The Capacity Planning Problem Considering the Procurement of Bottleneck Machines and Auxiliary Tools

Yin-Yann Chen, Hsiao-Yao Fan, Chiung-Wen Shih, and Po-Han Huang

***Abstract*—This study explores issues on medium-term multi-plant capacity allocation and expansion planning in the TFT-LCD industry. Since the Array stage is the bottleneck of this production network, our research objective is to simultaneously seek an optimal capacity allocation plan and capacity expansion policy under single-stage, multi-generation and multi-site structures. Capacity allocation decides on profitable product mixes and allocated production quantities of each product group at each production site. An increment strategy for the numbers of bottleneck machines and auxiliary tools—"photo mask" is proposed to increase the flexibility of production. The decisions include how to allocate appropriately the forecast demands of products among multiple sites and how to decide on the numbers of bottleneck machines and auxiliary tools. A mathematical programming model of capacity planning is formulated to solve this problem and find the best solution, which considers practical characteristics and constraints of TFT-LCD manufacturing. Finally, an industrial case study modified from a Taiwanese TFT-LCD manufacturer is illustrated and sensitivity analysis of some influential parameters is also addressed.**

***Index Terms*—capacity expansion, capacity planning, TFT-LCD**

I. INTRODUCTION

THE manufacturing process of TFT-LCD panel industry comprises three major stages, namely, the Array, Cell and Module processes. In each stage, there exist more than one production factories with different technological generations to constitute a complicated multi-site manufacturing environment. The front-end Array process, the critical bottleneck in the three processes, is similar to the semiconductor fabrication process, the only difference being that the thin-film transistors are placed on the “glass substrate” instead of the silicon wafer. The Cell process joins the Array substrate with a color-filter substrate, inserts the liquid crystal between the two substrate layers, and cuts the combined substrate into the various sizes of “LCD panels”. The back-end Module process involves taking the LCD panel and bonding the driver integrated circuits (IC), and assembling backlights, metal frame and other components to form the finished “TFT-LCD panels”. Since the bottleneck process, Array stage, is the capacity-oriented and capital-intensive environments that emphasize the high utilization of machines and reduce the loss of capacity, how to effectively procure, utilize, and align their production capacity across multiple sites is a crucial issue for the TFT-LCD industry. Consequently, this paper only focuses on the capacity allocation and expansion problem under single-stage and multi-site structures.

TFT-LCD companies often face critical capacity planning issues caused by demand and supply imbalance in multi-generation and multi-site production chains. A company must simultaneously seek an optimal capacity allocation plan and capacity expansion policy based on demand forecasts provided by sale and market departments. Capacity allocation needs to decide on profitable product mixes and allocated production quantities of each product group across all production sites. Capacity expansion is concerned with determining the timing, types, and sizes of capacity investments. In general, the TFT-LCD manufacturers have three capacity investment options: (1) building a new site to add to the total capacity of TFT-LCD manufacturers; (2) purchasing a new bottleneck machine to increase global available capacity of the existing site; and (3) acquiring a new auxiliary tool to expand the available capacity of a product group at a certain production site. The first options belong to the irregular decisions at strategic corporate planning and are not easily implemented by the TFT-LCD manufacturer since there are several factors and difficulties in practice such as higher investment costs, long construction/installation time, and limitations in space of existing sites, etc. This paper only focuses on the acquisition of new bottleneck machines and auxiliary tools, the second and the third investment option, to expand the available capacity at a certain production site.

II. LITERATURE REVIEW

Hopp and Spearman [1] propose that the capacity planning must consider how much and what type of capacity to install and have a major impact on all other production planning issues (e.g., aggregate planning, demand management, sequencing and scheduling). Additionally, when capacity decision makers have decided to add capacity, there are several issues to address: (1) how much and when should capacity be added? (2) what type of capacity should be added? (3) where should additional capacity be added?

