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Manufacturing intelligence for semiconductor demand forecast based on technology diffusion and product life cycle

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ABSTRACT

Semiconductor industry is capital intensive in which capacity utilization significantly affect the capital effectiveness and profitability of semiconductor manufacturing companies. Thus, demand forecasting provides critical input to support the decisions of capacity planning and the associated capital investments for capacity expansion that require long lead-time. However, the involved uncertainty in demand and the fluctuation of semiconductor supply chains make the present problem increasingly difficult due to diversifying product lines and shortening product life cycle in the consumer electronics era. Semiconductor companies must forecast future demand to provide the basis for supply chain strategic decisions including new fab construction, technology migration, capacity transformation and expansion, tool procurement, and outsourcing. Focused on realistic needs for manufacturing intelligence, this study aims to construct a multi-generation diffusion model for semiconductor product demand forecast, namely the SMPRT model, incorporating seasonal factor (S), market growth rate (M), price (P), repeat purchases (R), technology substitution (T), in which the nonlinear least square method is employed for parameter estimation. An empirical study was conducted in a leading semiconductor foundry in Hsinchu Science Park and the results validated the practical viability of the proposed model. This study concludes with discussions of the empirical findings and future research directions.

1. Introduction

Semiconductor industry is capital intensive, in which most chip makers focus on core competence of wafer fabrication to enhance the effectiveness of capital investments for technology migration and capacity expansion requiring long lead-time (Wu and Chien, 2008). Indeed, corporate manufacturing strategic decisions involve the interrelated elements including pricing strategies (P), demand forecast and demand fulfillment planning (D), capacity planning and capacity portfolio (C), capital expenditure (C), and cost structure (C), which will affect the overall return (R) of a company, as illustrated in the PDCCCR conceptual framework of Fig. 1 (Chien, 2009). Thus, semiconductor manufacturing companies have to forecast future demands to provide the basis for manufacturing strategic decisions including new fab construction, technology migration, capacity transformation and expansion, tool procurement, and outsourcing (Cakanyildirim and Roundy, 2002; Chou et al., 2007). Given demand uncertainty and forecast errors, companies often carry a safety stock in terms of the days of in the semiconductor supply chain. As shown in the *Bullwhip Effect* (Lee et al., 1997), the variations are amplified as moving upstream in the supply chain. Thus, it is critical for high-tech industry to develop flexible forecasting systems that allow them to quickly respond to mitigate the negative impacts of the *Bullwhip Effect* involved in the supply chain to maintain robust demand fulfillment strategies. However, the demand fluctuation due to shortening product life cycle and increasing product diversification in the consumer electronics era make the demand forecast problem increasingly difficult and complicated. Demand forecast errors cause either inefficient capacity utilization or capacity shortage that will significantly affect the capital effectiveness and profitability of semiconductor manufacturing companies.

In practice, most companies forecast the demand by combining regional sales inputs from various customers and then adjusted it with their domain knowledge and market insights. However, sales inputs tend to be biased by the customers and the *Bullwhip Effect* in the supply chain. Different forecasting methods have been applied in different areas. Most of the existing demand forecasting studies employ time series methods (Hamilton, 1994). However, these methods have difficulty for expressing the adoption process of new products. In addition, forecasting methods that are designed for a single generation cannot consider inter-generational substitution involved in semiconductor industry. Driven by Moore's Law, the semiconductor industry has continued technology migrations and wafer size enlargement to

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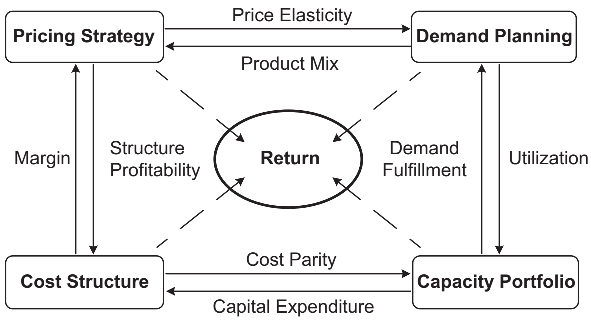

Fig. 1. Conceptual Framework of PDCCCR.

maintain technology innovation and cost reduction per transistor to penetrate into other segments for component substitution and thus achieve unparalleled growth (Leachman et al., 2007). Technology diffusion models are applied primarily to consumer durables (Meade and Islam, 2006), while little research has been done for semiconductor product demand forecast.

