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A model for batch available-to-promise in order fulfillment processes for TFT-LCD production chains

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ABSTRACT

The main purpose of this study is to explicitly highlight several special production characteristics in a thin-film transistor liquid crystal display (TFT-LCD) manufacturing industry and to present an available-to-promise (ATP) model that supports decision-making in order fulfillment processes for TFT-LCD manufacturing. A TFT-LCD production chain differs from others in its special production characteristics such as alternative bill-of-materials (BOMs), grade transition, etc., which are significant factors driving a success in an ATP implementation. Customers may specify a quality level and the materials to be used in a finished product in inquiry orders. The quality of the working-in-process can be altered using different assembled components. The ATP model enhances the responsiveness of order fulfillment processes. The ATP model directly links available material resources and capacity with inquiries or existing customer orders to improve the overall performance of the production chain. A case study using the model demonstrates the effectiveness and efficiency of the proposed ATP model in a TFT-LCD production chain and investigates the sensitivity of TFT-LCD plant performance to changes in order batching intervals.

1. Introduction

The demand for thin-film transistor liquid crystal display (TFT-LCD) products is projected to grow over the next few years due to declines in average unit prices and the replacement of Cathode Ray Tubes (CRTs) with flat panel technology (Pecht & Lee, 1997; Wang, Liu, & Wang, 2008). The TFT-LCD industry is a relatively young dynamic industry and draws attention on various research topics including Lin and Chen (2007), and Lin, Chen, and Chen (2007). In 2005, the total value of flat panel display sales worldwide was US$65.25 billion (Electronicstalk (Etalk), 2006), and LCDs accounted for over 95% of flat panel display sales by value. Most TFT-LCD products have been manufactured in East Asia since 1990 (emsnow Dominique Numakura's newsletter from Japan, 2006). Manufacturing was first dominated by Japan; Korea and Taiwan entered the market relatively later. Sharp (Japan), Samsung Electronics and LG Philips (Korea) and CMO and AUO (Taiwan) are the dominant manufacturers (Chang, 2005). The TFT-LCD manufacturers in Japan and Korea generate production schedules mainly based on product sales forecasts via the sales department within the firm. However, some of TFT-LCD makers supply assembled displays to brand-name firms as an original-equipment-manufacturer (OEM); this is the case for many Taiwanese TFT-LCD manufacturers. Thus, customer satisfaction associated with the management of orders is extremely essential to TFT-LCD suppliers in Taiwan compared to other TFT-LCD makers in other countries. Order fulfillment processes respond to inquiry orders from potential or existing customers. Efficient and effective order fulfillment processes enable firms to accurately estimate delivery date and the available quantity of materials for a specific inquiring order. Another motivating issue is that a TFT-LCD plant is highly capital-intensive requiring a few billion dollars of investment (Park et al., 2008). Thus, a high utilization TFT-LCD production chain is essential to be competitive in the global market.

To retain customers and increase market share in today's competitive markets is extremely important, especially in consumer product markets. This is particularly true in the current business-to-business (B2B) era. Inquiring orders are entered online in a customer's front end; customers expect to receive a reliable quote and promised delivery date within a short time period. In order fulfillment processes, the *available-to-promise* (ATP) model provides a synchronized supply and capacity plan that represents actual and future availability of supplies and capacity that can be utilized to accept new customer orders (Kilger & Schneeweiss, 2000). An early study describing the ATP concept is found in Schwendinger (1979). Fischer (2001) provides a comprehensive overview of ATP-related work and classified planning tasks associated with the ATP model.

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The ATP model for the TFT-LCD industry is complicated due to its special production processes, which are seldom noticed in the referred academic journals because this industry is located only in a few countries as mentioned earlier. The production characteristics of the TFT-LCD industry, however, deserve research attentions due to its capital-intensive feature and special production characteristics different from conventional production styles. A typical TFT-LCD manufacturing process consists of three major stages—array, cell, and module as illustrated in Fig. 1. The array process in TFT-LCD industries is very similar to semiconductor manufacturing processes, except that transistors are fabricated on a glass substrate instead of a silicon wafer. The cell process assembles thin-film transistor (TFT) panels from the array stage with color filter panels. This assembly process is followed by a process that injects liquid crystals. The module process is the last stage in TFT-LCD manufacturing in which cell glass panels from the cell stage are assembled with all other necessary parts, such as backlights, driver integrated circuits (ICs), and printed wired boards (PWBs), to complete the final TFT-LCD products. The production type in array and cell processes is typically a *push* framework due to the characteristics of capital-intensive investment and low-diversity in product categories. However, the production type in module processes is in the *pull* framework as TFT-LCD manufacturers face a fluctuating demand and involve a material-oriented production environment that depends on the availability of parts or components.

Customer satisfaction is one of the most important performance measures for a module process that assembles cell glass panels with other components and converts them into finished products, and finally delivers products to customers. The ability to respond quickly and effectively to customer inquiring orders is essential to the competitiveness of module plants. An efficient ATP model enables module plants to estimate accurate delivery dates, quantities of products, and their production schedules.

