\partial v(t, j) / \partial T_{TS,t}}{\partial v(t, j) / \partial p_{TS}} = I \frac{\beta_2}{\beta_1} \tag{7.4}$$

Eq. (7.4) indicates that the average value of time for delay in receiving ordered goods depends on consumer income per unit of time. Consumers with higher income are more concerned with delay in receiving ordered goods than consumers with lower incomes. The value of time for delay in receiving ordered goods can also be expressed as consumer willingness to pay for one unit of delay savings in receiving ordered goods. Moreover, consumers with higher incomes may be willing to pay higher prices of goods via Internet shopping to receive ordered goods with less delay as Eq. (7.4) shows.

Since it typically takes longer to receive goods purchased from an Internet store than when purchased at a conventional store, consumers usually prefer to make fewer purchases from Internet stores (Koyuncu and Bhattacharya, 2004). The heterogeneity of consumers implies that consumers may perceive the same delay in receiving goods differently; that is, different consumers have different waiting costs (Chen, 2001). In this study, consumer income distribution is applied to investigate the relationship between consumer socioeconomic characteristics, consumer demand for Internet shopping and delivery service strategies for Internet shopping. Assume that individual consumers with different personal incomes are served by the same supply condition, then the expected choice probability of selecting Internet shopping for all consumers can be further estimated by aggregating individual consumer choices based on the binary logit model and income distribution. The generalized exponential family of distributions[3] can describe income distribution (Bakker and Creedy, 2000). This study assumes that personal income I is distributed with a normal distribution[4], with mean μ and standard deviation σ. From Eq. (7.3), all other things being equal, $v(t,j)$ is a function of I, so the pdf of $v(t,j)$ can be expressed through the transformation of the pdf of I. The pdf of $v(t,j)$, $f_{v(t,j)}(v(t,j))$ then can be expressed as:

$$\begin{aligned} & f_{v(t,j)}(v(t,j)) \\ & = f_I\left(I = \frac{\beta_1(p_R - p_{TS})}{\beta_0 + \beta_2 T_{TS,t} - \beta_3 T_{t,R,j} - v(t,j)}\right) \times \left| \frac{\beta_1(p_R - p_{TS})}{(\beta_0 + \beta_2 T_{TS,t} - \beta_3 T_{t,R,j} - v(t,j))^2} \right| \\ & \qquad \forall t, \forall j \qquad (7.5) \end{aligned}$$

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[3] The exponential family includes useful distributions such as the Normal, Binomial, Poisson, Multinomial, Gamma, Negative Binomial, etc. (McCullagh and Nelder, 1989).

[4] The probability distribution function (pdf) of I is $f_I(I) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(\frac{I-\mu}{\sigma})^2}$.

Consequently, taking the expected value of choice probability of selecting Internet shopping yields the following expression for the expected choice probability:

$$E[P_{TS}(t,j)] = \int_0^1 P_{TS}(t,j) f(P_{TS}(t,j)) dP_{TS}(t,j), \qquad \forall t,\ \forall j \qquad (7.6)$$

where $E[P_{TS}(t,j)]$ represents the expected value of choice probability of selecting Internet shopping in zone j at time t.

The difference in the utility values of Internet shopping and conventional shopping determines the probability of selecting Internet shopping, $P_{TS}(t,j)$, in Eq. (7.2); that is, $P_{TS}(t,j)$ is a random variable transformed by $v(t,j)$. Consequently, the pdf of $P_{TS}(t,j)$, $f(P_{TS}(t,j))$, is presented as:

$$f(P_{TS}(t,j)) = f_{v(t,j)}(v(t,j)) = \ln\frac{P_{TS}(t,j)}{1-P_{TS}(t,j)}\left|\frac{1}{P_{TS}(t,j)(1-P_{TS}(t,j))}\right| \quad \forall t,\ \forall j \quad (7.7)$$

From Eq. (7.7), since $v(t,j) = \ln\frac{P_{TS}(t,j)}{1-P_{TS}(t,j)}$, the relationship between the differential of $v(t,j)$, $\mathrm{d}v(t,j)$, and that of $P_{TS}(t,j)$, $\mathrm{d}P_{TS}(t,j)$, can be further calculated as $\mathrm{d}v(t,j) = \frac{1}{P_{TS}(t,j)(1-P_{TS}(t,j))}\mathrm{d}P_{TS}(t,j)$. Then, substituting Eq. (7.7) for_ $f(P_{TS}(t,j))$ in Eq. (7.6), Eq. (7.6) can be rewritten as:

$$E[P_{TS}(t,j)] = \int_0^1 P_{TS}(t,j)\cdot f(P_{TS}(t,j)) dP_{TS}(t,j)$$

$$= \int_0^1 P_{TS}(t,j)\cdot f_v\left(v = \ln\frac{P_{TS}(t,j)}{1-P_{TS}(t,j)}\right) dv(t,j) \qquad (7.8)$$

Similarly, from $I = \frac{\beta_1(p_R - p_{TS})}{\beta_0 + \beta_2 T_{TS,t} - \beta_3 T_{t,R,j} - v(t,j)}$ in Eq. (7.5), the relationship between $\mathrm{d}I$ and $\mathrm{d}v(t,j)$ can be expressed as $\mathrm{d}I = \frac{-\beta_1(p_R - p_{TS})}{(\beta_0 + \beta_2 T_{TS,t} - \beta_3 T_{t,R,j} - v(t,j))^2}\mathrm{d}v(t,j)$. Furthermore, from Eqs. (7.2), (7.3) and (7.5), Eq. (7.8) can be rewritten as:

$$E[P_{TS}(t,j)] = \int_0^1 P_{TS}(t,j)\cdot f_v\left(v = \ln\frac{P_{TS}(t,j)}{1-P_{TS}(t,j)}\right)dv(t,j)$$

$$= \int_0^\infty \frac{e^{\beta_0+\beta_1\frac{p_{TS}-p_R}{I}+\beta_2 T_{TS,t}-\beta_3 T_{t,R,j}}}{1+e^{\beta_0+\beta_1\frac{p_{TS}-p_R}{I}+\beta_2 T_{TS,t}-\beta_3 T_{t,R,j}}} f_I(I)dI$$

$$= \int_0^\infty \frac{e^{\beta_0+\beta_1\frac{p_{TS}-p_R}{I}+\beta_2 t_{TS,t}-\beta_3 t_{t,R,j}}}{1+e^{\beta_0+\beta_1\frac{p_{TS}-p_R}{I}+\beta_2 t_{TS,t}-\beta_3 t_{t,R,j}}}\cdot\frac{e^{\frac{-(\frac{I-\mu}{\sigma})^2}{2}}}{\sqrt{2\pi}\cdot\sigma}dI \qquad \forall t,\ \forall j \qquad (7.9)$$

7.2.2 Variations in ordering time of consumer goods and locations

The impacts of ordering time of consumer goods on their choice probabilities are further analyzed. Delay in receiving ordered goods is demonstrated in past studies as an important influence on the probability of choosing Internet shopping (Raijas, 2002; Hsu et al., 2003). Once service cycle lengths are determined, delay in receiving ordered goods decreases with reducing time between ordering time of consumer goods and the end time of the service cycle, and vice versa. Moreover, the smaller the number of retail stores in areas or in regular store closed hours is, the longer access time to retail stores will be. Therefore, it is important to understand how ordering time of consumer goods, which is related to delay in receiving ordered goods and access time to retail stores, influences the utility functions and choice probabilities.

Suppose the entire study period is divided into S consecutive service cycles, and let T_i represent the duration of service cycle *i*, $T_i = (t_{i,0}, t_{i,m})$, $i = 1,2,....,s$, where *s* is the last service cycle during the entire study period, $t_{i,0}$ and $t_{i,m}$ represents the start and end times of the service cycle *i*, respectively. Consequently, the sum of the time duration of all service cycles represents the entire study period, *T*, namely $\sum_{i=1}^{s}(t_{i,m} - t_{i,0}) = T$. At each $t_{i,m}$, $i = 1,2,....,s$, Internet store operators begin to deliver ordered goods accumulated during service cycle i.

This study ignores the vehicle routing problem of goods delivery and simplifies the problem by employing T_R to represent average goods delivery time to consumers. Restated, consumers receive ordered goods between $t_{i,m}$ and $(t_{i,m} + T_R)$. Lead time[5] includes the time required for order transmission, order processing and order preparation. The above definition of lead time influences delay in receiving ordered goods. This study defines "lead time" as the total time used by Internet store operators for preparing goods for delivery, namely handling and processing time at each service cycle. Consequently, a relationship exists among delay in receiving ordered goods, ordering time of consumer goods and lead time. Delay in receiving ordered goods when consumers order goods via the Internet at time t, $T_{TS,t}$, thus can be given by

$$T_{TS,t} = \begin{cases} (t_{i,m} + T_R) - t, t \in (t_{i,0}, (t_{i,m} - T_\ell)) \\ (t_{i+1,m} + T_R) - t, t \in ((t_{i,m} - T_\ell), t_{i,m}) \end{cases}, \forall t \tag{7.10}$$

where T_ℓ represents lead time. Access time to retail stores depends on the density of retail stores opened during different service cycles and different zones. From Eq. (7.10), delay in receiving ordered goods is influenced by ordering time of consumer goods. Owing to the time required for goods handling and processing, if ordering time of consumer goods falls during $((t_{i,m} - T_\ell), t_{i,m})$, the ordered goods will not be shipped until the end of the service cycle $(i+1)$.

Access time to retail stores in zone j at time t, $T_{t,R,j}$, can be obtained via

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[5] According to Coyle et al. (1996), lead time is the total time that elapses from placing an order until its eventual receipt.

$T_{t,R,j} = \frac{R_{t,j}}{V}$, where $R_{t,j}$ [6] denotes the average distance to retail stores in zone j at time t, and V represents the average consumer travel speed.

Normally, total consumer demand for Internet store goods can be estimated by multiplying total consumer demand for goods and the expected probability of selecting Internet shopping. Assume total consumer demand for goods in zone j at time t is exogenous and denoted as $q_{t,j}$, then the time-dependent consumer demands for goods of the Internet store at time t for all zones, q_t^{TS}, can be expressed as $q_t^{TS} = \sum_{j=1}^{n} q_{t,j} E[P_{TS}(t,j)]$. Furthermore, total consumer demand for Internet store goods during service cycle i for discriminating service strategy, Q_i, can be further represented as:

$$Q_i = \sum_{t=t_{i,0}}^{t_{i,m}} q_t^{TS} = \sum_{t=t_{i,0}}^{t_{i,m}} \sum_{j=1}^{n} q_{t,j} E[P_{TS}(t,j)] \qquad i = 1,2,....,s \tag{7.11}$$

Furthermore, from Eq. (7.11), total consumer demand for goods from the Internet store during service cycle i increases with increasing expected value of the probability of selecting Internet shopping, $E[P_{TS}(t,j)]$.