Focused on realistic needs for manufacturing intelligence, this study aims to construct a manufacturing intelligence framework to derive the SMPRT model based on product life cycle and technology diffusion theories, for forecasting semiconductor product demand, in which the seasonal factor (S), market growth rate (M), price (P), repeat purchases (R), technology substitution (T) are considered from historical data. Manufacturing intelligence aims to extract useful information and derived patterns from production and supply chain data to support manufacturing strategic decisions (Kuo et al., 2010). To estimate the validity of this approach, an empirical study was conducted in a leading semiconductor company, in which realistic data of 36 quarters were employed to derive the parameters in the proposed model using the nonlinear least square method and then other testing data was used to examine the forecast accuracy. The results showed the practical viability to employ the proposed model for demand forecast with little error as the basis to enhance the decision quality for capacity planning to reduce the risks of capacity shortage or surplus.

The remainder of this study is organized as follows. Section 2 reviews the related models as the fundamental. Section 3 proposes a demand forecast framework for semiconductor product and develops a multi-generation diffusion model considering essential characteristics of the present problem. Section 4 validates the proposed model with empirical data from a leading semiconductor company in Taiwan. Section 5 concludes with discussions of empirical findings and future research directions.

2. Fundamental

According to Rogers (1995), diffusion of innovation is defined as the process by which new ideas and technology are communicated among the members of a social system and thus spread through certain channels over time at specific rate. The diffusion process comprises four key elements: innovation, communication channels, time, and social system.

2.1. Bass model

Bass (1969) presented a basic diffusion model for new consumer durables to forecast the sales of the new product with the first purchase. Bass (1969) divided the adopters into two groups. The first group consists of the innovators who adopt the product via mass media communications, while the second group consists of the imitators who adopt the product via word of mouth communications. The Bass model and derived diffusion models have been widely applied to various products.

Focusing on the first purchase, the Bass model assumed that an adopter can only buy one unit in the innovation process without making a repeat purchase. Bass model was based on the hazard function, in which the probability of adoption occurring at time t in circumstances where it has not yet occurred as follows:

$$\frac{f(t)}{1-F(t)} = p+qF(t) \tag{1}$$

where $f(t)$ is the probability destiny function of adopters at time t, $F(t)$ the cumulative destiny function of adopters at time t, p the coefficient of innovation (external coefficient), and q is the coefficient of imitation (internal coefficient).

If m denotes the market potential, the number of adopters at time t can be calculated using $n(t)=mf(t)$ and the cumulative number of adopters at time t can be calculated by using $N(t)=mF(t)$. Then, Bass model can be rewritten as follows:

$$\begin{aligned} n(t) &= \frac{dN(t)}{dt} = mf(t) = m[p+qF(t)][1-F(t)] \\ &= [pm+qN(t)][1-F(t)] = p[m-N(t)]+\frac{q}{m}N(t)[m-N(t)] \end{aligned} \tag{2}$$

The first part of Eq. (2) represents the adopters buying the new product due to external influences. The second part represents the adopters purchasing the new product due to internal influences. Fig. 2 illustrates the basic concept of the Bass model. During the introduction stage, external influences lead adopters to purchase the product. During subsequent stages, these external influences decrease while the internal influences increase, i.e., the diffusion process is symmetric. Given $t=0$ in Eq. (2), $n(0)=pm$ represents the initial adopters at the start of the diffusion process. The number of adopters reaches the peak at time T^*, which denotes the inflection point of the curve of the cumulative adopters.

The cumulative density function of adopters $F(t)$ and its peak time T^* can be derived from Eq. (1) as in Eqs. (3) and (4), respectively:

$$F(t) = \frac{1-e^{-(p+q)t}}{1+(q/p)e^{-(p+q)t}} \tag{3}$$

$$T^* = \frac{1}{(p+q)}\ln\left(\frac{q}{p}\right) \tag{4}$$

2.2. Multi-generation diffusion model

While the Bass model (1969) considered only the first purchase of new products for a single generation, Norton and Bass (1987) extended it into a multi-generation diffusion model for high-tech products. Norton and Bass model assumes the following: (1) the existence of a series of advancing generations,

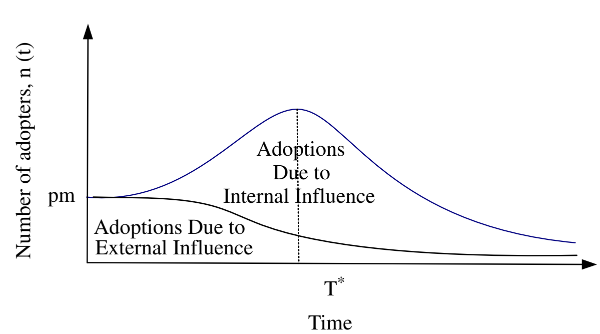

Fig. 2. The concept of the Bass model.