The foundations for the proposed ATP model are derived from *one of tasks* described by Lin, Chen, and Lin (2006) for a hierarchical planning and scheduling framework in TFT-LCD production chains. The ATP issues in a production chain have garnered research interest recently (e.g., Ball et al., 2004; Kilger & Schneeweiss, 2000). Mixed integer linear programming or linear programming models for ATP-related problems can be found in (Chen, Zhao, & Ball, 2001; Chen, Zhao, & Ball, 2002; Ervolina, Ettl, Lee, & Peters, 2009; Lin & Chen, 2005; Meyr, 2009; Pibernik, 2005; Zhao, Ball, & Kotake, 2005). Xiong, Tor, Khoo, and Chen (2003a), Xiong, Tor, and Khoo (2003b) developed a web-enhanced dynamic bill-of-material (BOM)-based ATP system. Moses, Grant, Gruenwald, and Pulat (2004) developed a method for real-time determination of order due dates that is applicable to build-to-order environments facing dynamic order arrivals. Pibernik and Yadav (2009) consider random demands to derive a Make-to-Stock order fulfillment system for reserving inventory in anticipation of future order arrivals from high priority customers and for order promising in real-time. Lin and Shaw (1998) proposed an approach for reengineering the order fulfillment process in supply chain networks to improve efficiency, flexibility, robustness, and adaptability. However, none of these studies focused on use of an ATP model in TFT-LCD industries. Jeong, Sim, Jeong, and Kim (2002) developed an ATP system for TFT-LCD manufacturing and proposed an efficient heuristic for calculating unused production capacity at the shop floor level with given production schedules. Furthermore, they proposed an efficient heuristic for scheduling TFT-LCD module assembly processes for effective use of unutilized capacity. Our study differs from Jeong et al. (2002) in that this research considers special production network characteristics in a TFT-LCD production chain with numerous downstream clients rather than a typical production chain. Additionally, the proposed model in this paper returns the ATP results in a reasonable computational time frame. Tsai and Wang (2009) constructed a generic three-stage model of multi-site ATP mechanism for the assemble-to-order manufacturing on a TFT-LCD manufacturer without consideration of several special production characteristics in TFT-LCD manufacturing. The ATP plan in a TFT-LCD production chain has become a critical and unique problem other than a general ATP model for following reasons: (1) a multi-generation and multi-site production system generated by coexistence of multiple generations of manufacturing technologies, (2) complex product hierarchies and product types caused by a wide range of applications, (3) alternative selections of bill-of-material (BOM) designated by customers, and (4) grade transition nature due to various combinations of components. To our best knowledge, none of the previous research considers these special production properties in a TFT-LCD production chain.

The major contribution of this study is to explicitly address these special production characteristics, which are significant factors driving a success in ATP implementation in a TFT-LCD production chain, accompanying with an ATP model tailored for TFT-LCD module plants. In addition, this study is designed to efficiently compute delivery date and quantity of TFT-LCD products by considering several special production characteristics such that module plants can reduce unsatisfactory orders due to insufficient capacity or materials. These special production characteristics include alternative Bill-of-Material (BOM) and multiple quality grades of cell glass panels and final TFT-LCD products. The remainder of this paper is organized as follows. Section 2 presents an overview and analysis of order fulfillment processes in a TFT-LCD industry. Section 3 formulates an ATP model for TFT-LCD module plants, followed by a case study in Section 4. Section 5 summarizes experimental results and concludes with several managerial implications.

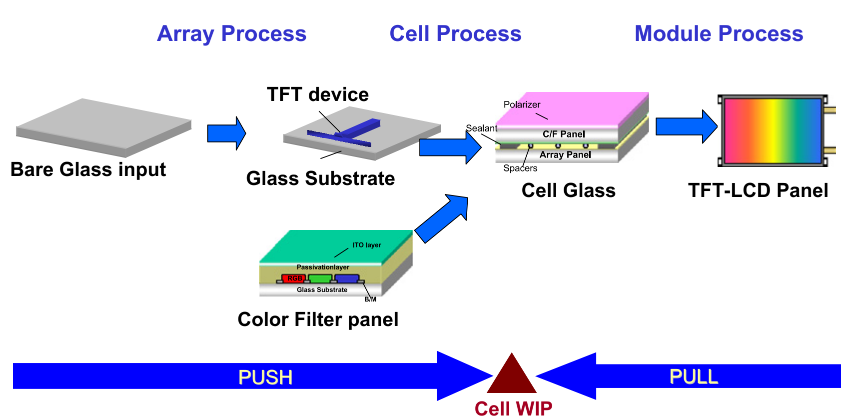

Fig. 1. An overview of TFT-LCD manufacturing processes.

2. Problem analysis

Order fulfillment processes in the TFT-LCD industry is complicated due to its special production network characteristics. In a module plant, cell glass panels passed from cell processes are assembled with all other necessary components, such as backlights, ICs, and PWBs, which may be specifically chosen by customers. One characteristic of the TFT-LCD industry is that manufacturing lines are categorized by different technology-related generation, i.e., panel size. Each generation cell plant may only produce a particular range of panel sizes. In addition, a module plant is constrained by its capacity and generation limitation associated with manufacturing panels; in other words, not all products can be assembled in a module plant. Furthermore, the three main processes, array, cell and module, may be located at several facilities in different locations. The production chain of the TFT-LCD industry is a multi-tiered and multi-sited network as shown in Fig. 2. Array and cell processes are usually located in the same facility or in proximity due to similar production characteristics such as technology-intensive and capital-intensive nature; however, module plants are generally located in different areas or countries other than the location of array and cell plants because module assembly is a labor-intensive process that differs from the other two processes. As a result, planning the transportation of cell glass panels between cell and module plants is an important issue. For example, one leading TFT-LCD manufacturer, LG Philips, moved its module plants in 2007 to China to reduce costs (computing.co.uk (CCU), 2007). Additionally, AUO built its module plants in Xiamen, China (Advanced IMAGING (AI), 2008); however, most of its cell plants of AUO remain in Taiwan. Fig. 2 presents a typical network topology of array, cell, and module plants, where array and cell plants (capital- and technology-intensive) are typically located in one area, and module plants (labor-intensive) are built in another location.

The components assembled in module processes may be specifically designated by customers based on their preferences or requirements. In other words, a finished product is manufactured by alternative production processes and devices. Lyon, Milne, Orzell, and Rice (2001) refers to this feature as alternative BOM specifically in semiconductor manufacturing. A TFT-LCD production chain is with similar characteristics to alternative BOM, but with more subtle and complicated properties. A product function can be provided by various devices or different combinations of components with different required amounts of components. Fig. 3 illustrates a typical example of alternative BOMs in a TFT-LCD production chain. A product model can be assembled by optional alternative BOMs (alternatives 1, 2, and 3). Customers choose a specific (or some) alternative BOM(s) based on their preference. For example, the component of the source IC adopted in alternatives 1 and 3 is the same device supplied by supplier 1, but the required amounts for alternatives 1 and 3 are inconsistent. The source IC in alternative 2 is different from the device of the source ICs used in alternatives 1 and 3 and is supplied by another supplier. A similar situation arises in Gate ICs and PCBs in the alternative BOMs in Fig. 3. Several reasons result in various alternative BOMs for a product model: (1) a low purchase cost and a short lead time due to competitiveness among suppliers, (2) less material reliance on one single supplier, and (3) customers' preference or designation of specific components used in finished product models for quality assurance purposes. Alternative BOMs complicate the order fulfillment process in a TFT-LCD production chain.

