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A comparative study on the performance of timing and sizing models of capacity expansion under volatile demand growth and finite equipment lifetime ☆

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ABSTRACT

Competition in global supply chains has become so severe that many suppliers in the high-tech manufacturing industry must shoulder high risk but have negative return on assets. While the literature is abundant with capacity models, there is a need for further research on capacity investment, especially in selecting and correctly using the right model. For a firm with lasting manufacturing operation, capacity expansion has two aspects: the timing and sizing of each expansion. The aim of a sizing method is to determine the scale of capacity expansion and that of a timing method is to determine the right time of the next expansion. The majority of capacity models in the literature can be classified as sizing models. In contrast, timing models have not received as much attention. In this paper, we compare the performance of the two types of models under volatile demand growth in order to find out the more appropriate type for the high-tech manufacturing environment. An empirical analysis of semiconductor demand is first presented. We find that the geometric Brownian motion process is appropriate for characterizing the volatility of demand growth. Based on this finding, simulation is used to compare a canonical timing and a canonical sizing models in various scenarios of demand growth, demand volatility and profit margin. We also advocate using profitability as a capacity investment criterion, in addition to the demand-satisfying criterion that is commonly used in the literature. Simulation results show that the timing model outperforms the sizing model. Finally, the behavior of the timing model is characterized as an aggressive method that can be used to exploit demand volatility for an advantage.

1. Introduction

Capacity investment planning is an important business function in industries with high capital investment cost, such as the chemical, telecommunications, electrical power, and public utility industries. Globalization of production has ushered in the era of global supply chains and created new dimensions for the capacity planning problems. At first, there are contracting and coordination problems of capacity provisioning. Recently, the competition in the global arena has become so severe that many suppliers, e.g., in the electronics industry, have negative return on assets (Shin, Kraemer, & Dedrick, 2012). Even for successful products, the total value is not evenly distributed in supply chains. It has been estimated that more than 50% of iPod's value is captured by Apple Inc. and its retailers (Linden, Kraemer, & Dedrick, 2009). Many suppliers earn meager profits but must shoulder high risk under actively managed practices such as dual sourcing and vendor managed inventory. While the literature is abundant with capacity models, many firms do not have satisfactory return on assets. There is a need for further research on capacity investment, especially in selecting and correctly using the right model.

In supply chains, interaction between business units of integrated firms or conglomerates generates a need for capacity contracting and coordination (Renna & Argoneto, 2012). Karabuk and Wu (2005) study the interaction in capacity allocation between multiple product managers and the corporate headquarter of a large corporation. In this internal supply chain, each product manager possesses private information on the demand of specific product lines but it is the headquarter which carries out manufacturing capacity investment planning and capacity allocation. Karabuk and

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Table 1
Typical investment cost of productive capacity.

Projects/plants	Capacity/specification	Cost ($M USD)
450 mm semiconductor fabrication plant (after 2015)	30 thousand wafers per month	10,000–12,000
300 mm semiconductor fabrication plant	50 thousand wafers per month	2000–3000
LCD panel, generation 8.5	50 thousand substrates/month	3000
Solar power plant, Germany	24 megawatts (first phase, world's largest), 2008	200
World's largest offshore wind farm	1000 megawatts	300–600
Commercial airplane	Airbus A380	327

Wu design an incentive scheme of bonus payments and participation charges that elicits private demand information from the product managers. When demand is volatile and investment cost is high, the profitability risk of expanding capacity will be high. If the risk is borne only by the manufacturer in a manufacturer–customer chain, capacity will tend to be under-invested, impairing the performance of the entire chain. Jin and Wu (2007) design a capacity reservation contract through which the risk can be shared between a manufacturer and its customers. Mathur and Shah (2008) take the perspective of a manufacturer who wants to influence the capacity decision of its supplier. They analyze the impact of various contract parameters on the supplier's capacity decision, supply chain efficiency, and relative allocation of supply chain profit across partners.