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Liang and Chou [2] and Chou et al. [3] classify the capacity planning tasks into three levels by their planning horizon. In the long term, the objective of capacity planning is to prepare for plant transition in anticipation of new process technology and new product and to support strategic plans of business. In the medium term, capacity can be changed by tool purchase and decommission. It should be noted that capacity is expanded in small increments, by gradually populating the factory with more machines. Capacity planning in this time frame is mainly a tool portfolio configuration problem. In the short-term, the overall capacity is largely fixed, but with some room for adjustment through equipment set-up change-over (i.e., alternative routing). Therefore, capacity planning problems are mainly about capacity allocation among job orders and alternative routing planning.

Based on different production environments, the capacity planning problems discussed in literature can be categorized into three major categories: single-site capacity planning, multi-site capacity planning without new site installation and multi-site capacity planning with new site installation (or called supply chain network design).

Through purchasing, renting, transferring or replacing new machines or auxiliary tools, single-site capacity planning problems focus on determining the best resource investigation for allocating and expanding the capacity of a particular site to meet required demands. Li and Tirupati [4] constructed a multi-product dynamic investment model to make technology selections and expansion decisions in a single production facility. Rajagopalan [5] unified the equipment replacement and capacity expansion research by developing a general model which considers the capacity for replacement as well as expansion. Rajagopalan and Swaminathan [6] developed a mathematical programming model as an effective solution to determine the optimal capacity expansion, production and inventory decisions. Wang and Lin [7], Wang and Hou [8], and Wang et al. [9] made preliminary studies on a capacity allocation and expansion problem with tool investments (such as test machines or handlers) in a semiconductor testing facility.

Uribe et al. [10] indicate that the main issue in capacity planning is to decide the amount of investment and the selection of resource to use. Their research formulates capacity planning problem as a two-stage stochastic integer program in which the first stage characterizes the optimal response under uncertainties and the second stage selects a tool set based on the characterization from the first stage.

For the multiple sites capacity planning without new site installation, most literatures focus on how to meet future demands through expanding the capacity of existing sites to minimize total costs or maximize total profits. Papageorgiou et al.[11] proposes mixed-integer linear programming model to formulate a capacity planning and investment problem for the manufacturing network of the pharmaceutical industry.

The multiple sites capacity planning with new site installation simultaneously integrate manufacturing network design/ facility location and capacity planning problems to address three issues: (1) what are the optimal product mixes and production quantities across multiple factories? (2) what capacity expansion method should be adopted to meet unsatisfied demands through expanding the capacity of existing sites or building a new site? and (3) where new site should be opened and how much capacity should be installed in the new site under the new site installation? These problems are also called capacitated facility location and strategic supply chain network design in the literature.

MirHassani et al. [12] develop a two-stage resource allocation to investigate a strategic capacity planning problem for supply chain under demand uncertainties. The first stage strategic decisions are concerned with the opening and closing of sites and distribution centers and setting their capacity levels. The second stage operational decisions, such as production quantities and transportation amounts represent recourse actions when demands are revealed.

From the studies we have surveyed on capacity planning issues, little attention has been directed to the auxiliary tools purchasing strategy. In this paper, the capacity allocation planning and expansion policy problem in the TFT-LCD industry is explored.

III. The Capacity Allocation and Expansion Model

A mixed integer linear programming model (MILP) to simultaneously get the best capacity allocation and expansion plan is developed. The purpose of capacity allocation is to generate the profitable product mix and the best production quantities of each product group across multiple sites in each period. The result of capacity expansion is to identify the purchasing amounts of the new bottleneck machines and the auxiliary tools at each site in each period. The overall objective of the capacity allocation and expansion model is to meet the future demand forecast with the maximized overall net profits. This model also considers many practical characteristics and constraints of TFT-LCD manufacturing.

The following notation is used for problem formulation.

Indices

i = Production site index

k = Product group index

t = Planning time period index

The following parameters are defined.

