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A stochastic dynamic programming approach for multi-site capacity planning in TFT-LCD manufacturing under demand uncertainty

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ABSTRACT

The study focuses on the dynamic multi-site capacity planning problem in the thin film transistor liquid crystal display (TFT-LCD) industry under stochastic demand. Capacity planning refers to the process of simultaneously implementing a robust capacity allocation plan and capacity expansion policy across multiple sites against stochastic demand. In addition, the demand situation in TFT-LCD manufacturing follows Markov properties, in which the correlations of the demand variations in the consecutive periods are high, and the demand status in the next period is stochastically determined by the present one. Therefore, this study constructs a stochastic dynamic programming (SDP) model with an embedded linear programming (LP) to generate a capacity planning policy as the demand in each period is revealed and updated. Using the backward induction algorithm, the SDP model considers several capacity expansion and budget constraints to determine a robust and dynamic capacity expansion policy in response to newly available demand information. The LP model then considers numerous TFT-LCD practical characteristics and constraints to decide a capacity allocation plan, and generate a one-period immediate reward used by the optimality recursion equation of the SDP model. Numerical results are also illustrated to prove the feasibility and robustness of the proposed SDP model compared to the traditional deterministic capacity planning model currently applied by the industry.

1. Introduction

The thin film transistor liquid crystal display (TFT-LCD) industry is a relatively young, next-generation, high technology industry that developed after the semiconductor manufacturing industry. According to DisplaySearch, a major display market research and consulting company, the shipment of LCD TV in North America, grew by 52% (7.5 million units) in the second quarter of 2008. Furthermore, the total value of TFT-LCD sales worldwide increased from US$ 60 billion in 2005 to over US$ 100 billion in 2008. The production network in TFT-LCD panel manufacturing consists of three manufacturing stages, namely array, cell, and module processes, and each stage has multiple production sites. The array process is where bottlenecks usually occur, a condition very similar to that in semiconductor wafer fabrication and in capacity-constrained and capital-intensive production environments. Effective utilization and management of its production capacity is, therefore, crucial for the TFT-LCD industry.

As a result of three significant trends, capacity and product mix planning has gradually become an important mid-term strategic issue closely monitored by the TFT-LCD industry. The first trend is the increase in product types, which lead to the production of a wide range of product groups, such as mobile phones, monitors, notebook PCs, TVs, and industrial displays. The second trend is the advancement of new technologies, which cause multiple generations of technologies to coexist in multi-site production systems. Production facilities that use different sizes of glass substrates are called different generation sites. “Glass substrate” is a key material used in manufacturing various TFT-LCD products in the array process. Higher generation sites use larger glass substrates and can produce different types of products. The third trend is the rapidly changing and stochastic Markovian demand model. As shown in Fig. 1, the sales volume of four product groups has rapidly changed over time. Moreover, through the partial autocorrelation analysis (see Box et al., 1994) usually employed to identifying the extent of the lag in an autoregressive time series model, we find that the partial autocorrelation function for the TFT-LCD demands of all product groups indicates a very large value at the lag of 1 month (see Fig. 2), with all lags greater than one showing negligible partial autocorrelation. This means that the TFT-LCD sale quantities in a specific month are highly correlated with ones in the previous month or the demand status of TFT-LCD industry in the next period is stochastically determined by the present one. Therefore, the time series of TFT-LCD demand

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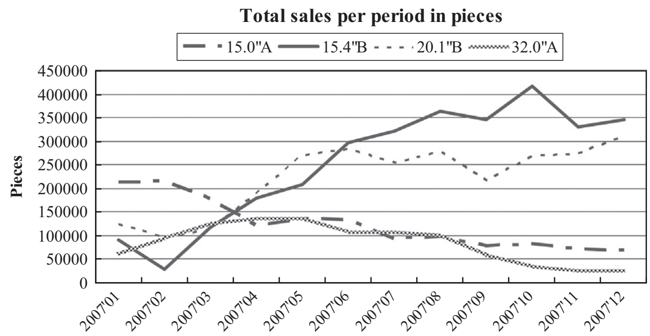

Fig. 1. Total sales volume of four product groups in TFT-LCD industry.

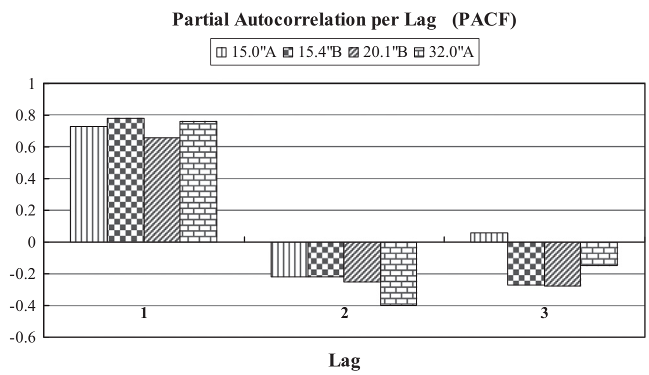

Fig. 2. Markovian demand demonstration through PACF analysis of four product groups.

exhibits an autoregressive behavior at the lag of 1 month. Consequently, this finding demonstrates that the evolution of demand must be represented using a Markovian demand model.