Assume the entire study period is equally divided into $S^{'}$ consecutive service cycles for uniform service strategy, and the duration of each cycle is $\frac{T}{S^{'}}$, where T is the entire study period. The duration of service cycle i for uniform service strategy is denoted using $T_i^{'}$, namely, $T_i^{'} = (t_{i,0}^{'}, t_{i,0}^{'} + \frac{T}{S^{'}})$, $i = 1,2,....,s^{'}$, where $s^{'}$ is the last

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[6] The average distance to retail stores can be approximated using one half of the square root of the average market area per retail store (Hsu and Tsai, 1999); that is, $\frac{1}{2}\sqrt{\frac{A_j}{n_{t,j}}}$, where A_j denotes the area of zone j, and $n_{t,j}$ represents the total number of retail stores in zone j at time t.

service cycle for uniform service strategy, and $t'_{i,0}$ and $t'_{i,0}+\frac{T}{S'}$ represent the start and end times of service cycle i assuming a uniform service strategy, respectively. Total consumer demand for Internet store goods during service cycle i for uniform service strategy, Q'_i, can be calculated as follows:

$$Q'_i=\sum_{t=t'_{i,0}}^{t'_{i,0}+\frac{T}{S'}}q_t=\sum_{t=t'_{i,0}}^{t'_{i,0}+\frac{T}{S'}}\sum_{j=1}^{n}q_{t,j}E[P_{TS}(t,j)] \qquad i=1,2,....,s' \tag{7.12}$$

7.3 Mathematical programming models for the optimal service cycles

The discussions completed to date deal with dynamic and time-sensitive consumer demand, and demonstrate how service cycle duration influences consumer demand for Internet store goods. This section further investigates how consumer demand for goods from Internet stores influences logistics costs for Internet store operators. Moreover, this study devises a mathematical programming model for determining the optimal number and duration of service cycles during the entire study period by considering the relationship between consumer demand and logistics costs and assuming that Internet store operators are seeking to maximize profit.

7.3.1 Logistics cost functions for discriminating service strategy

The average logistics cost functions for discriminating and uniform service strategies are formulated, respectively, by an analytical approach. Because of various numbers of orders accumulating during different service cycles during the entire study period, the average logistics cost during the study period is estimated using the weighting average method based on service cycle number and duration. Logistics cost is divided into transportation cost and inventory cost. This study ignores the problem of fleet capacity, and assumes the fleet to have sufficient capacity to carry all ordered goods. The transportation cost involves both fixed and variable transportation costs. Fixed transportation costs are costs attributable to each shipment regardless of shipment volume, while variable transportation costs involve loading/unloading costs and depend on quantity transported per shipment, namely the number of items ordered during each service cycle. Transportation costs increase with the number of items transported. This study denotes c as a base value of fixed transportation cost, w_t as a multiplier reflecting additional labor cost during different service cycles, such as weekend, night hours, or non-regular hours, because of the 24 hour nature of Internet stores and h as variable transportation cost per item shipped. The average transportation cost per item shipped during service cycle i for discriminating service strategy, ATC_i, can be expressed as follows:

$$ATC_i = \frac{1}{Q_i}(c \cdot w_t + hQ_i) = h + \frac{c \cdot w_t}{Q_i} \qquad i = 1,2,\ldots.,s \tag{7.13}$$

Economies of scale exist, as illustrated in Eq. (7.11), since ATC_i decreases with increasing total consumer demand for Internet store goods during service cycle i, Q_i. The average transportation cost per item during the entire study period for discriminating service strategy, ATC, can be further expressed as follows:

$$ATC = \frac{1}{S}\sum_{i=1}^{s} ATC_i = h + \frac{1}{S}\sum_{i=1}^{s}\frac{c \cdot w_t}{Q_i} \tag{7.14}$$

where S denotes the number of service cycles for discriminating service strategy.

Inventory costs discussed here reflect the relationship between the batch ordering of goods by Internet store operators to their suppliers and continuous ordering of goods by consumers. Consider the situation illustrated in Figure 7.2, and moreover consider that three curves in the figure represent the cumulative number of goods, which have been: (1) ordered by consumers; (2) delivered and (3) ordered by the operator of the

Internet store from suppliers. The shaded area in the figure represents the number of "item-hours" for items carried by the Internet store. Furthermore, denote $t_{i,o}$ as the time when the operator of the Internet store orders batch o of service cycles *i* and $Q_{i,o}$ as the number of items ordered in batch o of service cycle *i*.

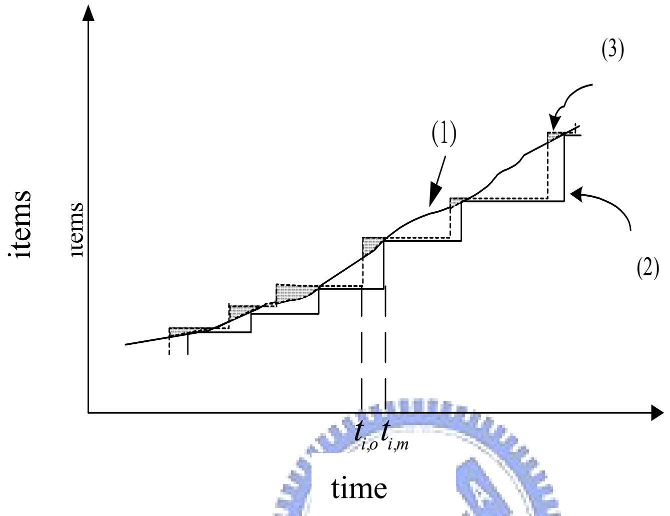

Figure 7.2 Inventory cost profile

The inventory cost per item of goods per unit time can be estimated based on purchasing cost per item, π and inventory carrying rate, ω. Therefore, the total inventory cost of service cycle i for discriminating service strategy, IC_i, results from the difference between the time when the operator ordered the batch and the time when the consumers ordered the goods; that is, $IC_i = \pi\omega[Q_{i,o}(t_{i,m} - t_{i,o}) - \sum_{t_{i,r}}^{t_{i,m}} q_t]$, $i = 1,2,....,s$.

Furthermore, the average inventory cost per item of goods of service cycle i for discriminating service strategy, AIC_i, can be determined by dividing IC_i by the total consumer demand during that cycle, namely:

$$AIC_i = \frac{1}{Q_i}\pi\omega[Q_{i,o}(t_{i,m} - t_{i,o}) - \sum_{t_{i,o}}^{t_{i,m}} q_t] \qquad i = 1,2,....,s \qquad (7.15)$$

Furthermore, the average inventory cost per item for the entire study period, for discriminating service strategy, AIC, can be presented as follows:

$$AIC = \frac{1}{S}\sum_{i=1}^{s} AIC_i = \frac{1}{S}\sum_{i=1}^{s}\frac{1}{Q_i}\pi\omega[Q_{i,o}(t_{i,m} - t_{i,o}) - \sum_{t_{i,r}}^{t_{i,m}} q_t] \tag{7.16}$$

Consequently, the average logistics cost per item during the entire study period for discriminating service strategy, ALC, can be expressed as the sum of the average transportation cost per item and the average inventory cost per item, restated

$$ALC = ATC + AIC$$

$$= h + \frac{1}{S}\sum_{i=1}^{s}\frac{1}{Q_i}(c \cdot w_t + \pi\omega[Q_{i,o}(t_{i,m} - t_{i,o}) - \sum_{t_{i,o}}^{t_{i,m}} q_t]) \tag{7.17}$$

7.3.2 Logistics cost functions for uniform service strategy

The average logistics cost per item for the uniform service strategy is formulated in a manner similar to that for discriminating service strategy, as mentioned above. The average transportation cost per item of service cycle i for uniform service strategy, $ATC_i^{'}$, can be presented as follows:

$$ATC_i^{'} = h + \frac{c \cdot w_t}{Q_i^{'}} \qquad i = 1,2,....,s^{'} \tag{7.18}$$

where $Q_i^{'}$ denotes total consumer demand for goods from the Internet store during service cycle i for uniform service strategy, as illustrated in Eq. (7.12).

Similarly, the average transportation cost per item of goods for the entire study period for uniform service strategy, $ATC^{'}$, can be formulated as:

$$ATC^{'}=\frac{1}{S^{'}}\sum_{i=1}^{s^{'}}ATC_{i}^{'}=\frac{1}{S^{'}}\sum_{i=1}^{s^{'}}ATC_{i}^{'}=h+\frac{1}{S^{'}}\sum_{i=1}^{s^{'}}\frac{c\cdot w_{t}}{Q_{i}^{'}} \tag{7.19}$$

Similar to the analyses in Section 7.3.1, the average inventory cost per item of goods of service cycle i for uniform service strategy, $AIC_{i}^{'}$, can be formulated as:

$$AIC_{i}^{'}=\frac{1}{Q_{i}^{'}}\pi\omega[Q_{i,o}(t_{i,0}+\frac{T}{S}-t_{i,o})-\sum_{t_{i,o}}^{t_{i,0}+\frac{T}{S}}q_{t}] \qquad i=1,2,....,s^{'} \tag{7.20}$$

The average inventory cost per item during the entire study period for the uniform service strategy, $AIC^{'}$, then can be further formulated as:

$$AIC^{'}=\frac{1}{S^{'}}\sum_{i=1}^{s^{'}}AIC_{i}^{'}=\frac{1}{S^{'}}\sum_{i=1}^{s^{'}}\frac{1}{Q_{i}^{'}}\pi\omega[Q_{i,o}(t_{i,0}+\frac{T}{S^{'}}-t_{i,o})-\sum_{t_{i,o}}^{t_{i,0}+\frac{T}{S^{'}}}q_{t}] \tag{7.21}$$

7.3.3 Formulation of the optimal problem

Profit throughout the entire study period can be calculated based on the price of goods via Internet shopping (p_{TR}), purchasing cost per item (π), average logistics cost per item (ALC) and total consumer demand for Internet store goods throughout the entire study period, $\sum_{i=1}^{s}Q_{i}$, such as

$$\tau=(p_{TR}-\pi-ALC)\cdot\sum_{i=1}^{s}Q_{i} \tag{7.22}$$

where τ represents profit throughout the study period. Eq. (7.22) illustrates the relationship between profit, the average logistics cost per item and total consumer demand for Internet store goods throughout the study period, whereby the larger total consumer demand for Internet store goods during the entire study period or the smaller the average logistics cost per item of goods, larger profit achieved by the Internet store operator. Additionally, profit throughout the entire study period for uniform service strategy, $\tau^{'}$, can be formulated as:

$$\tau^{'} = (p_{TR} - \pi - ALC^{'}) \cdot \sum_{i=1}^{s^{'}} Q_i^{'} \tag{7.23}$$

