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ORIGINAL ARTICLE

Advanced planning and scheduling for TFT-LCD color filter fab with multiple lines

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Abstract Intense global competition and declining profit have caused most thin film transistor liquid crystal display manufacturers to increase their competitiveness by improving productivity and reducing cycle times. An advanced planning and scheduling (APS) system was developed with Microsoft Visual Basic for Application to automatically generate production schedules for a color filter fab with multiple lines. This system can assign orders to production lines, plan order release time, and balance the equipment loading. Both forward scheduling and backward scheduling were used in APS. Experimental results indicated that APS can significantly reduce manual scheduling time while maintaining the quality of scheduling results. Compared to manual operations, it can save more than 87 % of scheduling time and the quickness is especially important when rescheduling is needed due to production uncertainties such as equipment breakdown or material shortage. Production controllers can use this APS to generate initial schedule and make adjustment based on experience.

Keyword Scheduling · Advanced planning and scheduling · Color filter · TFT-LCD

1 Introduction

Improving technologies, decreasing prices, and increasing demands have led to fast growth in thin film transistor liquid crystal display (TFT-LCD) manufacturing industry. Widely used in computers (e.g., desktop, notebook, netbook, and tablet), televisions, and smart phones, TFT-LCD gradually replaces cathode ray tube. It is a capital-intensive and high-tech industry where the investment for new generation panel factory is nearly equal to a semiconductor fab, in the scale of US billion dollars. Due to the large dimension of product (e.g., 2,500 mm by 2,200 mm for generation 8.5), automated equipment and material handling system is generally applied. The manufacturing of TFT-LCD consists of four basic processes: array, color filter (CF), cell, and module, as shown in Fig. 1. Array process is similar to semiconductor manufacturing process, except that transistors are fabricated on a glass substrate instead of a silicon wafer. Furthermore, array process requires neither diffusion nor ion implantation operation. Color filter process fabricates color layers on glass substrates. Cell process combines color filter substrate and array substrate and fills liquid crystal between them. The assembled substrates are then divided into individual panels with specific sizes according to customer demands. Module process assembles additional components, such as driver-integrated circuits and backlight, to these panels to become modules for the future use of final TFT-LCD products. From the viewpoint of supply chain, consumer demands pulls the requirements of module process, that in turn pulls the requirements of cell process and consequently CF and array processes.

Material cost is the highest proportion of the total cost of TFT-LCD products. TFT-LCD components can be divided

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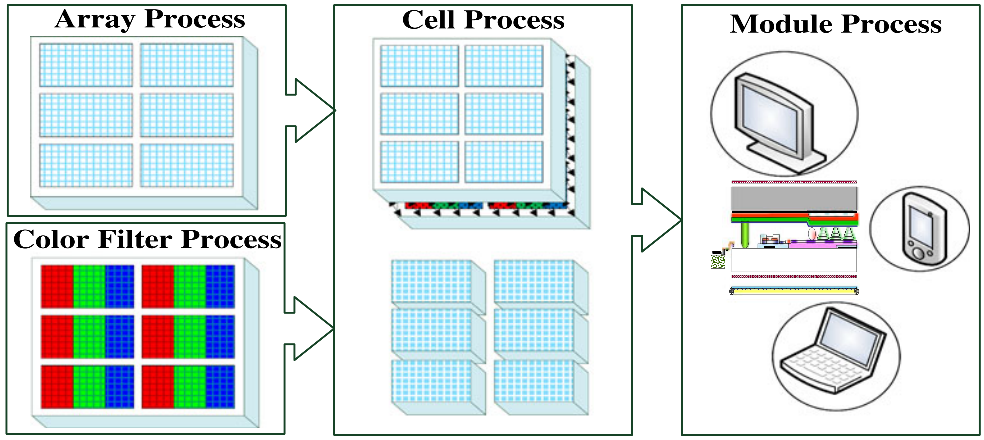

Fig. 1 The four major manufacturing processes of TFT-LCD

into several major parts: CF, polarizer, backlight module, IC driver, glass substrate, printed circuit board, and so on. Among these, CF is a key component counting around 20 % of the cost of TFT-LCD. CF process consists of several major steps: black matrix, red, green, blue, indium tin oxide (ITO), multi-domain vertical alignment (MVA), photo spacer, and final inspection, as shown in Fig. 2.

It is critical to increase production efficiency and reduce cost of CF through effective operation management, such as planning and scheduling. A typical CF manufacturing site has one or multiple fabs, each with multiple lines. The production costs are different among fabs and lines. Furthermore, there exist characteristics for each fab and line, such as available capacity, minimum order quantity, and preferred product specification, type, and dimension. Due to these complexity, it takes hours for a production controller or shop floor supervisor to manually integrate the order information (e.g., type, size, spec., due date) and abovementioned capacity information and generate feasible (hopefully not too far away from "near-optimal") production schedules. The manual scheduling and dispatching process becomes inefficient and impractical when urgent rescheduling is required due to the change of customer orders (e.g., urgent orders or order cancelation) or uncertainties on shop floor (e.g., equipment breakdown or shortage of photoresist).

This study presents the development of an advanced planning and scheduling (APS) system for one 4.5-generation CF fab with two production lines in north Taiwan, as shown in Fig. 3. This APS can quickly generate production schedules for multiple lines meeting the downstream requirements of cell and module processes. It was coded with Microsoft Visual Basic for Application (VBA) and can quickly assign and dispatch orders by taking into account the order demand and capacity supply, resulting in balanced equipment loading among production lines. The effectiveness of APS becomes especially significant when rescheduling is required.