Parameters

- *Demand Parameters*

de_{kt} = Demand forecast of product group k in period t (pieces)

pr_{ikt} = Marginal profit for selling one unit of product group k produced by site i in period t (\$/piece)

ph_k = Possible phase-out time of product group k

- *Supply Parameters*

cw_{it} = Available global capacity of site i in period t (sheets) (determined by the number of bottleneck machines)

cf_{ik} = Capacity consumption factor of product group k at site i

ca_{ikt} = Available capacity of product group k at site i in period t (sheets)
(determined by the number of auxiliary tools)

cr_{ik} = Economic cutting ratio of product group k at site i (pieces/sheet)

ye_{ikt} = Yield rate of product group k at site i in period t

- *Capacity Expansion Parameters*

ea_{ik} = Capacity expansion capability for product group k at site i
(If ea_{ik} =1, site i has a capability to expand capacity of

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product group k ; if ea_{ik} =0 , site i has no capability)

eb_{ikt} = Capacity expansion upper bound for product group k at site i in period t (sheets)

eu_{ik} = Added capacity amount for purchasing one new auxiliary tool of product group k at site i (sheets/one auxiliary tool)

el_{ik} = Procurement lead time for the auxiliary tools of product group k at site i

dp_i = Depreciation time length for purchasing one new bottleneck machine of site i

su_i = Added capacity amount for purchasing one new bottleneck machine of site i

sl_i = Procurement lead time for the bottleneck machines of site i

- *Cost Parameters*

ec_{ikt} = Capacity investment cost for purchasing one new auxiliary tool of product group k at site i in period t ($)

ic_{ikt} = Unit inventory holding cost of product group k at site i in period t

sc_{it} = Capacity investment cost for purchasing one new bottleneck machine of site i in period t

- *Budget Parameters*

b_t = The upper bound for budget in period t ($)

- *Financial Parameters*

tax_t = Tax rate at the end of time period t

ip_t = Interest paid at the end of time period t

cdf = Capital discount factor

The decision variables are as follows.

Decision variables

- *Capacity Allocation Continue Variables*

XQ_{ikt} = Production quantity of product group k at site i in period t (sheets)

ZO_{ikt} = Sale quantity of product group k produced by site i in period t

IQ_{ikt} = Inventory quantity of product group k at site i in period t

- *Capacity Expansion Discrete (Integer) Variable*

EM_{ikt} = Procurement amount of new auxiliary tools for expanding the capacity of product group k at site i in period t

SM_{it} = Purchasing amount of new bottleneck machines for increasing the global capacity of site i in period t

- *Financial Variable*

$EBIT_t$ = Earning before interests and taxes at the end of time period t ($)

NCF_t = Net cash flows at the end of time period t ($)

The objective function is defined as follows.

Objective function

Maximize

$$\sum_{t=1}^{T}\left[NCF_t \times \left(1+cdf\right)^{-t}\right] \quad (1)$$

The objective of the strategic supply chain planning process is to maximize the long-term economic performance of the corporation. In this study, the figure is the net present value (NPV) of the streams of net cash flows (NCF). This model also considers many practical characteristics and constraints of TFT-LCD manufacturing described in the previous section. The constraints are formulated as follows.

Constraints

- Demand Satisfaction Constraint

$$\sum_i ZQ_{ikt} \le de_{kt} \qquad \forall k,t \quad (2)$$

- Site-Product Available Capacity Constraint

$$XQ_{ikt} \le ca_{ikt} \qquad \forall i,k,t \le el_{ik} \quad (3)$$

$$XQ_{ikt} \le ca_{ikt} + eu_{ik} \times \sum_{t'=1}^{t'=t-el_{ik}} EM_{ikt'} \quad \forall i,k,t > el_{ik} \quad (4)$$

- Capacity Expansion Capability Constraint

$$EM_{ikt} \le M_{ikt} \times ea_{ik} \quad \forall i,k,t \quad \left(define\ M_{ikt} = \frac{eb_{ikt}}{eu_{ik}} \right) \quad (5)$$