A nonlinear programming problem is formulated here for determining the optimal number and duration of service cycles for discriminating service strategy by maximizing profit subject to demand-supply equality. From Eqs. (7.8), (7.11), (7.17) and the discussion above, the nonlinear programming problem for maximizing profit throughout the study period given discriminating service strategy is as follows:

$$\underset{S,\ T_i=(t_{i,0},t_{i,m}),\,t_{i,o},\,Q_{i,o}}{\text{Max}} \quad \tau = (p_{TR} - \pi - ALC)\sum_{i=1}^{s} Q_i \tag{7.24a}$$

st.

$$ALC = ATC + AIC$$

$$= h + \frac{1}{S}\sum_{i=1}^{s}\frac{1}{Q_i}(c \cdot w_t + \pi\omega[Q_{i,o}(t_{i,m} - t_{i,o}) - \sum_{t_{i,r}}^{t_{i,m}} q_t]) \tag{7.24b}$$

$$Q_i = \sum_{t=t_{i,0}}^{t_{i,m}} q_t^{TS} = \sum_{t=t_{i,0}}^{t_{i,m}}\sum_{j=1}^{n} q_{t,j} E[P_{TS}(t,j)] \qquad i = 1,2,\ldots\ldots,s \tag{7.24c}$$

$$E[P_{TS}(t,j)] = \int_0^{\infty} \frac{e^{\beta_0 + \beta_1 \frac{p_{TS}-p_R}{I} + \beta_2 T_{TS,t} - \beta_3 T_{t,R,j}}}{1 + e^{\beta_0 + \beta_1 \frac{p_{TS}-p_R}{I} + \beta_2 T_{TS,t} - \beta_3 T_{t,R,j}}} \cdot \frac{e^{\frac{-(\frac{I-\mu}{\sigma})^2}{2}}}{\sqrt{2\pi} \cdot \sigma} dI \tag{7.24d}$$

$$\sum_{i=1}^{s}(t_{i,m} - t_{i,0}) = T \tag{7.24e}$$

Eq. (7.24a) represents the objective function that maximizes profit throughout the study period. Eq. (7.24b) defines the average logistics cost per item as Eq. (7.17). Moreover, Eq. (7.24c) represents the total consumer demand for Internet store goods during service cycle i. Eq. (7.24d) expresses expected value of probabilities of selecting Internet shopping. Furthermore, Eq. (7.24e) constrains that the summation of the duration of all service cycles must be equal to the entire study period. The nonlinear programming model for maximizing profit throughout the study period for uniform service strategy can be formulated in a manner similar to that for discriminating service strategy. This study further compares the objective value between discriminating and uniform service strategies and suggests that with the higher value for adoption by Internet store operators. Furthermore, this study compares the values of profit obtained by the Internet store from discriminating and uniform service strategies using $\xi = \frac{\tau - \tau^{'}}{\tau} \times 100\%$, where τ and $\tau^{'}$ represent profit using discriminating and uniform service strategies, respectively. If ξ is positive, discriminating service strategy is suggested; otherwise, uniform service strategy is recommended.

7.4 Case study

A case study is presented to demonstrate the application of the proposed model using data available from R-company selling flowers via the Internet in Taiwan. For simplicity, this study merely chose six cities from all of the cities currently served by R-company as study zones, and assumed one operating day, namely 24 hours, as the study period, with the unit of time for study being one hour. Base values for parameters in the utility were calibrated using data collected via street interviews conducted at Taipei Railway Station and several large shopping districts in Taipei City[7]

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[7] The survey was for three weeks in March 2002. After eliminating incomplete questionnaires, 952 complete questionnaires remained. The questionnaire consists of two data sets. The first set asked shoppers several questions to obtain socioeconomic and demographic data such as income, resident area and Internet experience. The sample had a fair proportion of different-income people, with an average monthly income of NT$ 55,000, and the residences of the population were spread widely throughout Taipei City. In the second set, respondents were asked whether they purchase via Internet stores based on different values for various attributes of Internet shopping and conventional shopping such as prices of goods via Internet shopping and conventional shopping, delay in receiving ordered goods, access time for purchasing goods via retail stores, etc. The commercial software package LIMDEP (Econometric Software, 1996) was used to calibrate the model's parameters. Similar to the finding of Hsu et al. (1998), this study found that the most significant factors are price of goods, delay in receiving ordered goods, and access time for consumers purchasing goods via retail stores.

and base values for logistics cost functions are estimated from Ministry of the Interior, ROC. (2001) as listed in Tables 7.1 and 7.2, respectively. Table 7.1 lists the initial values of base demand and supply parameters while Table 7.2 lists the related data on study zones. The multipliers reflecting extra cost during different service cycles, w_t are two during AM 0:00~7:00 and PM 9:00~12:00, and one during other times of day. Figures 7.3(a) and 7.3(b) illustrate time-dependent consumer demand for goods in Taipei City and over the entire study area, respectively. From Figure 7.3(b), consumer demand for goods is extremely low during AM 0:00~5:00, and peaks near PM 6:00.

Due to the complexity in solving a nonlinear programming problem, some approximate methods are required and the greedy algorithm is applied in this study due to its simple implementation and speed. In this study, the initial values, including the number and duration of service cycles, are randomly generated. Then the greedy algorithm is applied to obtain the best results for service duration for a specific number of service cycles. To verify this optimal solution, this study tests a variety of initial values for the duration of a specific number of service cycles. After several trials, the optimal duration for a specific number of service cycles can then be determined. This procedure is repeated until the optimal durations of service cycles were obtained for each number of service cycle. By comparing the profit values obtained using different numbers of service cycles with the optimal duration, the global optimal number and duration of service cycles that obtain the largest profit can then be determined. The model is programmed using Visual C++, a computer-modeling program developed by Microsoft. Table 7.4 and Figures 7.4-7.5 summarize the initial solution results.

Figure 7.4 is time-dependent consumer demand for Internet store goods for discriminating service strategy. From Figure 7.4, the solid line represents the accumulated time-dependent consumer demand for Internet store goods for discriminating service strategy, while the dotted line represents the number of goods to be shipped during each service cycle. Moreover, Figure 7.4 reveals that numerous items are demanded between 9:00 and 20:00, and a densely spaced service cycle; in contrast, the duration of a single service cycle is 13 hours at night, implying extremely low demand during this cycle. Table 7.3 lists the results and the optimal objective function value for discriminating and uniform service strategies, respectively. The optimal number of service cycles for uniform service strategy is six, and each service cycle lasts approximately 2 hours, as listed in Table 7.3. Consumer demand for goods differs significantly between uniform and discriminating service strategies, namely 818 and 864 items, respectively. However, the average logistics cost per item for the uniform service strategy is NT$ 149.51, which exceeds the NT$ 141.41 for discriminating service strategy. For discriminating service strategy, a high density of service cycles exists during periods with high consumer demand, thus further stimulating consumer demand for Internet store goods. The average logistics cost per item for discriminating service strategy can also be reduced by employing short service cycles during regular hours and long service cycles during late night hours to avoid the high extra cost. Comparing the objective value for discriminating and uniform service strategies yielded a positive value of ξ, namely 18.44%, and indicated that discriminating service strategy is the optimal strategy for Internet store operators.

Table 7.1 The initial values of base demand and supply parameters

Symbol	Definition	Initial Value
μ	Mean of the probability distribution of consumer income	353.4 NT$/hr
σ	Standard deviation of the probability distribution of consumer income	199.2 NT$/hr
I	Consumer average hourly income	353.4 NT$/hr
β_0		0.4^* (2.02)
β_1		-8.4^* (-3.35)
β_2		-0.018^* (-2.76)
β_3		-0.095^* (-1.98)
V	The average consumer travel speed	25 Km/hr
p_{TS}	The price of goods via Internet shopping	NT$ 1,050
π	Purchasing cost per item of goods	NT$ 850
p_R	The price of goods via conventional shopping	NT$ 1,280
h	Variable transportation cost per item	NT$ 135
c	Base value of fixed transportation cost	NT$ 850
T_ℓ	Lead time	0.5 hr

*Significant at the 5% level; t-statistics are reported in parentheses.

Table 7.2 The related data about study zones

Zone, j	Area (km^2), A_j	Number of retail stores, $n_{t,j}$			
		9:00~11:00	11:00~22:00	22:00~23:00	23:00~9:00
Taipei city	272	83	105	76	6
Taipei county	2,186	37	97	43	3
Ilan county	2,137	11	15	7	1
Taoyuan county	1,221	48	68	35	2
Hsinchu county	1,428	17	20	9	1
Hsinchu City	104	31	34	17	2

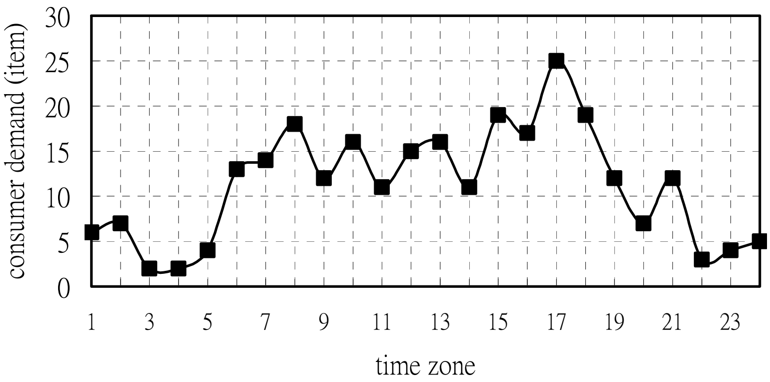

Figure 7.3(a) Time-dependent consumer demand for goods in Taipei City

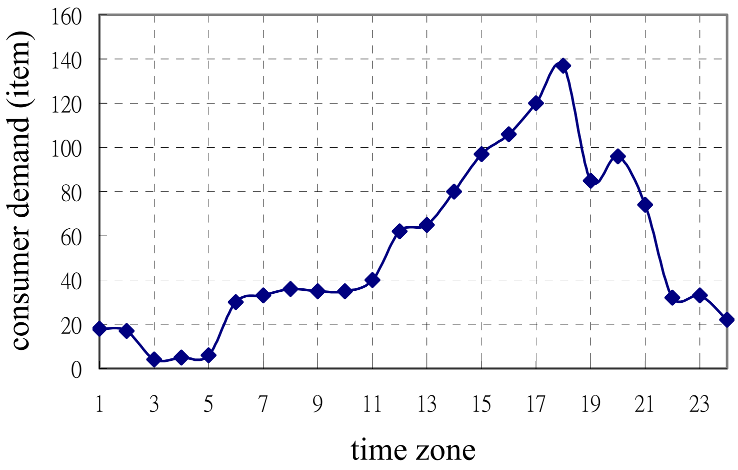

Figure 7.3(b) Total time-dependent consumer demand for goods over the entire study area