Another feature of TFT-LCD manufacturing is the hierarchical structure of products; that is TFT-LCD products have several *characteristic levels*: application, size, resolution, product model, alternative BOM, and product grade as shown in Fig. 4. The array and cell processes involve the first four levels, ranging from applications to product models, whereas module processes focus on the levels of alternative BOM and product grade, which are also special characteristics of the module process. Product grade is typically defined by the number of defect points on a finished product, and alternative BOMs are different options associated with materials or components for final product assembly. In other industries, customers usually place an order specifying finished product grade and ordering quantities. However, in the TFT-LCD industry, customer orders specify product grade, and choose the BOMs. That is, customers select preferred materials or components from designated suppliers.

This study describes these characteristics in detail as follows. As mentioned, cell glass panels transported from cell processes are assembled with other components acquired from other suppliers. Since customers can select material suppliers, a finished product is possible with several alternative BOMs. If a customer has selected more than one supplier for at least one component, the module plant can switch these components from one supplier to another based on the inventory level. A similar idea of the alternative BOM is also described by Chen et al. (2002). Furthermore, this study considers another special feature of product grade in TFT-LCD module plants. Product grade is an important feature in product models and finished products (Fig. 4). The grade of cell glass panels can be converted into different finished product grades depending on the quality of assembled components or different BOMs. For example, a low-grade cell glass panel can be converted into a high-grade TFT-LCD panel when a module plant assembles

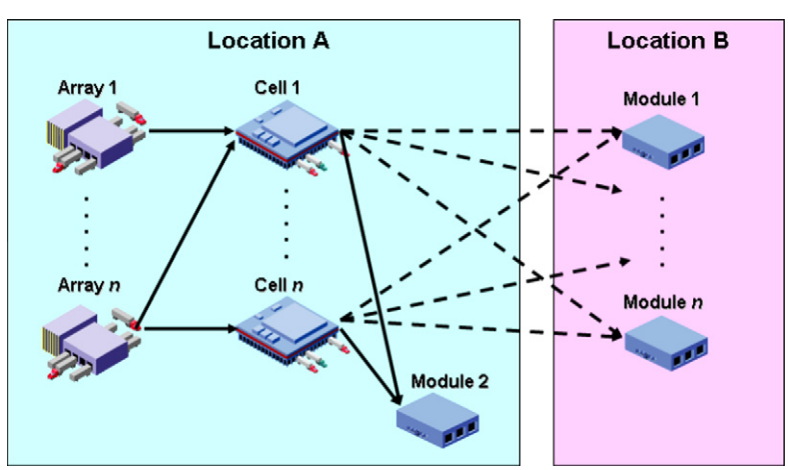

Fig. 2. The structure of a TFT-LCD production chain.

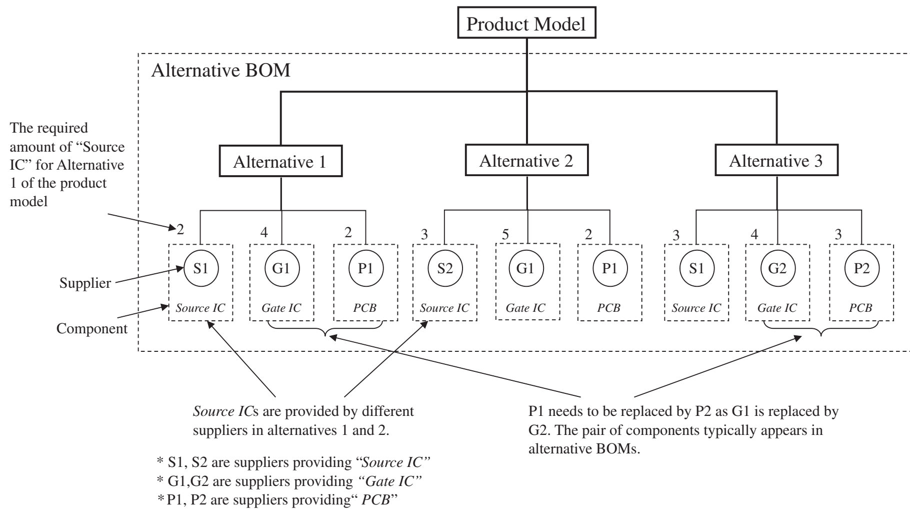

Fig. 3. An illustration of alternative BOM (adapted from Lin, Chen, & Lin, 2009).

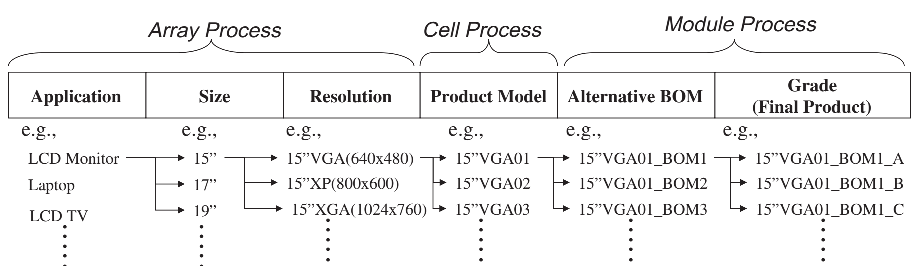

Fig. 4. The structure of TFT-LCD products.

cell glass panels with good quality materials. In this study, for simplicity, we assume transition percentages are given as parameters, which are generally available from historical data. Fig. 5 presents the topological structure of these characteristics. For instance, finished products are assembled with glass panels, source ICs, gate ICs, backlights, and other components. Customer orders specify the grade of finished products and choose the alternative BOMs, including information of suppliers who supply the materials or components.