Under the pressure of competition to improve asset efficiency, high-tech manufacturing is an area that has inspired many research studies recently. For most high-tech products, especially in the electronics, computer and communications industries, the growth of demand has an exponential trend but with high levels of volatility. To meet growing demand, new plants must be built or existing capacity must be expanded. However, the capital cost of modern plants is extremely high. As shown in Table 1, modern manufacturing plants for semiconductor fabrication and liquid crystal display (LCD) fabrication have an investment cost of several billion US dollars per factory. Capacity expansion and investment is also a frequent business decision. For instance, since the inauguration of the first 300 mm wafer fabrication plant in 2001, more than 100 such plants have been built in the world. Active research has led to several review papers on capacity planning of high-tech manufacturing in the last few years (Geng & Jiang, 2009; Wu, Erkoc, & Karabuk, 2005).

High-tech manufacturing is generally faced with escalating investment cost and rapid technological progress. Equipment investment is largely irreversible. This is the case in semiconductor manufacturing and many other industries (Zhu, 2012). As predicted in an insightful paper by Hicks (1996) and illustrated in Chou, Huang, Jahn, and Kuo (2010), these characteristics have together created serious cash flow problems for firms that invested in semiconductor manufacturing plants. Prudent capacity expansion is crucial to a firm's competitiveness. On the one hand, the literature is abundant with capacity models. On the other hand, many firms do not have satisfactory return on assets. There is a clear need for further research on capacity investment.

Most models of capacity expansion can be classified as capacity sizing models and/or capacity timing models, besides plant location and facility type models. The aim of a sizing method[1] is to determine the scale of capacity expansion and that of a timing method is to determine the right time of the next expansion. Some authors consider both time and scale variables. Ryan (2004) considers a capacity expansion problem in which the primary objective is to satisfy demand with minimal (discounted) investment cost over an infinite horizon. Each expansion is triggered when demand reaches some fixed proportion (p) of the capacity position. The size of each expansion is also expressed as some fixed multiple (v) of the capacity position. They developed a stopping rule policy to determine the expansion time and then solved the optimal size problem under the timing policy. In a subsequent paper, Marathe and Ryan (2009) make a significant advancement by framing the problem as a mathematical programming problem with lead time and a service level constraint and solving the two variables (p and v) jointly by a cutting plane method.

Our review of the literature reveals that time models are typically aimed at satisfying the demand or maintaining a minimal service level (with respect to satisfying stochastic demand). Manne (1961) constructs a capacity expansion model and studies the effect of uncertain demand growth on the total expected cost. He concludes that "the greater the risk of running out of capacity… the greater the amount which it pays to invest in order to avert this contingency". Dangl (1999) considers the case in which a firm has to determine optimal investment time and optimal capacity level at the same time and concludes that "uncertainty in future demand leads to an increase in optimal installed capacity". Ryan (2004) considers a problem with non-zero lead-time and concludes that "When demand uncertainty is high, larger expansions are necessary". These results are consistent among themselves and they logically follow from the aim of demand-satisfying. With this aim in place, higher uncertainty in demand will require that a higher capacity be installed. However, if demand-satisfying is not the sole concern, it may not be the case that a firm will want to install more capacity. Profitability ought to be considered as an investment criterion as important as the mandate to satisfy the demand. Since demand uncertainty is detrimental to profit, the amount of capacity resource to install would be negatively related to the level of uncertainty.

There are very few comparative or appraisive studies on capacity expansion methods and their applicability in various industry settings. Lieberman (1989) investigates the behavior of capacity utilization as implied by three capacity size models. He examines plant capacity, total industry output, and capital investment cost data of 40 chemical product industries and analyzes the determinants of capacity utilization by using multiple regression analysis. He finds that empirical test results are consistent with most predictions derivable from the Newsvendor and Whitt–Luss models. In addition, capacity utilization is found to be negatively related to demand variability. Chou, Cheng, Yang, and Liang (2007) compares the performance of aggressive and conservative expansion strategies under volatile demand by using an option-based model. Their results show that profits are affected more significantly by demand volatility than by demand growth. Julka, Baines, Tjahjono, Lendermann, and Vitanov (2007) assess the state of research in multi-factor models for capacity expansion of manufacturing plants. By extensive literature review and structured assessment of the strengths and weaknesses of research papers, their main conclusions have two folds. First, substantial work has been carried out in capacity planning and solution techniques are rigorous, but no models are holistic enough to handle all important

[1] A planning method usually employs a specific model. We will use the words model and method interchangeably. We will also use timing/sizing models and time/size models interchangeably.