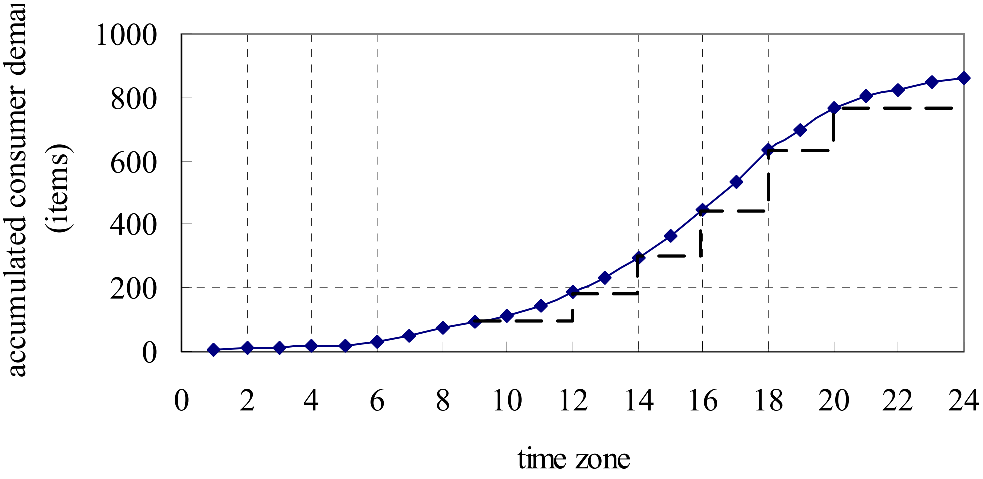

Figure 7.4 Accumulated consumer demand for Internet store goods for discriminating service strategy

Table 7.3 Results and the optimal objective function value for discriminating and uniform service strategies

Strategy	Discriminating	Uniform
Optimal number of service cycles	6	6
Consumer demand for Internet store goods (items)	864	818
Average logistics cost per item (NT$)	141.41	149.51
Objective function value (Profit, NT$)	50,569	41,240
Duration of service cycles	9:00~12:00 12:00~14:00 14:00~16:00 16:00~18:00 18:00~20:00 20:00~9:00	0:00~4:00 4:00~8:00 8:00~12:00 12:00~16:00 16:00~20:00 20:00~0:00
ξ	18.44%	

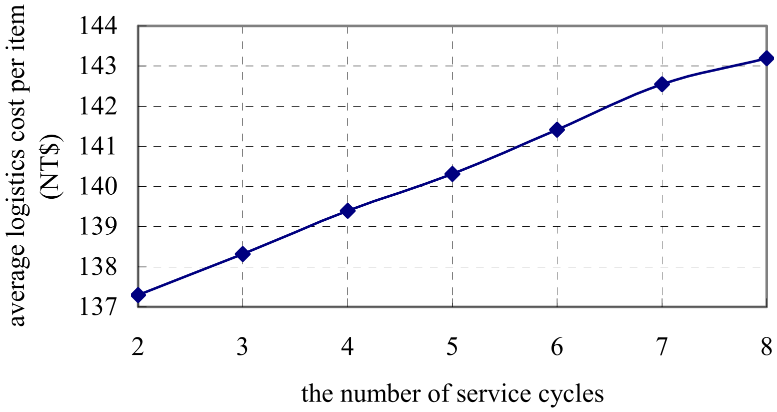

Figure 7.5(a) Average logistics cost per item vs. the number of service cycles for discriminating service strategy

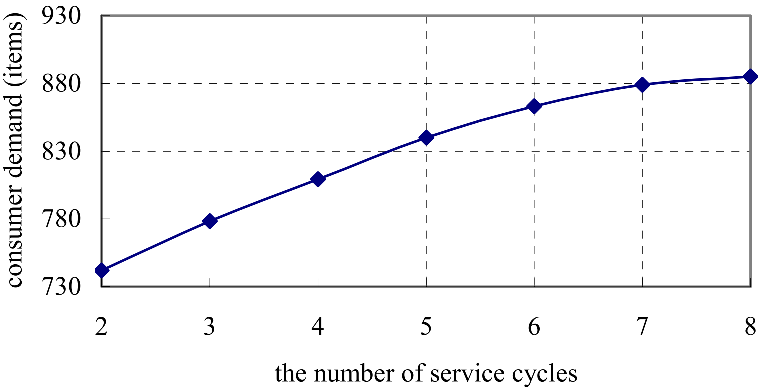

Figure 7.5(b) Consumer demand for Internet store goods vs. the number of service cycles for discriminating service strategy

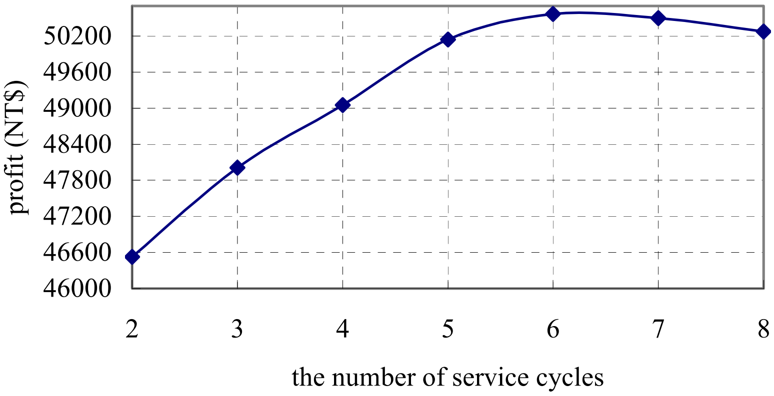

Figure 7.5(c) Profit vs. the number of service cycles for discriminating service strategy

Figures 7.5(a), (b) and (c) individually examine the relationships among average logistics cost per item, consumer demand for Internet store goods, profit and the number of service cycles required to discriminate service strategy. Figure 7.5(a) illustrates the average logistics cost per item versus the number of service cycles required for discriminating service strategy. As illustrated in Figure 7.5(a), the average logistics cost per item increases with increasing number of service cycles during a day. Figure 7.5(b) displays consumer demand for Internet store goods versus the number of service cycles required to discriminate service strategy. However, although consumer demand for Internet store goods increases with the number of service cycles but at a deceasing rate, as shown in Figure 7.5(b), profit does not continuously increase in the same way. Figure 7.5(c) illustrates profit versus the number of service cycles required to discriminate service strategy, and demonstrated that profit is maximized when a day contains six service cycles. Furthermore, the optimal batch ordering time for the Internet store operator when ordering from the supplier is 0.5 hours before the end of each service cycle.

So far, this study has conducted a numerical example for a company selling flowers in Taiwan. Next, this study further explores the influences of changes in key decision parameters on optimal service strategy, along with optimal service cycle number and duration. The base value of fixed transportation cost includes vehicle depreciation, purchasing cost, and so on. Increased number of service cycles per day leads to more frequent dispatching and thus higher transportation costs. Table 4 lists the optimal objective function values for discriminating and uniform service strategies under different base values of fixed transportation cost, namely NT$ 1200. Comparing the results of Tables 7.3 and 7.4 reveals that the higher value of the base value of fixed transportation cost produces higher average logistics cost per item for both discriminating and uniform service strategies. The frequencies of service cycles under fixed transportation costs, namely NT$ 1200 and NT$ 850, are the same, meaning that rather than serving consumers by reducing frequent service cycles when facing the increased cost, Internet store operators should adopt the original strategy for attracting consumer demand. However, the value of ξ, which indicates the advantage of discriminating regarding uniform service strategies, is larger for higher fixed transportation cost, namely 24.82% vs. 18.44%, as listed in Tables 7.3 and 7.4, respectively.

The multiplier reflecting extra costs during different service cycles implies compensation wages because of shipping and handling goods during non-regular hours, for example night hours. Internet store operators can reschedule service cycles to avoid the high logistics costs associated with the increasing values of the multiplier reflecting extra cost. However, such rescheduling may influence the likelihood of individual consumers choosing Internet shopping, and influences consumer demand for Internet store goods.

Table 7.5 lists the optimal objective function values for discriminating service strategy for different multiplier values reflecting extra costs. As the Table displays, the optimal number of service cycles is six for a multiplier value of two. However, the optimal number of service cycles is seven when the multiplier values are 2.5 and 3.0. The reason for this decision is that because of the logistics costs increase with increasing multiplier, and thus the Internet store operator should employ more frequent service cycles for attracting more consumers to offset the influence of increasing multiplier value on logistics cost. Furthermore, to avoid high additional costs during non-regular hours, the additional service cycle is employed during regular hours, as listed in Table 7.5.

Table 7.4 Results and the optimal objective function value for discriminating and uniform service strategies under different values of base value of fixed transportation cost

Base value of fixed transportation cost (NT$)	1,200	
Strategy	Discriminating	Uniform
Optimal number of service cycles	6	6
Consumer demand for Internet store goods (items)	859	818
Average logistics cost per item (NT$)	143.76	155.60
Objective function value (Profit, NT$)	48,321	36,326
Duration of service cycles	9:00~13:00 13:00~15:00 15:00~17:00 17:00~18:00 18:00~20:00 20:00~9:00	0:00~4:00 4:00~8:00 8:00~12:00 12:00~16:00 16:00~20:00 20:00~0:00
ξ	24.82%	

Table 7.5 Results and the optimal objective function values for discriminating service strategy under different values of multiplier reflecting extra cost

Multiplier reflecting extra cost	2.0	2.5	3.0
Optimal number of service periods	6	7	7
Consumer demand for Internet store goods (items)	864	879	879
Average logistics cost per item (NT$)	141.41	142.98	144.17
Objective function value (Profit, NT$)	50,569	50,120	49,074
Duration of service cycles	9:00~12:00 12:00~14:00 14:00~16:00 16:00~18:00 18:00~20:00 20:00~9:00	9:00~12:00 12:00~14:00 14:00~16:00 16:00~17:00 17:00~18:00 18:00~20:00 20:00~9:00	9:00~12:00 12:00~14:00 14:00~16:00 16:00~17:00 17:00~18:00 18:00~20:00 20:00~9:00

In this study, consumer income significantly influences demand, which further determines the optimal number and duration of service cycles. Consumer income reflects consumer perceptions regarding delay in receiving ordered goods. Even with the same service cycles and delay in receiving ordered goods, valuations of Internet shopping differ among consumers. Specifically, consumers with different income levels have different levels of concern with delay in receiving ordered goods and price levels. The model captures variations in consumer characteristics by employing consumer income distribution and individual logit model to estimate the expected choice probability of choosing Internet shopping for all consumers. An aggregation bias exists, which affects the accuracy of the optimal decision if variations in consumer income are not considered while using an average customer income value to represent the perceptions of different consumers regarding delay in receiving ordered goods. Table 7.6 lists the optimal objective function values without and with consideration of variations in consumer characteristics.