Module plants must quickly respond to inquiring orders and state the quantity that they are capable of supplying within a desired due date. Based on our experience at TFT-LCD module

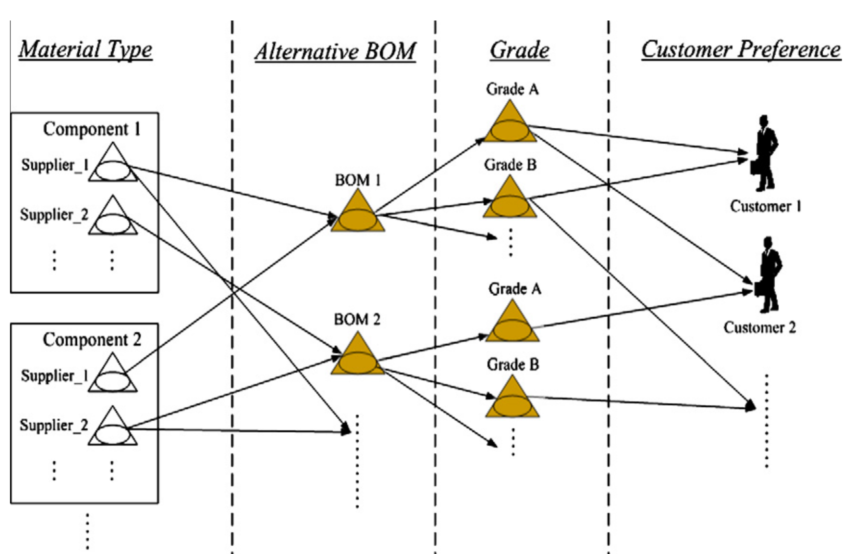

Fig. 5. Customer order preference with options of the product grade and BOMs.

plants, a customer is usually willing to compromise on order quantity when module plants cannot satisfy all order quantities required by customers. The proposed model allows module plants to partially satisfy inquiring orders; however, a penalty is applied to account for long-term effects of not satisfying order quantities. Furthermore, in this study, the ATP model repetitively runs on a rolling horizon basis. This allows for reconfiguration of the production schedule for promised orders based on recent inquiring orders and available inventory. In other words, the production schedule for promised orders may change to accept additional new inquiring orders as long as promised orders meet the promised due date.

Current TFT-LCD industry practice in order fulfillment processes is through past experience to designate the module plants for various types of finished products and the current practice utilizes conventional material requirement planning (MRP) programs, which neglect the special production characteristics in TFT-LCD production chains, for generating the production schedule. Thus, the current practice frequently results in unbalance production work-loading, high level of unsatisfied inquiring orders, and excess in the inventory level of components. In Section 3, we propose an ATP model in the order fulfillment process for TFT-LCD production chains under consideration of the production characteristics mentioned in this paper.

3. The order fulfillment process and ATP model

The development of the proposed ATP model for order fulfillment processes is based on a framework that considers several issues, including product grade, alternative BOMs, and production and transportation constraints in cell and module processes. Decision problems in order fulfillment processes are described as follows:

- promised quantities of finished products in response to customer inquiry orders;
- production schedule based on promised quantities;
- transportation schedule of cell glass panels between cell and module plants;
- inventory levels of key materials in module plants.

The order fulfillment process allows module plants to rapidly respond to inquiring orders. Fig. 6 presents the detailed steps in the proposed order fulfillment process. The sequence of steps is indicated by the number shown in Fig. 6. The input data for the ATP model are costs associated with transportation and production, transportation constraints, and production capabilities. The ATP model returns the outputs of the available capacity to promise, the transportation schedule for shipments of cell glass panels from cell plants to module plants, production schedule in module plants, and promised and unsatisfied orders. Module plants respond to customers based on the quantity a firm can deliver within a desired due date. In this study, customer orders can be partially fulfilled. If customers are unsatisfied with the quote and withdrawing their inquiring orders, the proposed ATP model releases the capacity dedicated to those inquiring orders and updates the remaining capacity available-to-promise.

This study formulates the ATP model based on linear programming, and its solutions can be obtained through standard techniques and software. The ATP model uses the following notation for indices, decision variables, and parameters. First, this study defines the indices used in the model.

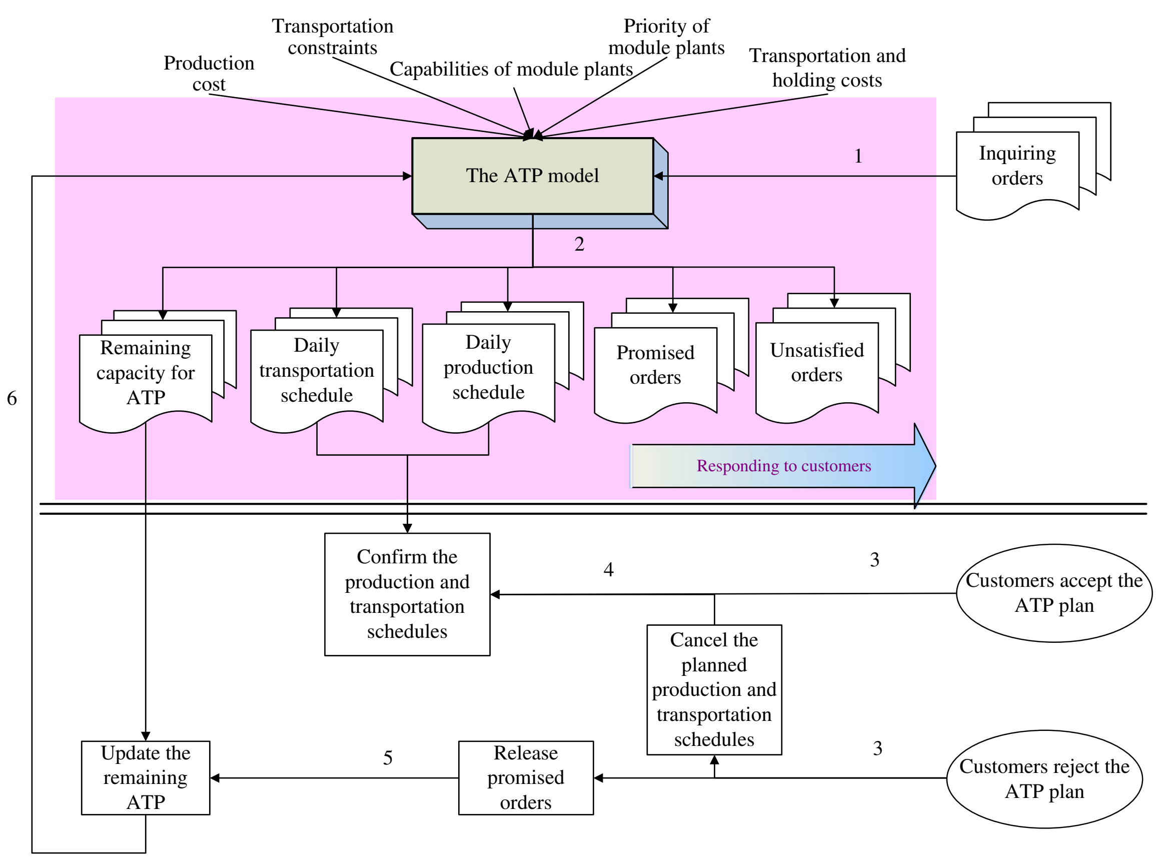

Fig. 6. Steps in the order fulfillment process.