In the complicated environment described above, TFT-LCD manufacturers encounter the strategic capacity planning problem of balancing demand and supply to determine dynamic capacity allocation and expansion decisions in response to new yet uncertain demand information. The capacity allocation decision entails determining the profitable product mix and production quantities of each product group at a given site in a particular period. To meet the projected stochastic demands, capacity expansion decisions must identify the procured amounts of the new auxiliary tools and expanded quantities of product group-specific capacity at a suitable site within a particular timeframe.

Furthermore, the deterministic programming model (e.g., linear programming, integer programming, etc.), which is most often used in the industry, can generate an optimal capacity plan using the expected demand information, but fails to consider demand uncertainties. Thus, adjusting the capacity expansion plan to meet updated demands is impossible. Although the traditional two-stage stochastic programming in previous literature considers uncertain demand situations using discrete scenarios that contain associated probabilities, it typically assumes demand independence over time; this aspect oversimplifies the representation of real-world demand evolution. These two-stage methods do not incorporate dynamic capacity adjustment decisions (allocation and expansion) that depend on future market development. Therefore, the present study constructs a multi-stage stochastic dynamic programming (SDP) model with an embedded linear programming (LP) model, which considers numerous TFT-LCD practical characteristics and constraints to generate a dynamic capacity planning policy as the demand in each period is revealed and updated. Through the backward induction algorithm, the SDP model considers several capacity expansion and budget constraints to determine a robust and dynamic capacity expansion policy in response to newly available demand information. The LP model then considers numerous TFT-LCD practical characteristics and constraints to decide a capacity allocation plan within single period, and generate a one-period immediate reward used by the optimality recursion equation of the SDP model. Finally, a modified industrial case involving a TFT-LCD manufacturer in Taiwan is presented to verify the feasibility of the proposed model using the backward induction algorithm. The numerical results show that the proposed SDP model, compared to the deterministic model, can provide a hedged robust solution against demand uncertainties and yield higher total profits.

The rest of the paper is organized as follows. Section 2 reviews several works in the literature regarding stochastic capacity planning problems. Section 3 defines the stochastic dynamic multi-site capacity planning problem in TFT-LCD manufacturing, and formulates a stochastic dynamic programming model. By conducting a numerical study, Section 4 verifies the feasibility and robustness of the proposed SDP model compared to the deterministic model explicitly practiced in the current industry. Finally, Section 5 presents the concluding remarks.

2. Literature survey

In the literature, two-stage stochastic programming is a dominant approach to handling stochastic capacity planning under various uncertainties. Swaminathan (2000, 2002) proposes a scenario-based stochastic programming approach to tool capacity planning in a wafer fabrication facility under demand uncertainties. To address the computational complexities in stochastic programming, the author develops several heuristics in solving tool procurement problems. Hood et al. (2003) and Barahona et al. (2005) propose two-stage stochastic integer programming models and LP relaxation-based heuristics for robust tool procurement planning in semiconductor manufacturing under demand uncertainties. Christie and Wu (2002) and Karabuk and Wu (2003) present a scenario-based stochastic programming model for strategic capacity planning under demand and capacity uncertainties in the semiconductor industry. According to Karabuk and Wu (2003), capacity planning in the semiconductor industry can be described as an iterative process between capacity expansion and capacity configuration. Meanwhile, Geng et al. (2009) propose a scenario-based stochastic programming model, which considers demand and capacity uncertainties via scenarios to maximize the overall equipment efficiency. Based on the decentralized structure of tool procurement, production, and inventory decision-making processes, the authors present different recourse approximation strategies that share varying degrees of information. Rastogi et al. (2011) present a two-stage stochastic integer-programming model for the semiconductor supply network. The model made strategic capacity decisions while accounting for the uncertainties in demand for multiple products. Levis and Papageorgiou (2004) formulate multi-site capacity planning, which determines both product portfolio and capacity in the face of uncertain clinical trial outcomes, as a two-stage, multi-scenario, mixed-integer linear programming model. MirHassani et al. (2000) present a two-stage capacity planning model in the face of future uncertainties. Lin et al. (2011) consider the special characteristics of the TFT-LCD manufacturing systems to propose a scenario-based, two-stage stochastic programming model, and seek a robust capacity allocation and expansion policy against demand uncertainties. Meanwhile, Bihlmaier et al. (2009) investigate investment decisions on product flexibility and capacity provision through an accelerated Benders decomposition approach. Their two-stage stochastic model is tailored to the automotive industry, and integrates tactical workforce planning aspects. Hahn and Kuhn (2012) provide a corresponding framework for value-based performance and risk optimization in