As listed in Table 7.6, owing to considering variations in consumer characteristics, operators of Internet stores employ more frequent service cycles to serve various consumers and thus satisfy more demand. The optimal number of service cycles from models without considering variations in consumer characteristics is two, less than for models that do consider variations. Because of many shipments during the entire study period, the average logistics cost per item for models that consider variations in consumer characteristics exceeds that for models that merely use an average consumer income value; however, the operator gains more profit for models that consider variations in consumer characteristics, as illustrated in Table 7.6.

Table 7.6 Results and the optimal objective function values without and with consideration of variations in consumers' characteristics

	Without consideration of variations in consumers' characteristics	With consideration of variations in consumers' characteristics
Optimal number of service cycles	2	6
Consumer demand for Internet store goods (items)	742	864
Average logistics cost per item (NT$)	137.30	141.41
Objective function value (Profit, NT$)	46,545	50,569
Duration of service cycles	14:00~19:00 19:00~14:00	9:00~12:00 12:00~14:00 14:00~16:00 16:00~18:00 18:00~20:00 20:00~9:00

Table 7.7 Comparisons of results from models with and without consideration of temporal and spatial variations in consumer demand of Internet shopping.

	Without consideration		With consideration of spatial and temporal variations
	Temporal	Spatial	
Optimal number of service cycles	6	5	6
Consumer demand for Internet store goods (items)	847	840	864
Average logistics cost per item (NT$)	142.91	140.31	141.41
Objective function value (Profit, NT$)	48,355	50,139	50,569
Duration of service cycles	3:00~7:00 7:00~10:00 10:00~13:00 13:00~18:00 18:00~22:00 22:00~3:00	9:00~13:00 13:00~16:00 16:00~18:00 18:00~20:00 20:00~9:00	9:00~12:00 12:00~14:00 14:00~16:00 16:00~18:00 18:00~20:00 20:00~9:00

Besides socioeconomic characteristics such as income, consumer demand for Internet shopping is also characterized by temporal and spatial variations, which could influence the optimal decision regarding the number and duration of service cycles. Spatial variations reflect various competitions between Internet stores and retail stores in different zones. Besides spatial variations, consumer demand also displays time-dependent distribution. Serving consumers with service cycles without considering time-dependent consumer demand may incur high logistics cost and low consumer demand. This study compares profit, average logistics cost per item and consumer demand for Internet store goods from models that do and do not consider temporal and spatial variations in consumer demand of Internet shopping, respectively. For models that do not consider spatial variations in consumer demand of Internet shopping, the average time required to access retail stores during each hour is obtained by averaging access time to retail stores across all zones. Additionally, consumer demand for goods during each hour for zones is uniform and obtained by dividing total consumer demands for goods by the entire study period, namely 24 hours.

Table 7.7 compares the results from models with and without consideration of temporal and spatial variations in consumer Internet shopping demand, respectively. As listed in Table 7.7, though the optimal number of service cycles from models with and without considerations of temporal variations in consumer Internet shopping demand is the same, the durations of service cycles differ considerably. For models that consider time-dependent consumer demand, demand increases and logistics cost reduce because of the service cycle being densely spaced during periods with larger demands and long duration of service cycles during night hours. Consequently, the Internet store operator achieves increased profit. As for comparisons between model with and without considerations of spatial variations, service cycles are less frequent for models that do not consider spatial variations in consumer demand for Internet shopping. Moreover, profit is lower because of issues regarding spatial variations in consumer locations and competition between Internet and retail stores in urban and non-urban areas being ignored in optimizing the service cycles.

Delivery service strategies must not only minimize logistics costs, but also must satisfy consumer needs. Previous investigations have considered physical distribution problems other than demand-supply interaction by assuming exogenous consumer demand. This study compares the number and duration of service cycles determined with and without demand-supply interaction. A nonlinear mathematical programming model without demand-supply interaction, namely Eqs. (7.24a), (7.24b) and (7.24e), is applied to optimize the service cycles, where data on consumer demand for goods from Internet stores is given and displays time-dependent consumer demand for goods, as illustrated in Figure 7.2(b). For comparison, the operator is assumed to adopt an identical market share that in models with demand-supply interaction, namely 68%.

Table 7.8 compares the results from models with and without demand-supply interaction. The table shows that the optimal number of service cycles using models without demand-supply interaction is two, which is less than that using models with demand-supply interaction. This finding implies that without considering demand-supply interaction, the Internet store operator seems to minimize average logistics cost per item by assuming inelastic demand and applying the least frequent service cycles. However, further applying the proposed model to calculate the revised results, namely Eqs. (7.11), (7.17) and (7.21), yields lower demands because of higher delay in receiving ordered goods with the service cycles, and implies that the operator overestimates the market demand. As for models dealing with demand-supply interaction, the influence of service cycles on consumer demands is examined in such a way that demands reduce with increasing delay in receiving ordered goods. Furthermore, consumer demands then influence operator logistics cost. Finally, the optimal number and duration of service cycles from the demand-supply convergent state leads to higher profit than for models without demand-supply interaction, as listed in Table 7.8.

As Chen (2001) indicated, consumers may be willing to pay a higher price for goods to receive them faster and that different consumers have varying waiting costs. Since consumer income is positively related to the price consumers are willing to pay for goods as Eq. (7.4) shows, the Internet store operator may increase profit by serving high-income consumers with frequent service cycles and high-priced goods. However, consumer intention to shop via the Internet may be reduced due to the high price of goods and, thereby, influence profit. This study further investigates the relationship between consumer average hourly income, the price of goods via Internet shopping and the optimal frequency of service cycles.

Table 7.9(a) lists two scenarios based on consumer average hourly income and the price of goods via Internet shopping. The price of goods and consumer average hourly income are higher under scenario 2 than those under scenario 1, in which the standard deviation of the probability distribution of consumer income remains the same. Moreover, the percentage change in consumer average hourly income and in the price of goods via Internet shopping between scenario 1 and 2 are both 11.65%.

Table 7.9(b) presents a comparison of the objective function values from scenarios 1 and 2. The optimal number of service cycles in scenario 2 is 7, which is larger than that in scenario 1. Due to the frequent service cycles in scenario 2, the average delay in receiving ordered goods in scenario 2 is less than that in scenario 1. Additionally, consumer demand for Internet store goods in scenario 2 is not reduced by the high price of goods. This finding indicates that as consumer average hourly income increases, consumer demand for Internet store goods becomes less price sensitive and, thereby, an increase in price will increase profit. Conversely, this finding also demonstrates that consumers with high incomes are more sensitive to delay in receiving ordered goods than the price of goods; that is, these consumers may be willing to pay more to receive ordered goods faster. Therefore, profit in scenario 2 is increased.

Table 7.8 Comparisons of results from models with and without demand-supply interaction

	Model with demand-supply interaction	Model without demand-supply interaction	
Duration of service cycles	9:00~13:00 13:00~15:00 15:00~17:00 17:00~18:00 18:00~20:00 20:00~9:00	8:00~17:00 17:00~8:00	
		Initial results	Revised results
Consumer demand for Internet store goods (items)	864	864	720
Average logistics cost per item (NT$)	141.41	136.97	137.36
Objective function value (Profit, NT$)	50,569	54,330	45,106
Market share	68%	68%	58%

Table 7.9(a) Scenarios based on consumer average hourly income and the price of goods via Internet shopping

	Scenario 1	Scenario 2
Consumer average hourly income (NT$/hr)	353.4	400.0
The price of goods via Internet shopping (NT$)	1,050	1,188

Table 7.9(b) Comparisons of results from different scenarios

	Scenario 1	Scenario 2
Optimal number of service cycles	6	7
Consumer demand for Internet store goods (items)	864	865
Average logistics cost per item (NT$)	141.41	145.84
Objective function value (Profit, NT$)	50,569	166,218
Duration of service cycles	9:00~12:00 12:00~14:00 14:00~16:00 16:00~18:00 18:00~20:00 20:00~9:00	10:00~13:00 13:00~15:00 15:00~16:00 16:00~17:00 17:00~19:00 19:00~22:00 22:00~10:00

7.5 Summary

Recent studies have investigated Internet shopping carriers and provider issues and their effects on consumer services and operating strategies. Most of these empirical studies dealt these issues by collecting empirical data and testing hypotheses. This study further develops a mathematical programming model that can determine the optimal number and duration of service cycles for Internet shopping by exploring demand-supply interaction and time-dependent consumer demand. This study shows how demand-supply interaction can be carefully considered in advance of solving delivery service problems. This study also shows how variations in consumer socioeconomic, temporal and spatial distributions influence consumer demand for Internet store goods and, thereby, profit.

The results show discriminating service strategy yields better objective values than uniform service strategy, from which indicates that the Internet store operator and consumers may benefit from spacing service cycles according to time-dependent consumer demand. This finding also suggests that in practice an Internet store operator should employ frequent and short service cycles for periods with increased demand and long service cycles when demand is very low. The results further show that when transportation cost increases, the optimal frequent service cycles remains the same or increases. This finding indicates that the impact of reduced consumer demand for Internet store goods on profit is more significant than the increased logistics cost and, therefore, Internet store operators should employ more frequent service cycles to attract consumers and offset the influence of increasing costs.

The results show that variations in consumer socioeconomic, temporal and spatial characteristics play important roles in determining the optimal number and duration of service cycles and that not considering these variables yields reduced profit. This finding implies that the Internet store operator should carefully investigate the temporal and spatial distribution of consumer demand, income and needs and provide a delivery service strategy tailored to these criteria. For example, service cycles could be intensely spaced for a consumer area or region with numerous retail stores or during periods of large consumer demand. The finding also implies that consumers with high income are more sensitive to delivery delay than to the price of goods and, thus, serving these consumers with frequent service cycles for high price of goods could yield increased profit.