We will use the following indices:

a:	alternative BOM;
d:	grade of cell glass;
f:	cell plant;
g:	grade of finished products;
i:	order number;
m:	material type;
p:	product type;
s:	supplier;
t:	time period;
z:	module plant.

In this study, cell glass panels are converted to finished products in module plants. Thus, for simplicity, the same index p is used to describe cell glass panels and finished products in the ATP model. Let O denote the set of inquiry orders given by customers and $\widehat{O}$ be the set of promised orders. The notation for decision variables in the model are as follows:

$DQ_{z,i,p,a,g,t}$:	promised quantity of product p of grade g and alternative BOM a in order $i \in O \cup \widehat{O}$ in module plant z in time period t;
$FR_{z,p,a,g,t}$:	remaining quantity of product p of grade g and alternative BOM a in module plant z at time period t;
$FW_{f,p,d,t}$:	remaining quantity of cell glass panel p of grade d in cell plant f at time period t;
$MR_{z,s,m,t}$:	remaining quantity of material m in module plant z at time period t supplied by supplier s;
$TQ_{f,p,d,t,z}$:	shipping quantity of cell glass panel p of grade d from cell plant f to module plant z at time period t;
$UQ_{i,p}$:	unmet quantity of product p in order $i \in O \cup \widehat{O}$;
$XQ_{z,p,d,a,t}$:	scheduled production quantity of cell glass panel p of grade d for alternative BOM a in module plant z at time period t;
$ZW_{z,p,d,t}$:	remaining quantity of cell glass panel p of grade d in module plant z at time period t.

Symbol *INIT* denotes the initial time in the planning horizon. The last time period, T, in the planning horizon is the latest due date among all potential orders. In addition, let M be a big number for modeling purposes. The notation used to define parameters for the proposed model is as follows:

PT:	production lead time in module processes;
TT:	shipping lead time between cell and module plants;
$ap_{i,p}$:	promised quantity of product p in order $i \in \widehat{O}$;
$ca_{z,t}$:	total capacity in module plant z at time period t;
$cr_{i,p,a,g}$: =1	if alternative BOM a and grade g is allowed for production of product p in order $i \in O \cup \widehat{O}$,
=0	otherwise;
$cv_{s,m,p,a}$: =1	if material m supplied by supplier s is allowed for use in alternative BOM a for production of product p,
=0	otherwise;
due_i:	due date of order $i \in O \cup \widehat{O}$;
$fc_{p,a,g}$:	holding cost of product p for grade g and alternative BOM a;
$fo_{z,p,a,g,t}$:	promised quantity of product p for grade g and alternative BOM a in module plant z at time period t, $t \leqslant PT$;
$fr_{z,p,a,g,INIT}$:	initial inventory quantity of product p for grade g and alternative BOM a in module plant z;
$fw_{f,p,d,INIT}$:	initial inventory quantity of cell glass panel p for grade d in cell plant f;
$mb_{p,m}$:	quantity of material m needed for producing one unit of product p;
mc_m:	holding cost of material m;
$mr_{z,s,m,INIT}$:	initial inventory quantity of material m supplied by supplier s in module plant z;
$ms_{s,m,t,z}$:	quantity of material m received by module plant z from supplier s at time period t;
$pc_{z,p,a}$:	unit production cost of product p for alternative BOM a in module plant z;
$pr_{i,p}$:	selling price of product p in order $i \in O \cup \widehat{O}$;
$pg_{z,p,d,a,g}$:	grade transition rate of product p from grade d to grade g in module pant z when alternative BOM a is used;
$qt_{i,p}$:	total inquiry quantity of product p in order $i \in O$;
$tc_{f,p,z}$:	transportation cost of product p from cell plant f to module plant z;
$tq_{z,p,d,t}$:	quantity of cell glass panel p of grade d received in module plant z at time period t, $t \leqslant TT$;
up_i:	penalty cost of unmet demand per unit in order $i \in O \cup \widehat{O}$;
$ws_{f,p,d,t}$:	supply quantity of cell glass panel p of grade d in cell plant f at time period t;
$zw_{z,p,d,INIT}$:	initial inventory quantity of product p of grade d in module plant z.

Using this notation, the linear programming model for order fulfillment processes can be stated as:

Maximize

$$\sum_{z}\sum_{i\in O\cup\widehat{O}}\sum_{p}\sum_{a}\sum_{g}\sum_{t=1}^{T} pr_{i,p}\cdot DQ_{z,i,p,a,g,t} - \sum_{z}\sum_{p}\sum_{d}\sum_{a}\sum_{t=1}^{T} pc_{z,p,a} \cdot XQ_{z,p,d,a,t} - \sum_{z}\sum_{s}\sum_{m}\sum_{t=1}^{T} mc_m\cdot MR_{z,s,m,t} - \sum_{z}\sum_{p}\sum_{a}\sum_{g} \times \sum_{t=1}^{T} fc_{p,a,g}\cdot FR_{z,p,a,g,t} - \sum_{i\in O\cup\widehat{O}}\sum_{p} up_i\cdot UQ_{i,p} - \sum_{f}\sum_{p}\sum_{d}\sum_{t=1}^{T} \times \sum_{z} tc_{f,p,z}\cdot TQ_{f,p,d,t,z}$$