- Capacity Expansion Upper Bound Constraint

$$eu_{ik} \times \sum_{t'=1}^{t'=t-el_{ik}} EM_{ikt'} \le eb_{ikt} \quad \forall i,k,t > el_{ik} \quad (6)$$

- Inventory balance constraint

$$IQ_{ik0} = iq_{ik0} \qquad \forall i,k \quad (7)$$

$$IQ_{ik(t-1)} + XQ_{ikt} \times cr_{ik} \times ye_{ikt} - ZQ_{ikt} = IQ_{ikt} \quad \forall i,k,t \quad (8)$$

- Site Global Capacity Constraint

$$\sum_k (XQ_{ikt} \times cf_{ik}) \le cw_{it} \qquad \forall i,t < sl_i \quad (9)$$

$$\sum_k (XQ_{ikt} \times cf_{ik}) \le cw_{it} + su_i \times \sum_{t'=1}^{t'=t-sl_i} SM_{it'} \quad \forall i,t > sl_i \quad (10)$$

- Budget Constraint

$$\sum_i \sum_k \left(ec_{ikt} \times EM_{ikt}\right) + \sum_i \left(sc_{it} \times SM_{it}\right) \le b_t \quad \forall t \quad (11)$$

- Financial Constraint

$$\begin{aligned} EBIT_t = & \sum_i \sum_k (pr_{ikt} \times ZQ_{ikt}) - \sum_i \sum_k (ic_{ikt} \times IQ_{ikt}) \\ & - \sum_i \sum_k \left\{ \left(\frac{ec_{ikt} \times EM_{ikt}}{ph_k - t + 1 - el_{ik}} \right) \times \left[\min(ph_k, T) - t + 1 - el_{ik} \right] \right\} \\ & - \sum_i \left\{ \left(\frac{sc_{it} \times SM_{it}}{dp_i} \right) \times (T - t + 1) \right\} \qquad \forall t \end{aligned} \quad (12)$$

$$NCF_t = \left(1 - tax_t\right) \times \left(EBIT_t - ip_t\right) \quad \forall t \quad (13)$$

- Domain Constraints：

$$XQ_{ikt}, ZQ_{ikt}, IQ_{ikt} \in R^+ \cup \{0\} \quad \forall i,k,t \quad (14)$$

$$EM_{ikt}, SM_{it} \in N \cup \{0\} \quad \forall i,k,t \quad (15)$$

IV. Discussion

The capacity allocation planning and expansion policy problem in the TFT-LCD industry is presented in this paper. This study proposes a mixed integer linear programming (MILP) to formulate the capacity allocation and expansion model, which considers many practical characteristics and constraints of TFT-LCD manufacturing.

Consequently, from the demand fulfillment comparisons of these two strategies (limited and full expansion capabilities) shown in Figure 1, the average demand fulfillment rate of full expansion capabilities is more than the rate of limited expansion capabilities and the product groups with the higher marginal profit are completely satisfied. However, it is not a regular law that the product groups with the highest marginal

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profit must be satisfied since we need to consider other factors including economic cutting ratio and demand quantities.

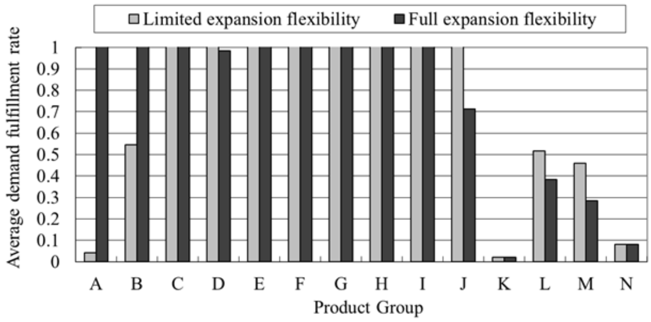

Figure 1. Average demand fulfillment rate between limited and full expansion capabilities

As shown in Figure 2, the analysis results based on the variations of different influential parameters indicate that total profit exhibits an increasing trend as all parameter levels gradually become larger except for the expansion cost level.