Conversely, this study shows that without considering demand-supply interaction, the Internet store operator typically minimizes average logistics cost per item by assuming inelastic demand and then applying least-frequent service cycles. However, this strategy yields lower profit than strategies that consider demand-supply interaction. In this study, demand-supply interaction is examined in a way that reduces logistics cost due to a large accumulation of goods based on long and less frequent service cycles; however, this strategy also results in an increased delay in receiving ordered goods, thus reducing consumer intention to shop via the Internet. Consequently, this finding in this study implies that the delivery service strategy may not only affect consumer demand for Internet store goods, but also operator logistics costs. In practice, Internet store operators may investigate the effects of service cycles on consumer demand for Internet store goods and its relationship with logistics costs.

This study can be extended in several ways. On the demand side, this study focused only on choice probabilities for two shopping modes rather than that among shopping stores within each mode. Future studies may use the joint or nested logit models to determine consumer choice probabilities for a specific Internet store. Second, the case study is based on an Internet store selling flowers in Taiwan with a study period of one operating day. Future studies may apply the model to different goods, such as computers and extend the study period beyond one day. Such studies would need to examine the impact of different characteristics of goods on consumer intention toward Internet shopping and calibrate a consumer demand function. Finally, as Chen (2001) suggested, profit may be improved by segmenting the market and then serving different market segments with different combinations of prices and service cycle frequencies. Future studies may expand this study's model and address this issue by determining an optimal segmenting strategy and investigating the relative influences of the price of goods and delay in receiving ordered goods on consumer intention to shop via the Internet in the contexts of these different segments.

Chapter 8

Conclusions

This chapter summarizes the important findings as well as some managerial implications with respect each part of this dissertation. Furthermore, future research areas that extend from the study and might produce interesting results are also point out.

8.1 Research summary

The purpose of this dissertation is to investigate the supply chain design problems, coping with the impacts of scale economies and demand fluctuations on the network. In view of this, a series models are formulated in accordance with various issues emphasized. According to the issues of significance, there are five distinct parts in this dissertation, where the study object of the first four parts is high-tech product manufacturers, while the last part focuses on the end consumer shopping behavior and employs Internet store operators as the study object. Summaries of major results and important findings of this dissertation are summarized as follows.

Part I: *An integrated plant capacity and production model with economies of scales*

(1) This study showed how economies of scale can be considered in solving the capacity and production problems. This study also showed that the capacity utilization as well as the production amount in the short run, and the size of capacity of multiple plants in the long run are related, and that those two factors influence the total cost.

(2) The results show that because of the high customer demand, the manufacturer can operate manufacturing plants with large-size capacity combined with full-capacity production, thereby lowering the production cost. Since the government of Taiwan

provided incentives for developing the high-tech industry, and since there is a large local customer demand due to the economies of agglomeration in the semiconductor industry, T-company' core operations are based in FABs in Taiwan.

(3) The results of this study also show that when determining the production volumes for multiple manufacturing plants, those with large-size capacity combined with low capital and variable production costs have a higher priority in filling this capacity, compared to those with small-size capacity combined with relative high capital and variable production costs, not only because of their higher capability to satisfy customer demand but also because they are more cost effective.

(4) Although there is a tradeoff between production cost economies and transportation cost diseconomies, the results show that the benefits in terms of cost savings for the wafer foundry company brought by centralized production are larger than the increased transportation cost as a result of decentralization. Therefore, this finding suggests that the manufacturer may adopt a production strategy of centralizing production in manufacturing plants with large-size capacity and then shipping the products to customer in different regions.

(5) As to raw material procurement, the results show that the impact of high fixed costs on the total cost can be absorbed by large-amount procurement, and that the benefits of a low unit purchase cost are larger than the high fixed cost. Also, active vendors tend to serve manufacturing plants that are nearby.

(6) To reduce outbound costs, the product should be shipped from a manufacturing plant to a customer that is located within a short distance. The results also show that the production cost is the highest of all costs involved for a wafer foundry. This finding implies that the wafer foundry industry shows production with

economies of scale, and that this production is the most valued-added in the entire supply chain. Therefore, the manufacturer must be aware of the impact on the total cost of capacity utilization by its manufacturing plants with different-size capacity.

(7) The results also show that a manufacturing plant with very high capital and variable production costs is not recommended when the demand is extremely low. However, without using small-size capacity combined with high capacity utilization, operating large-size capacity with a relative low utilization is more cost effective for the manufacturer as long as the customer demand is large enough to offset the high capital cost.

(8) This model can be applied to investigate the relationship between the total average production cost and production allocation when deciding whether to operate a new manufacturing plant, or to develop a new technology, such as 0.09 μm process technology, which may lead to larger production. Finally, it is worth noting that the optimal capacity utilization of a manufacturing plant is related to its capacity size, the larger the capacity size the larger the utilization.

Part II: *Reliability evaluation and adjustment for supply chain network design with demand fluctuations*

(1) This study focuses on reliability evaluation and adjustment of the supply chain network design in responding different demand fluctuations. The reliability evaluation method proposed in this study evaluates the performance of different manufacturing plants on condition that abnormal fluctuations occur. Two mathematical programming models with respect to demand expansion and demand shrinkage are further developed.

(2) This study shows how the advantage and disadvantage brought by the adjustment can be carefully considered in advance when solving the network adjustment problems. This study also shows how the duration of an abnormal state and the related allocation costs influence the judgment on whether or not performing an adjustment.

(3) The results show that when severe demand fluctuations occur, the performance of different manufacturing plants depends on production allocation among and various expectations towards these plants. A full-capacity production plant combined with high expectation often follows a low reliability value under a demand expansion, while other plants with surplus capacities maintain a good performance. On the other hand, demand shrinkage will cause a further reduction in a manufacturing plant whose output is originally sparse, yielding a low reliability value.

(4) The results show that performing an adjustment in response to demand expansion benefits the manufacturers in way that total production cost can be reduced and revenue loss is avoided, which outweigh the derivate additional costs.

(5) The results suggest the manufacturers to stick to the initial proposed decisions and neglect the abnormal demand if the product value is low combined with high extra allocation cost. On the other hand, it is worth performing an adjustment and continuing to outsource for a high value-added product, even though the payment is pricey.

(6) The threshold of an adjustment is increased with an increased duration of abnormal months, meaning 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 the manufacturer could neglect an abnormal state with a short period,

because the accumulated benefits during this short period might not compensate the high allocation costs.

(7) The results show that severe demand shrinkage from customers with significance may result in low capacity utilizations for most manufacturing plants, resulting in an overall high production cost. In the circumstance, the result implies a centralized production is necessary, where the determinations of least economical plants being idle and the rests being full-capacity production are suggested. The results also imply that a partial adjustment is always encouraged, rather than a whole network consideration, since the whole network reconstruction will incur extra costs.

(8) In sum, the results of the study provide a reference for the manufacturer in the decision making procedures of network planning under demand fluctuations, as they cope with related benefits, costs and the duration of abnormal months.

Part III: *Incorporating dispatching decisions into supply chain network design with production and shipping economies*

(1) This study explored the impact of different flow values, total amount of flows between two locations as well as their spatial distance on the optimal shipping frequency and size. Moreover, the impacts of the key-component price by suppliers, which are located at different distance to the manufacturing plants, on the optimal supplier selection were also investigated.

(2) The results show that the manufacturer can reduce the production cost by operating a large-scale plant at an area with low capital cost and skilled employees. And to further achieve production economies, the monthly production amount of a large-size capacity manufacturing plant should be characterized with full-capacity production. If there are large demands in the market and the customers are wide

spread, the results imply that the manufacturer may corporate with OEM whose production cost is low and is in close proximity to the suppliers and customers.

(3) The results show that there might be a chance for a manufacturing plant to be assigned to serve distant customers, instead of serving customers in the same area, as long as this assignment leads to a minimized total cost for the entire supply chain network. The results imply that optimal assignments are determined from a network perspective, not from an individual node-to-node basis. The results also show that as long as the decreased purchase cost can offset the increased shipping cost, the manufacturer can procure a large amount of key-components from a supplier who offers a low purchase price, and then assign that supplier to serve multiple manufacturing plants in different regions.

(4) These results show that the total monthly procurement amount between two locations has a greater impact than their distance on the optimal shipping frequency. The results show that it requires a smaller procurement amount for two close locations than for two distant locations to maintain the same shipping frequency and to realize shipping economies. The more distant two locations are, the larger the monthly procurement amount should be.

(5) The results show the inventory costs for different goods flowing in a supply chain significantly influence the optimal shipping frequency. The results imply that the final product must be shipped with a high frequent shipment strategy, not only to reduce the inventory cost but also to attain a better service by shortening the waiting time. The results also imply that the procurement network ought to be rescheduled if it leads to cost beneficial results.

(6) Finally, it was demonstrated that the model results with considerations of spatial

distance and total monthly product amount and monthly procurement amount have a better performance in cost savings than the model results with an average identical shipping frequency strategy.

Part IV: *Optimal delivery service strategy for high-tech product manufacturers with time-dependent demand*

(1) This study explores how to optimize delivery service strategy for the high-tech product manufacturer in terms of service cycle frequency and duration for different customers in various regions as well as their corresponding plant assignments. In the study, the impacts of time-dependent customer demand and spatial distribution of customers and plants on logistics cost are investigated. Moreover, the impacts of demand-supply interaction on the optimal capacity and production amount of the manufacturing plants are also analyzed.

(2) The results show the average delivery service frequency differs between months and between different combinations of the customers and manufacturing plants. A high density of service cycle strategy is suggested for periods with considerable customer demand and combinations of the customers and plants whose distance is short. Regarding the assignment of which manufacturing plants to serve customers in different regions, the results show the assignment of a distant manufacturing plant in serving customers exists. The results imply that the optimal assignments are determined from an entire network perspective, not from an individual node-to-node basis.

(3) The results show the impacts of customer demand for the manufacturer product on profit lie not only on the logistics cost, but also on the production cost; therefore, profit. The manufacturer tends to employ large-size capacity for all manufacturing plants when the impacts of demand-supply interaction on production are not

considered. The results show the decisions on capacity and production amount may not lead to profitable results if the demand-supply interaction is not considered. The results also show there is a tradeoff relationship between production cost economies and transportation cost diseconomies. However, the result also implies that the benefits brought by centralized production outweigh the increased transportation cost by decentralized, thus a higher profit. This finding suggests the manufacturer to adopt a strategy with centralized production and deliver the products to customers in different regions with frequent delivery service cycles.