Subject to:

$$\sum_{z}\sum_{a}\sum_{g}\sum_{t=1}^{due_i} DQ_{z,i,p,a,g,t} \leqslant qt_{i,p} \quad \forall i\in O, p \tag{1}$$

$$\sum_{z}\sum_{a}\sum_{g}\sum_{t=1}^{due_i} DQ_{z,i,p,a,g,t} = ap_{i,p} \quad \forall i\in \widehat{O}, p \tag{2}$$

$$DQ_{z,i,p,a,g,t} \leqslant M\cdot cr_{i,p,a,g} \quad \forall z,i,p,a,g,t \tag{3}$$

$$\sum_{z}\sum_{p}\sum_{a}\sum_{g}\sum_{t=due_i+1}^{T} DQ_{z,i,p,a,g,t} = 0 \quad \forall i\in O \tag{4}$$

$$\sum_{p}\sum_{d}\sum_{a} XQ_{z,p,d,a,t} \leqslant ca_{z,t} \quad \forall z,t \tag{5}$$

$$MR_{z,s,m,t-1} + ms_{s,m,t,z} - \sum_{p}\sum_{d}\sum_{a} mb_{p,m}\cdot cv_{s,m,p,\alpha} \cdot XQ_{z,p,d,a,t} = MR_{z,s,m,t} \quad \forall z,s,m,t \tag{6}$$

$$FW_{f,p,d,t-1} + ws_{f,p,d,t} - \sum_{z} TQ_{f,p,d,t,z} = FW_{f,p,d,t}$$

$$\forall f,p,d,t \quad (7)$$

$$ZW_{z,p,d,t-1} + tq_{z,p,d,t} - \sum_{a} XQ_{z,p,d,a,t} = ZW_{z,p,d,t}$$

$$\forall z,p,d,t \leqslant TT \quad (8)$$

$$ZW_{z,p,d,t-1} + \sum_{f} TQ_{f,p,d,t-TT,z} - \sum_{a} XQ_{z,p,d,a,t} = ZW_{z,p,d,t}$$

$$\forall z,p,d,t > TT \quad (9)$$

$$FR_{z,p,a,g,t-1} + fo_{z,p,a,g,t} - \sum_{i \in O \cup \widehat{O}} DQ_{z,i,p,a,g,t} = FR_{z,p,a,g,t}$$

$$\forall z,p,a,g,t \leqslant PT \quad (10)$$

$$FR_{z,p,a,g,t-1} + \sum_{d=1} pg_{z,p,d,a,g} \cdot XQ_{z,p,d,a,(t-PT)} - \sum_{i \in O \cup \widehat{O}} DQ_{z,i,p,a,g,t} = FR_{z,p,a,g,t}$$

$$\forall z,p,a,g,t > PT \quad (11)$$

$$UQ_{i,p} = qt_{i,p} - \sum_{z} \sum_{a} \sum_{g} \sum_{t=1}^{T} DQ_{z,i,p,a,g,t}$$

$$\forall i \in \widehat{O}, p \quad (12)$$

$$MR_{z,s,m,t-1} = mr_{z,s,m,INIT} \quad \forall z,s,m,t = 1 \quad (13)$$

$$ZW_{z,p,d,t-1} = zw_{z,p,d,INIT} \quad \forall z,p,d,t = 1 \quad (14)$$

$$FW_{f,p,d,t-1} = fw_{f,p,d,INIT} \quad \forall f,p,d,t = 1 \quad (15)$$

$$FR_{z,p,a,g,t-1} = fr_{z,p,a,g,NIT} \quad \forall z,p,a,g,t = 1 \quad (16)$$

The objective function in the ATP model maximizes the total profit, which is the sum of sales revenue, production costs, holding cost for materials and finished products, penalty costs, and costs associated with transportation between cell and module plants. Constraint (1) requires that the total promised quantity of products cannot exceed the total inquiry quantity of customer orders. Constraint (2) ensures that the total promised quantity of orders is scheduled for production. Constraint (3) is a logical constraint ensuring that the promised orders satisfy the requirement of the alternative BOM and grade in an order. Constraint (4) indicates that customers cannot accept a late delivery when an order has been promised by a module plant. Constraint (5) is the capacity limitation in module plants. Constraints (6)–(11) are the flow balance equations for materials, cell glass panels, and finished products, respectively. The ATP model computes the unmet demand in constraint (12) and assigns the initial data in constraints (13)–(16).

This section presents an ATP model for TFT-LCD module processes. In the proposed ATP model, the length of time periods is predefined as a basic time unit (e.g., a shift, day, or week) in the planning horizon. Inquiring orders may have different delivery lead times. The production schedule for promised orders with long delivery lead times can be rescheduled as long as completion time for promised orders can be satisfied. The proposed ATP model repetitively runs on a rolling horizon basis. The ATP model reconfigures the production schedule based on recent inquiring orders and available inventory so that the ATP model may accommodate an additional order. Another issue is the frequency of running the ATP model. The frequency of running the ATP model determines the duration of the *batching interval*, which is the time interval between two consecutive time points when running the ATP model. A long batching interval duration likely results in an improved comprehensive consideration for the ATP calculation because additional potential orders are considered in the ATP model such that a planner can optimally allocate limited resources to a set of potential orders. However, a long batching interval leads to a prolonged waiting time to be planned for inquiring orders. This situation increases the possibility of obtaining unsatisfactory inquiring orders since a long waiting time may result in an inability to finish orders within the requested due date. Consequently, the duration of the batching interval is a trade-off between the number of inquiring orders considered and the waiting time to be planned in the ATP model.

Although this research is developed based on characteristics of TFT-LCD panel manufacturing, the ATP model can be widely applied to production systems with alternative BOM or product grades. Recently vendor management has become an important issue in supply chain management. In order to mitigate the risk of supply chain disruption, companies usually purchase key components from several suppliers. Since components are sourced from different suppliers, alternative BOM is a nature consequence in those supply chain systems. Moreover, grade of products is a commonly shared characteristic in technology industry. For example, in personal computers and consumer electronic devices, quality graded products such as dynamic random access memory (DRAM) and central process units (CPU) are commonly used. Since DRAM and CPU are key components for almost all computing and electronic devices, it is inevitable to have quality grade transition in the manufacturing of those products. In systems with either alternative BOM or quality grade transition, the proposed ATP model provides a guideline for order commitment and fulfillment decision makers.

4. Case study

To demonstrate use of the proposed ATP model, a case study of order fulfillment processes in TFT-LCD module plants is investigated. This study collects a real dataset from a TFT-LCD firm that manufactures six products: three sizes of television sets (32, 34, and 37 in.); two sizes of laptop monitors (15.4 and 12.1 in.); and one desktop monitor (17 in.). The firm has four module plants, two array plants and two cell plants in different locations. Cell plant I primarily produces large glass panels (32, 34, and 37 in.), and cell plant II assembles mid-sized glass panels—15.4-, 12.1-, and 17-in. panels. Module plants 1, 2, and 3 are located in the country different from those that are home to the array and cell plants, whereas module plant 4 is in the same location as the array and cell plants. In this case study, not all products can be manufactured in all module plants because of limitations associated with plant capabilities for different generations of products. Table 1 presents the total capacity and manufacturing capability for specific products in different module plants.