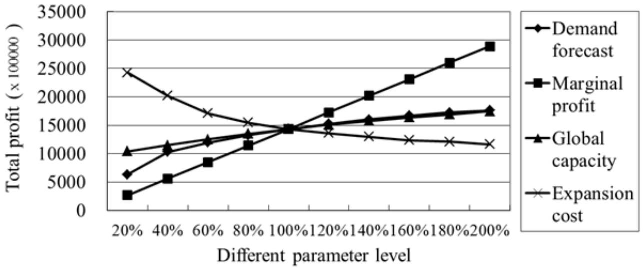

Figure 2. Total profit fluctuations based on the variations of different influential parameters

For the marginal profit parameter, the increasing line of total profit is linear and the changing ratio of total profit is equal to the varying ratio of the marginal profit levels. For the expansion cost parameter, total profit will slowly decrease when the expansion cost increases. For the demand forecast and global capacity parameters, the increment rate of total profit becomes smooth with an increase in the parameter levels.

REFERENCES

[1] W. J. Hopp, and M. L. Spearman, "Factory Physics: Foundations of Manufacturing Management", Third Edition, McGraw-Hill, 2008.

[2] Y. Y. Liang, and Y. C. Chou, "Option-based Capacity Planning for Semiconductor Manufacturing", *2003 IEEE International Symposium on Semiconductor Manufacturing*, pp.77–80, 2003.

[3] Y. C. Chou, C. T. Cheng, F. C. Yang, and Y. Y. Liang, "Evaluating alternative capacity strategies in semiconductor manufacturing under uncertain demand and price scenarios", *International Journal of Production Economics*, Vol. 105, pp.591–606, 2007.

[4] S. Li, and D. Tirupati, "Dynamic Capacity Expansion Problem with Multiple Product: Technology Selection and Timing of Capacity Additions", *Operations Research*, Vol. 42, No. 5, pp.958–976, 1994.

[5] S. Rajagopalan, "Capacity Expansion and Equipment Replacement: A Unified Approach", *Operations Research*, Vol. 46, No. 6, pp.846–857, 1998.

[6] S. Rajagopalan, and J. M. Swaminathan, "A Coordinated Production Planning Model with Capacity Expansion and Inventory Management", *Management Science*, Vol. 47, No. 11, pp.1562–1580, 2001.

[7] K. J. Wang, and S. H. Lin, "Capacity expansion and allocation for a semiconductor testing facility under constrained budget", *Production Planning & Control*, Vol. 13, No. 5, pp.429–437, 2002.

[8] K. J. Wang, and T. C. Hou, "Modeling and resolving the joint problem of capacity expansion and allocation with multiple resources and a limited budget in the semiconductor testing industry", *International Journal of Production Research*, Vol. 41, No. 14, pp.3217–3235, 2003.

[9] K. J. Wang, S. M. Wang, and S. J. Yang, "A resource portfolio model for equipment investment and allocation of semiconductor testing industry", *European Journal of Operational Research*, Vol. 179, pp.390–403, 2007.

[10] A. M. Uribe, J. K. Cochran, and D. L. Shunk, "Two-stage simulation optimization for agile manufacturing capacity planning", *International Journal of Production Research*, Vol. 41, No, 6, pp.1181–1197, 2003.

[11] L. G. Papageorgiou, G. E. Rotstenin, and N. Shah, "Strategic supply chain Optimization for the Pharmaceutical Industries", *Industrial & Engineering Chemistry Research*, Vol. 40, pp.275–286, 2001.

[12] S. A. MirHassani, C. Lucas, G. Mitra, E. Messina, and C. A. Poojari, "Computational solution of capacity planning models under uncertainty", *Parallel Computing*, Vol. 26, No. 5, pp.511–538, 2000.

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