(4) This study shows that without considering demand-supply interaction, the manufacturer typically pursues transportation cost economies and minimized logistics cost by assuming inelastic customer demand and applying less delivery service cycles. However, this strategy overestimates customer demand and yields higher production cost, leading to a reduced profit than strategies that consider demand-supply interaction. The finding in this study also implies that the delivery service strategy may not only affect customer demand for the manufacturer product and logistics cost, but also production cost.

Part V: *Optimal delivery service strategy for Internet shopping with time-dependent demand*

(1) This study develops a mathematical programming model that can determine the optimal number and duration of service cycles for Internet shopping by exploring demand-supply interaction and time-dependent consumer demand. This study shows how demand-supply interaction can be carefully considered in advance of solving delivery service problems. This study also shows how variations in consumer socioeconomic, temporal and spatial distributions influence consumer demand for Internet store goods and, thereby, profit.

(2) The results show discriminating service strategy yields better objective values than uniform service strategy, from which indicates that the Internet store operator and consumers may benefit from spacing service cycles according to time-dependent consumer demand. This finding also suggests that in practice an Internet store operator should employ frequent and short service cycles for periods with increased demand and long service cycles when demand is very low.

(3) The results show that when transportation cost increases, the optimal frequent service cycles remains the same or increases. This finding indicates that the impact of reduced consumer demand for Internet store goods on profit is more significant than the increased logistics cost and, therefore, Internet store operators should employ more frequent service cycles to attract consumers and offset the influence of increasing costs.

(4) The results show that variations in consumer socioeconomic, temporal and spatial characteristics play important roles in determining the optimal number and duration of service cycles and that not considering these variables yields reduced profit. This finding implies that the Internet store operator should carefully investigate the temporal and spatial distribution of consumer demand, income and needs and provide a delivery service strategy tailored to these criteria. For example, service cycles could be intensely spaced for a consumer area or region with numerous retail stores or during periods of large consumer demand. The finding also implies that consumers with high income are more sensitive to delivery delay than to the price of goods and, thus, serving these consumers with frequent service cycles for high price of goods could yield increased profit.

(5) This study shows that without considering demand-supply interaction, the Internet store operator typically minimizes average logistics cost per item by assuming

inelastic demand and then applying least-frequent service cycles. However, this strategy yields lower profit than strategies that consider demand-supply interaction. Consequently, this finding in this study implies that the delivery service strategy may not only affect consumer demand for Internet store goods, but also operator logistics costs. In practice, Internet store operators may investigate the effects of service cycles on consumer demand for Internet store goods and its relationship with logistics costs.

8.2 Extensions for future research

The extensions from the study results for future research are discussed as follows.

(1) In this study, the demand for high-tech product from different customer is not correlated and is independent from each other. Some abnormal event may occur and even have impacts 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 global financial crisis. Second, the fixed allocation cost reflects the difficulty in searching 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 outsourcing firm selection decisions.

(2) The case study of parts 1 and 2 is based on a wafer foundry company in the semiconductor industry, which is characterized with extremely high capital cost. Future study may apply the model to different industry. Such studies would need to examine the impact of capital cost and customer demand on production allocation

among manufacturing plants and how the revenue is affected when the demand is not satisfied.

(3) Regarding supplier selections, the key-component quality of different suppliers is not considered, and the effects of taxes and duties on the supply chain network design are not discussed in this study. Future studies may incorporate these issues and investigate the impacts of these influences on the optimal supply chain network design.

(4) To simplify the study, in the third part, we only selected the thin screen as the key-component in the case study. Also, the problem of manufacturing requirements planning (MRP), which relies on the bill of material (BOM) of the product, was ignored. Future studies may expand this study's model and address this issue by determining the optimal shipping frequency and shipment size for different key-components. Such studies would need to investigate the relationship between different key-components and the construction and installation phase of the final product, and examine the impact of the manufacturing or assembly procedure of the products on the optimal shipping frequency and shipment size for different key-components.

(5) Regarding the fifth part, this study focused only on choice probabilities for two shopping modes rather than that among shopping stores within each mode. Future studies may use the joint or nested logit models to determine consumer choice probabilities for a specific Internet store.

(6) The case study of the fifth part is based on an Internet store selling flowers in Taiwan with a study period of one operating day. Future studies may apply the model to different goods, such as computers and extend the study period beyond

one day. Such studies would need to examine the impact of different characteristics of goods on consumer intention toward Internet shopping and calibrate a consumer demand function.

(7) Finally, as Chen (2001) suggested, profit may be improved by segmenting the market and then serving different market segments with different combinations of prices and service cycle frequencies. Future studies may expand this study's model and address this issue by determining an optimal segmenting strategy and investigating the relative influences of the price of goods and delay in receiving ordered goods on consumer intention to shop via the Internet in the contexts of these different segments.

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GLOSSARY OF SYMBOLS

Part I: *An integrated plant capacity and production model with economies of scales*

G(***N***, ***A***)	A supply chain network, where ***N*** and ***A*** represent the set of nodes and the set of links, respectively, in a directed graph **G**
k	A specific echelon in a supply chain
n_k	A node at echelon *k*, which can refer to an alternative at echelon *k*, $n_k \in N$
$w_{k-1,k}$	The demand flows of a node at echelon *k* from its upper echelon (*k*-1) when the supply flow of that node is one unit
f_{n_k}	The supply flows of a node at echelon *k*, n_k
$f_{n_k}^{n_{k-1}}$	The flows between a node at the upper echelon, n_{k-1}, and a node at the lower echelon, n_k
$\delta_{n_k}^{n_{k-1}}$	An indicator variable representing whether the node at the upper echelon, n_{k-1}, is an active node to the node at the lower echelon, n_k
$\beta_{n_{k+1}}^{n_k}$	An indicator variable representing whether a node at the lower echelon, n_{k+1}, is a demand node for node at its upper echelon, n_k
v_{n_k}	The capacity of n_k
$\prod_k^s w_{k,k+1}$	The total supply flows at echelon *k* when the customer demand is one unit
$\hat{k}$	The echelon of manufacturing plants
$n_{\hat{k}}$	A manufacturing plant
$C(v_{n_{\hat{k}}})$	The capital costs of manufacturing plant $n_{\hat{k}}$
$c(v_{n_{\hat{k}}})$	The variable production costs of manufacturing plant $n_{\hat{k}}$
$V_{n_{\hat{k}-1}}$	The fixed cost of the manufacturer with raw material vendor $n_{\hat{k}-1}$
$\gamma_{n_{\hat{k}-1}}$	An indicator variable representing whether raw material vendor $n_{\hat{k}-1}$ is an active vendor for the manufacturer
$p_{n_{\hat{k}-1}}$	The unit raw material purchase cost from raw material vendor $n_{\hat{k}-1}$
$t_{n_{\hat{k}}}^{n_{\hat{k}-1}}$	The average unit-distance transportation cost per unit of raw material between the locations of raw material vendor $n_{\hat{k}-1}$ and manufacturing

	plant $n_{\hat{k}}$
$d_{n_{\hat{k}}}^{n_{\hat{k}-1}}$	The average distance from the location of raw material vendor $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$
$S_{n_{\hat{k}-1}}$	The maximum amount of raw material supplied by vendor $n_{\hat{k}-1}$
$Y_{n_{\hat{k}}}$	The capacity utilization of manufacturing plant $n_{\hat{k}}$

Part II: *Reliability evaluation and adjustment for supply chain network design with demand fluctuations*

$\tilde{f}_{n_k}^{t}$	The random production amount of manufacturing plant *k* in month *t*
$\bar{f}_{n_k}^{t}$	The random realization of $\tilde{f}_{n_k}^{t}$ and a potential value of production amount of manufacturing plant n_k under all demand fluctuations over month *t*
$\bar{Y}_{n_k}$	The maximally acceptable capacity utilization of manufacturing plant n_k
$\underline{Y}_{n_k}$	The minimally acceptable capacity utilization of manufacturing plant n_k
$R_{n_k}(\tilde{f}_{n_k}^{t})$	The reliability of manufacturing plant n_k with random production amount $\tilde{f}_{n_k}^{t}$
θ_{n_k}	The proportion of the production from manufacturing plant n_k to that from all plants
$\tilde{f}_{n_s}^{t}$	The random demand from customer n_s in month *t*
$\bar{f}_{n_s}^{t}$	The mean of random variable $\tilde{f}_{n_s}^{t}$
$\sigma(\tilde{f}_{n_s}^{t})$	The standard deviation of random variable $\tilde{f}_{n_s}^{t}$
$\mathbf{K}_{n_s}$	The set of all distinct states, which occur on the market during the planning year
$w_{n_s}^{i}$	A specific abnormal state
W	The number of distinct abnormal states
$w_{n_s}^{0}$	Normal state, in which no abnormal fluctuation occurs
$\Pr(w_{n_s}^{i})$	The probability that state $w_{n_s}^{i}$ occurs during the planning year

$\tilde{v}^{i}_{n_s}$	The duration of abnormal state $w^{i}_{n_s}$
$v^{ij}_{n_s}$	A realization of $\tilde{v}^{i}_{n_s}$ with probability p_j
V_{n_s}	The number of realizations of $\tilde{v}^{i}_{n_s}$
$I^{i,j}_{n_s}$	The set of months belonging to the time interval within which an abnormal state $w^{i}_{n_s}$ continues on the location of customer n_s i.e. $I^{i,j}_{n_s} \equiv \{t \| \lfloor t^{*}_{i} \rfloor \le t < \lceil t^{*}_{i} + v^{ij}_{n_s} \rceil\}$ given state duration $v^{ij}_{n_s}$
$\tilde{f}^{t}_{n_s,i}$	The average demand from customer n_s in month t given abnormal state $w^{i}_{n_s}$
$\mathbf{t}$	The set of months belonging to the time interval within which excessive demand continues, $\mathbf{t} \equiv \{I^{i,j}_{n_s}, \forall n_s, \forall i\}$
$n(\mathbf{t})$	The number of months in $\mathbf{t}$ where the adjustment is scheduled and executed
$\mathbf{J}$	The set of the detected unreliable manufacturing plants, $\mathbf{J} \equiv \{\dot{n}_k\}$
m_k	A specific alternative outsourcing firm, where the product quality is indifferent from the manufacturer
o_{m_k}	The unit-product outsourcing cost paid for outsourcing firm m_k
$h_{\bar{n}_k}$	The unit-production compensation cost for manufacturing plant $\bar{n}_k$
O_k	The fixed allocation cost
$q_{\dot{n}_k,m_k}$	The production amounts allocated from manufacturing plant $\dot{n}_k$ to outsourcing firm m_k
$\Delta_{\dot{n}_k,\bar{n}_k}$	The production amounts allocated from manufacturing plant $\dot{n}_k$ to reliable manufacturing plant $\bar{n}_k$
$x^{\dot{n}_k}_{m_k}$	The indicator representing whether there exists production allocation relationships between $\dot{n}_{\hat{k}}$ and m_k
$y^{\dot{n}_k}_{\bar{n}_k}$	The indicator representing whether there exists production allocation relationships between $\dot{n}_{\hat{k}}$ and $\bar{n}_k$
$\bar{p}$	The average unit-material purchase cost
R	The extra material purchase cost over $n(\mathbf{t})$ months
$\bar{f}_{\dot{n}_k}$	The realized average monthly production amount of manufacturing plant $\dot{n}_k$ under demand expansion