Customers specify their preferred component suppliers when placing orders. Because module plants cannot foresee customer preferences of alternative BOMs, and processing time in module plants typically takes only 1–2 business days, a make-to-stock for module plants is not generally economical. Instead, module plants typically adopt a production strategy of make-to-order in order to reduce inventory costs for finished products. Prior to implementing the proposed ATP model, the module plant responds to customer inquiring orders based on remaining capacities without considering the special production characteristics in TFT-LCD

Table 1
Capability for manufacturing products in different module plants.

Site	Capacity[a]	12.1″	15.4″	17″	32″	34″	37″
Module 1	5000	•		•	•		
Module 2	5000	•	•			•	
Module 3	5000				•	•	•
Module 4	3000		•	•			•

• The product type is capable to produce in the module plant.
[a] The capacity information has been manually modified due to data confidentiality.

Table 2
Alternative BOMs for television sets.

Product		32″				34″				37″				
Alternative BOM		1	2	3	4	1	2	3	4	1	2	3	4	5
Suppliers	PCB	P2	P1	P2	P3	P3	P2	P3	P3	P2	P1	P2	P2	P2
	S_IC	S3	S2	S3	S1	S3	S3	S1	S3	S3	S2	S1	S2	S3
	G_IC	G1	G2	G2	G1	G2	G2	G1	G2	G2	G1	G1	G2	G3
	B/L	B2	B2	B1	B2	B2	B1	B2	B2	B1	B1	B2	B1	B2

Table 3
Alternative BOMs for computer monitors.

Product		15.4″			12.1″			17″	
Alternative BOM		1	2	3	1	2	3	1	2
Suppliers	PCB	P2	P2	P3	P3	P2	P2	P2	P3
	S_IC	S3	S3	S1	S3	S1	S1	S1	S2
	G_IC	G3	G2	G1	G2	G3	G1	G1	G2
	B/L	B2	B1	B2	B2	B2	B2	B2	B1

Table 4
Transition percentages of grade for different alternative BOMs.[a]

		Grade 1	Grade 2	Grade 3
15.4″				
Alternative BOM 1	Grade 1	0.69	0.2	0.11
	Grade 2	0.04	0.66	0.3
	Grade 3	0.03	0.43	0.54
Alternative BOM 2	Grade 1	0.71	0.2	0.09
	Grade 2	0.11	0.77	0.12
	Grade 3	0.05	0.4	0.55
Alternative BOM 3	Grade 1	0.52	0.32	0.16
	Grade 2	0.07	0.73	0.2
	Grade 3	0.01	0.22	0.77
32″				
Alternative BOM 1	Grade 1	0.52	0.35	0.13
	Grade 2	0.08	0.88	0.04
	Grade 3	0.08	0.26	0.66
Alternative BOM 2	Grade 1	0.75	0.16	0.09
	Grade 2	0.04	0.67	0.29
	Grade 3	0.02	0.33	0.65
Alternative BOM 3	Grade 1	0.94	0.05	0.01
	Grade 2	0.16	0.59	0.25
	Grade 3	0.01	0.45	0.54
Alternative BOM 4	Grade 1	0.98	0.02	0
	Grade 2	0.17	0.5	0.33
	Grade 3	0	0.03	0.97
17″				
Alternative BOM 1	Grade 1	0.59	0.4	0.01
	Grade 2	0.07	0.63	0.3
	Grade 3	0.02	0.08	0.9
Alternative BOM 2	Grade 1	0.52	0.26	0.22
	Grade 2	0.1	0.88	0.02
	Grade 3	0.01	0.01	0.98
12.1″				
Alternative BOM 1	Grade 1	0.53	0.29	0.18
	Grade 2	0.13	0.51	0.36
	Grade 3	0.08	0.33	0.59
Alternative BOM 2	Grade 1	0.63	0.22	0.15
	Grade 2	0	0.9	0.1
	Grade 3	0	0.27	0.73
Alternative BOM 3	Grade 1	0.71	0.18	0.11
	Grade 2	0.05	0.53	0.45
	Grade 3	0	0.14	0.86
34″				
Alternative BOM 1	Grade 1	0.97	0.02	0.01
	Grade 2	0.19	0.62	0.19
	Grade 3	0.08	0.13	0.79
Alternative BOM 2	Grade 1	0.84	0.13	0.03
	Grade 2	0.15	0.56	0.29
	Grade 3	0.07	0.4	0.53
Alternative BOM 3	Grade 1	0.8	0.15	0.05
	Grade 2	0	0.93	0.07
	Grade 3	0	0.06	0.94
Alternative BOM 4	Grade 1	0.89	0.11	0
	Grade 2	0	0.58	0.42
	Grade 3	0	0.08	0.92
37″				
Alternative BOM 1	Grade 1	0.91	0.07	0.02
	Grade 2	0.02	0.78	0.2
	Grade 3	0.01	0.22	0.77
Alternative BOM 2	Grade 1	0.78	0.12	0.1
	Grade 2	0.08	0.77	0.15
	Grade 3	0.04	0.44	0.52
Alternative BOM 3	Grade 1	0.92	0.04	0.04
	Grade 2	0.11	0.69	0.2
	Grade 3	0.05	0.25	0.7
Alternative BOM 4	Grade 1	0.61	0.29	0.1
	Grade 2	0.05	0.85	0.1
	Grade 3	0	0.03	0.97
Alternative BOM 5	Grade 1	0.94	0.05	0.01
	Grade 2	0.08	0.82	0.1
	Grade 3	0.01	0.28	0.71

[a] Each element specifies the transition percentage from the grade of glass panels to the grade of finished products.

manufacturing or applying any optimization techniques. These issues result in a low fulfillment rate and high level of component inventory. The proposed ATP model improves performance in these measures and facilitates prompt response to customer inquiries such that a firm can increase its profitability and customer satisfaction.

