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An integrated plant capacity and production planning model for high-tech manufacturing firms with economies of scale

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ABSTRACT

This study developed a nonlinear mixed integer programming (MIP) model for high-tech manufacturer to determine the optimal supply chain network design. The impacts of economies of scale on the optimal capacity and the production amount are also explored. A heuristic solution approach, based on simulated annealing (SA), is developed to solve the optimal problem. An example of a wafer foundry company is provided to demonstrate the application of the model. Results show that when determining the production amount for multiple plants, a large-sized capacity plant with low capital costs and low production costs has a high priority for fulfilling the capacity due to not only having the higher capability to satisfy the customer demand but also the advantage of saving costs. The results show that the benefits brought about by centralized production are larger than the increased transportation cost. The results also show without using many small-sized capacity plants combined with high utilization, operating few larger-sized capacity plants with lower utilization is more cost effective for the manufacturer as long as the customer demand is large enough to offset the high capital cost.

1. Introduction

It has been recognized that operating cost economies of scale are associated with facility size and utilization (Cohen and Moon, 1990). For high-tech manufacturers, the investment in capacity usually involves high capital costs. Economies of scale allow manufacturers with a large-sized capacity to operate more economically than those with a small-sized capacity. However, it could result in high production costs if the market demand is insufficient to realize economies of scale, and if the capacity utilization of the manufacturing plant is low. The manufacturer can also invest many small-sized capacity plants instead. Though there is a good chance of reaching a full-capacity production, the production cost may not be minimized due to lack of economies of scale and incapability of applying advanced technology in these plants. 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.

Determining the capacity for plants is fundamental to the manufacturer's long-term planning, while the production assignment among plants is classified as medium- and short-term decisions (Santoso et al., 2005). Manufacturer's total production cost depends mainly on capacity utilization of all the plants, which is the result of the decisions, i.e. plant capacity and production assignment among the plants. Moreover, market demand governs total production amount. In other words, market demand,

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capacity and production amount of the plants determine manufacturer's total production cost. The wafer fabrication manufacturing is characterized with high capital cost and the impacts of economies of scale on production cost are obvious. The final product of the manufacturer is die, which can be produced in either 12-, 8- or 6-inch wafers. Due to the complexity production process, the variable production cost per wafer and capital cost of a 12-inch wafer plant is the highest than the others. However, operating 12-inch wafer fabrications (FABs) is a more economical alternative than the others due to the lower production cost per die when there is larger customer demand to yield higher capacity production. The capacity utilization and plant capacity determines the total production cost of the manufacturer. In other words, whether or not the manufacturer reaches a minimized cost depends on the allocation of total production between different-sized capacity plants for all different market demand. This study aims to determine the optimal location, capacity and production of the plants to minimize total cost by considering the production characteristics of wafer fabrication industry and economies of scale.

Past studies have investigated plant-loading issues in which the problems are characterized by fixed facility capacity and given facility locations. Cohen and Moon (1990) applied regression analysis to investigate the impacts of production economies of scale, manufacturing complexity, and transportation costs on supply chain facility network. 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. 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-sized plants will result in various influences on their total cost, its extent is seldom discussed. Moreover, 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.

Regarding the supply chain management field, a lot of issues have been extensively discussed. One of those discussed the integration and coordination of different functions or participants in the chain, such as buyer–vendor coordination (e.g., Tzafestas and Kapsiotis, 1994; Viswanathan and Piplani, 2001), production–distribution coordination (e.g., Goetschalckx et al., 2002) and inventory–distribution coordination (e.g., Fu and Piplani, 2004; Chen et al., 2001). Other studies developed supply chain network design models in which different factors are considered. 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. Tsiakis and Papageorgiou (2008) constructed a mixed integer linear programming (MILP) model to determine the optimal configuration of a production and distribution network subject to operational and financial constraints. Guinet (2001) focused on the multi-site production planning problem by primal-dual approach to examine the workshop scheduling problem. Levis and Papageorgiou (2004) formulated a mathematical programming model to study the long-term capacity-planning problem under uncertainty in pharmaceutical industry. There are few previous studies on supply chain design models considering the high capital costs invested in the capacity by high-tech manufacturers, and how capacity utilization of different-sized plants affects the total average production cost.

In a different line of research, issues in the supply chain of high-tech manufacturing industries have been discussed. Julka et al. (2007) established the current state of research in multi-factor models for capacity expansion in the manufacturing industry. The weakness and strength of past research and opportunities to future studies are also summarized. Nazzal et al. (2006) presented a comprehensive framework for strategic capacity expansion of production equipment so as to cut down cycle times. Chou et al. (2007) evaluated alternative capacity strategies in semiconductor manufacturing under uncertain demand and price scenarios. In the paper, the capacity planning is defined as the preparation for plant transition in anticipation of new process and new product. There are also papers conducting operational level issues regarding high-tech manufacturing industries. Chen et al. (2005) considered production scheduling planning, and developed a capacity-planning system, which considered the capacity and capability of equipment for multiple semiconductor manufacturing FABs. In their paper, "capacity" refers to the upper threshold of the load on an operating unit and "capability" refers to a specific processing capability of a machine, respectively.

Past studies have focused on the manufacturing production issues in which the decisions involve either long-term or short-term. There are few studies putting emphasis on issues about plant capacity and production allocation among plants, in which the long-term and short-term decisions are integrated and treated as endogenous decision variables, taking into account of location, market demand and economies of scale especially for plants in wafer fabrication industry. The distinguishing features of the study are the comprehensive consideration