$\bar{f}_{\bar{n}_k}$	The realized average monthly production amount of manufacturing plant $\bar{n}_k$ under demand expansion
$f'_{\dot{n}_k}$	The adjusted monthly production amount of manufacturing plant $\dot{n}_k$
$f'_{\bar{n}_k}$	The adjusted monthly production amount of manufacturing plant $\bar{n}_k$
Q	The total difference in production cost over $n(\mathbf{t})$ months
P	Unit-product price
ϕ	The proportion of penalty cost to product price
T	The total penalty cost over $n(\mathbf{t})$ months
$\bar{t}_{\bar{n}_k}$	The average unit-product transportation costs from manufacturing plant $\bar{n}_k$ to customers
$\bar{t}_{m_k}$	The average unit-product transportation costs from outsourcing firm m_k to customers
E	The total transportation cost over $n(\mathbf{t})$ months
$\mathbf{y}$	The set of months belonging to the time interval within which shrunk demand occurs, $\mathbf{y} \equiv \{I^{i,j}_{n_s}, \forall n_s, \forall i\}$
$n(\mathbf{y})$	The number of months in $\mathbf{y}$, where the adjustment is scheduled and executed
$e_{\ddot{n}_k,\hat{n}_k}$	The allocated amount between manufacturing plants $\ddot{n}_k$ and $\hat{n}_k$
$q^{\ddot{n}_k}_{\hat{n}_k}$	The indicator representing whether there is reallocation relationship between manufacturing plants $\ddot{n}_k$ and $\hat{n}_k$
$w_{\ddot{n}_k}$	The unit-product allocation costs of manufacturing plant $\ddot{n}_k$
$w_{\hat{n}_k}$	The unit-product allocation costs of manufacturing plant $\hat{n}_k$
$W_{\ddot{n}_k}$	The total variable allocation cost of manufacturing plant $\ddot{n}_k$ over $n(\mathbf{y})$ months
$W_{\hat{n}_k}$	The total variable allocation cost of manufacturing plants $\hat{n}_k$ over $n(\mathbf{y})$ months
X^1	The total difference in production costs for all unreliable manufacturing plants over $n(\mathbf{y})$ months
X^2	The total difference in production costs for all reliable manufacturing plants over $n(\mathbf{y})$ months

Part III: *Incorporating dispatching decisions into supply chain network design with* *production and shipping economies*

$z_{n_{\hat{k}}}^{n_{\hat{k}-1}}$	The average shipment size from key-component supplier $n_{\hat{k}-1}$ to manufacturer plant $n_{\hat{k}}$ during one month
$h_{n_{\hat{k}}}^{n_{\hat{k}-1}}$	The monthly shipping frequency of the key-component from supplier $n_{\hat{k}-1}$ to manufacturing plant $n_{\hat{k}}$
$g(v_{n_{\hat{k}}})$	The monthly production amount at manufacturing plant $n_{\hat{k}}$
$c_{n_{\hat{k}-1}}^{j}$	The basic purchase cost of key-component j without any discount,
$u_{n_{\hat{k}-1}}^{j}(\bar{z}_{n_{\hat{k}-1}}^{j})$	The discount when the average shipment size is $\bar{z}_{n_{\hat{k}-1}}^{j}$
$t_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$	The variable shipping cost per unit key-component j for $(n_{\hat{k}-1}, n_{\hat{k}})$
$G_{n_{\hat{k}}}^{j,n_{\hat{k}-1}}$	The fixed shipping cost
c^{j}	The inventory cost per unit key-component j per month
$z_{n_s}^{n_{\hat{k}}}$	Shipment size of the final product from manufacturing plant $n_{\hat{k}}$ to customer n_s
$h_{n_s}^{n_{\hat{k}}}$	The shipping frequency between manufacturing plant $n_{\hat{k}}$ to customer n_s

Part IV: *Optimal delivery service strategy for high-tech product manufacturers with time-dependent demand*

i_s	A specific service cycle a for customer s under discriminating service strategy during the study period
$T(i_s)$	Duration of service cycle i_s under discriminating service strategy
I_s	The total service cycle for customer s during the study period
$t_0(i_s)$	The start time of service cycle i_s
$t_m(i_s)$	The end time of service cycle i_s
T	The study period
f_{i_s}	Total demand of customer s for the manufacturer during service cycle i_s.
$f_k(i_s)$	Product amount produced by plant k and deliver to customer s for service cycle i_s

$\beta_k(i_s)$	The indicator variable representing whether plant k serves and delivers products to customer s for service cycle i_s
f_k	Total amount delivered by plant k during the study period
t_k^j	A specific delivery time of plant k during the study period
m_k	Delivery frequency of plant k
o	The objective manufacturer
r	A representative of other manufacturers in the market
$U_x(s,t)$	The total utility of customer s who purchase products from manufacturer x at time t
$V_x(s,t)$	The deterministic component of $U_x(s,t)$
ε_x	The unobservable or immeasurable factors of $U_x(s,t)$
$\Pr_o(s,t)$	Customer choice probability of purchasing products from manufacturer o at time t
$v(s,t)$	The difference in utility values of customer purchasing from manufacturer o and r
p_o	Product price of manufacturer o
p_r	Product price of manufacturer r
y	The reasonable payment ratio
$T_o^{s,t}$	Delay in receiving products from manufacturer o at time t
$T_r^{s,t}$	Delay in receiving products from manufacturer r at time t
H_{i_s}	The average transportation time from plants to customer s
T_s^k	Average transportation time from locations of plant k to customer s
q_s^t	Total demand for products of customer s at time t
$q_s^t \Pr_o(s,t)$	Time-dependent demand for manufacturer product of customer s at time t
τ	Profit throughout the study period for discriminating service strategy
$I_s^{'}$	The service cycle for customer s during the study periods with uniform service strategy
$T(i_s^{'})$	The duration of a specific service cycle
$t_0(i_s^{'})$	The start time of service cycle $i_s^{'}$

$f_{i_s'}$	Total demand for manufacturer product of customer s during service cycle i_s' for uniform service strategy
τ'	Profit throughout the entire study period for uniform service strategy

Part V: *Optimal delivery service strategy for Internet shopping with time-dependent demand*

$U_{x,k}(t,j)$	The total utility of consumer x who orders goods in zone j at time t via shopping mode k
$V_{x,k}(t,j)$	The deterministic component of $U_{x,k}(t,j)$
$\varepsilon_{x,k}$	The unobservable or immeasurable factors of $U_{x,k}(t,j)$
TS	Internet shopping
R	Conventional shopping
$P_{x,TS}(t,j)$	The choice probability of choosing Internet stores for consumer x in zone j at time t
p_{TS}	The price of goods via Internet shopping
p_R	The price of goods via conventional shopping
$T_{TS,t}$	Delay in receiving ordered goods for consumers ordering goods via Internet at time t, and includes the goods handling/processing time and transportation time
$T_{t,R,j}$	Access time for consumers purchasing goods via retail stores in zone j at time t
I	Consumer average income per unit time
VOT	The average value of time for delay in receiving ordered goods
$f_{v(t,j)}(v(t,j))$	The pdf of $v(t,j)$
$E[P_{TS}(t,j)]$	The expected value of choice probability of selecting Internet shopping in zone j at time t
S	The number of service cycles for discriminating service strategy
T_i	The duration of service cycle i
$t_{i,0}$	The start time of the service cycle i
$t_{i,m}$	The end times of the service cycle i
T_R	Average goods delivery time to consumers

T_ℓ	Lead time
$T_{t,R,j}$	Access time to retail stores in zone j at time t
$R_{t,j}$	The average distance to retail stores in zone j at time t,
V	The average consumer travel speed
$q_{t,j}$	Total consumer demand for goods in zone j at time t
q_t^{TS}	The time-dependent consumer demands for goods of the Internet store at time t for all zones
Q_i	Total consumer demand for Internet store goods during service cycle i for discriminating service strategy
S'	The number of service cycles for uniform service strategy
T_i'	The duration of service cycle i for uniform service strategy
$t_{i,0}'$	The start time of service cycle i assuming a uniform service strategy
Q_i'	Total consumer demand for Internet store goods during service cycle i for uniform service strategy
c	Base value of fixed transportation cost
w_t	A multiplier reflecting additional labor cost during different service cycles
h	Variable transportation cost per item shipped
ATC_i	The average transportation cost per item shipped during service cycle i for discriminating service strategy
ATC	The average transportation cost per item during the entire study period for discriminating service strategy
$t_{i,o}$	The time when the operator of the Internet store orders batch o of service cycles I
$Q_{i,o}$	The number of items ordered in batch o of service cycle i
π	Purchasing cost per item
ω	Inventory carrying rate
IC_i	The total inventory cost of service cycle i for discriminating service strategy
AIC_i	The average inventory cost per item of goods of service cycle i for discriminating service strategy
AIC	the average inventory cost per item for the entire study period, for discriminating service strategy

	discriminating service strategy
ALC	The average logistics cost per item during the entire study period for discriminating service strategy
$ATC_i^{'}$	The average transportation cost per item of service cycle i for uniform service strategy
$Q_i^{'}$	Total consumer demand for goods from the Internet store during service cycle i for uniform service strategy
$ATC^{'}$	The average transportation cost per item of goods for the entire study period for uniform service strategy
$AIC_i^{'}$	The average inventory cost per item of goods of service cycle i for uniform service strategy
$AIC^{'}$	The average inventory cost per item during the entire study period for the uniform service strategy
τ	Profit throughout the study period for discriminating service strategy
$\tau^{'}$	Profit throughout the study period for uniform service strategy

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A. Journal Papers

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