This case study considers four major components: printed circuit boards (PCBs), source ICs (S_ICs), gate ICs (G_ICs), and backlights (B/Ls). Tables 2 and 3 list the detailed alternative BOMs for different finished products such as television sets and computer monitors, respectively. Each column in Tables 2 and 3 represents one alternative BOM for each finished product. Take the first column of product type 32″ in Table 2 as an example. Four different

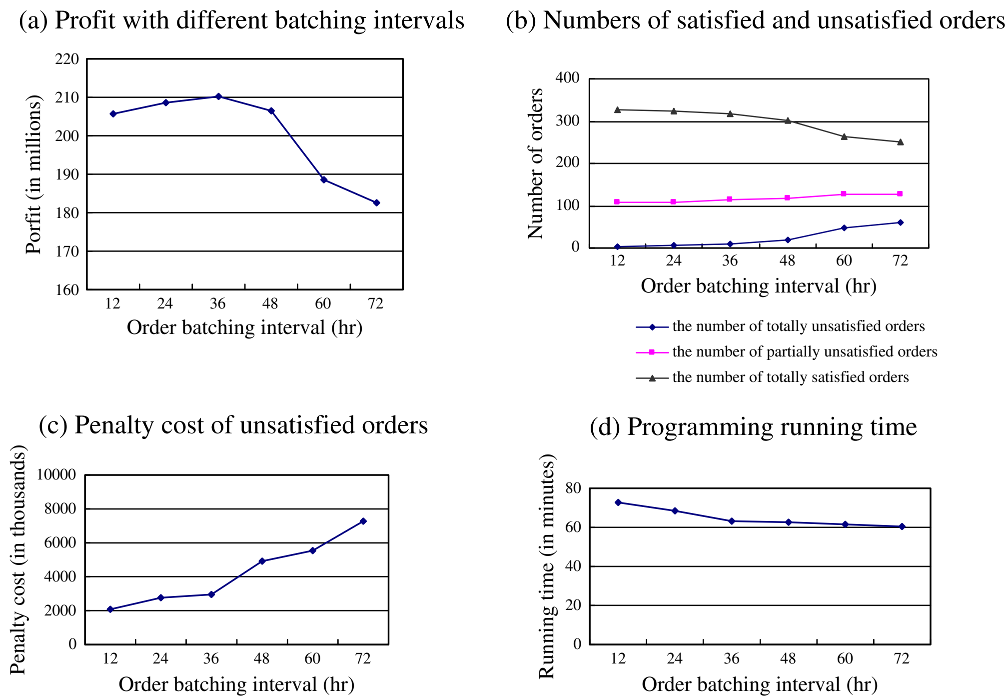

Fig. 7. Experimental results for the ATP model as a function of batching interval duration.

possible combinations exist for bill-of-materials for the 32″ product. Customer preferences are subject to material compatibility constraints of alternative suppliers. However, in the TFT-LCD industry, customers may have flexibility in choosing alternative BOMs; that is, customers can choose several alternative BOMs. In addition to the issue of alternative BOMs in TFT-LCD manufacturing, another important feature is product grade transition between cell and module processes. As discussed, the grade of cell glass panels can be converted into different grades of finished products depending on component quality (i.e., different alternative BOMs). Table 4 lists the detailed transition percentages of grades for different alternative BOMs.

The time period in this case study is 12-h (1 shift). A set of potential orders for 60 time periods is generated (roughly 1 month). These potential orders are generated to simulate inquiring orders specifying the type and quantity of finished products with desired due dates and associated alternative BOMs requirements. The batching interval is the duration between two consecutive time points for running the ATP model. This study investigates the effects of different settings of batching interval duration varying from 12–72 h. In each execution, the starting time point is intuitively the current execution time and ending time point of the planning horizon is chosen as the latest due date specified in the inquiring orders. Fig. 7 presents experimental results.

Fig. 7a shows the profit change with respect to changes in batching interval duration. From the curve in Fig. 7a, profit increases slightly as batching interval duration increases from 12 to 36 h, demonstrating that the ATP model can optimize a large set of inquiring orders and take advantage of additional customer order information to improve resource allocation and obtain profitable order commitments. Profit decreases when batching interval duration exceeds 36 h. This is due to the decrease in the number of satisfied orders because a long waiting time to be planned in the ATP model results in an increased possibility to miss a requested due date. Fig. 7b shows the number of unsatisfied, partially unsatisfied, and satisfied orders as a function of batching interval duration. This curve shows decreases in the number of satisfied orders as batching interval duration increases. However, the numbers of partially or totally unsatisfied orders increase as batching interval duration increases. The penalty of unsatisfied orders increases as batching interval duration increases due to the increase in the number of unsatisfied orders (Fig. 7c and b). Finally, this study also examines computational time of the proposed ATP model as shown in Fig. 7d. Computational time decreases as batching interval duration increases, likely due to little rescheduling of promised orders in cases with large batching interval durations. In addition, implementing an ATP model is impractical when the computational time is larger than, or close to, batching interval duration, which is the time interval between two consecutive executions of the ATP model. Otherwise, the computational results in one time period are unavailable for use in the next time period. The experimental study demonstrates that ATP results can be obtained within 80 min in this case study for different batching interval durations. This quick response allows module plants to respond to customer inquires promptly in practice.

5. Conclusions

The main contribution of this study is to highlight the special production characteristics in TFT-LCD manufacturing as well as the ATP model tailored to TFT-LCD module plants. The previous studies seldom notice these special production characteristics, which are the significant factors driving a success in ATP implementation in a TFT-LCD production chain. The proposed ATP model enhances the responsiveness of order fulfillment processes to customer orders. This study first describes the special production characteristics in TFT-LCD manufacturing that affect decisions for delivery date and the quantity promised to customer inquiring orders. The proposed ATP model considers alternative BOMs to allow customers to choose their suppliers; supplier selection is common for OEM-based TFT-LCD manufacturing. This study considers the grade transition between cell glass panels and finished products in the ATP model. The model provides an effective and efficient solution for order fulfillment processes by making optimal use of available resources in module plants. Hence, module plants can improve their customer service and achieve reliable order promises. The case study illustrates the effects of varying batching interval duration on total profit, number of unsatisfied and satisfied orders, penalty cost due to unsatisfactory inquiring orders, and ATP model computational time. This case study also demonstrates that the ATP model is practical and efficient for TFT-LCD module plants.

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