This paper is organized as follows. Section 2 reviews related literature. Section 3 describes the methodology of APS. Next, Section 4 presents the experiments and results. Finally, Section 5 draws conclusions and provides future research directions.

2 Literature review

The research of production planning and scheduling in TFT-LCD array, cell, and module processes has received considerable attention in recent years because of the fast growth and intense competition of TFT-LCD industry. However, there is only little research about production planning and scheduling in CF manufacturing so far, to the best of our understanding.

Related research about production management in CF manufacturing is surveyed. Chen et al. [1] considered a

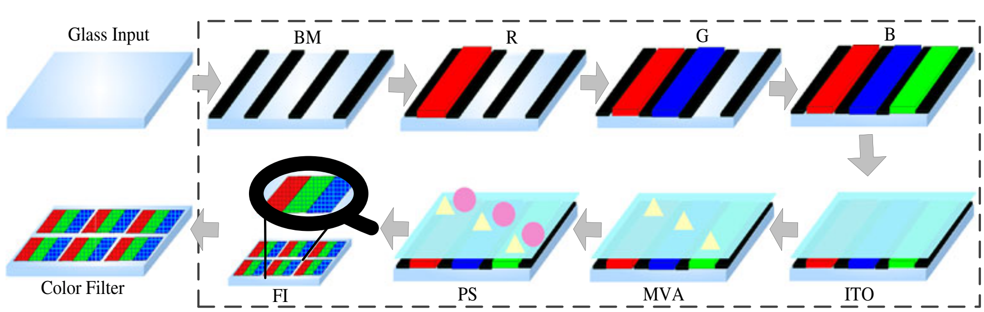

Fig. 2 A typical CF process includes black matrix (*BM*), red (*R*), green (*G*), blue (*B*), indium tin oxide (*ITO*), multi-domain vertical alignment (*MVA*), photo spacer (*PS*), and final inspection (*FI*)

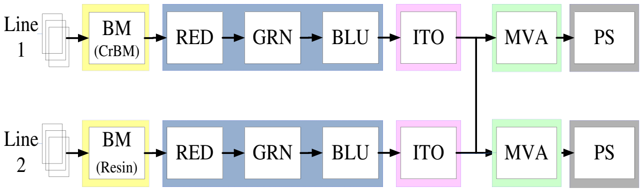

Fig. 3 The studied CF fab with two lines

scheduling problem in CF manufacturing, and flow shop scheduling problem with sequence-dependent setup times was defined to minimize the earliness/tardiness penalties by a modified ant colony optimization method. Chen et al. [2] proposed an order assignment policy to effectively and efficiently assign orders to CF fabs to minimize order tardiness and balance fab utilization. Chen et al. [3] developed one release control policy: iterative simulation-based regular release to increase CF fab throughput. Chen et al. [4] proposed a finite capacity planning policy (FCPP) for multiple CF fabs where each fab has several identical production lines. Results show that FCPP can effectively and efficiently balance the loading between fabs and also balance the loading between lines in each fab.

Researches related to production management in TFT-LCD industry and capacity planning is surveyed. Wang et al. [5] applied mixed integer linear programming to solve the product mix problem in TFT-LCD industry. Lin et al. [6] developed a simulation model for TFT-LCD cell process and studied the effects of lot release time and dispatching rule. Chen et al. [7] combined agent technology with advanced planning and scheduling system for multi-tier and multi-site production system of TFT-LCD manufacturing. Lin et al. [8] proposed a single-period and a multi-period mathematical programming model represented by the network diagram to optimize the purchase quantity from suppliers while satisfying demand under the existence of specific characteristics and constraints. Pa [9] presented a new method using excimer irradiation and a graded modular tool in a micro-electrochemical machining process for the rapid removal of ITO nanostructure from the CF surface of

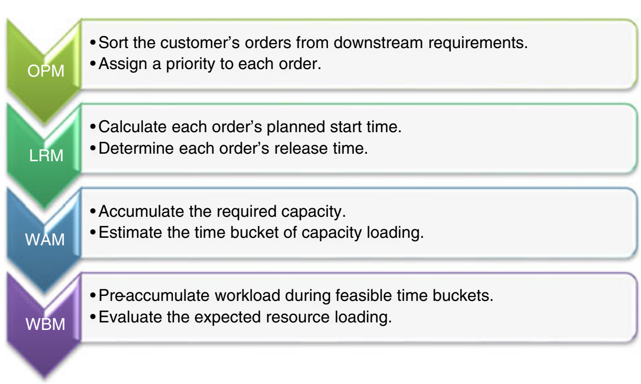

Fig. 4 Major functions of four APS modules

defective TFT-LCD and to provide an efficient recycling method. Sureshkumar and Madhusudanan [10] proposed a linear programming model to minimize relative capacity shortage in which workers are considered to be cross-trained. The computational demonstration showed the effectiveness of the model. Tsai and Wang [11] constructed a generic three-stage model of multi-site available-to-promise (ATP) mechanism for TFT-LCD manufacturer to obtain an appropriate ATP plan.

It is of significance to efficiently utilize various resources. In many practical environments, it is necessary to consider setup times as separate from processing times and reduce setup cost in scheduling. Park et al. [12] developed a simulation-based daily planning and scheduling system and used it in a modern LCD fab in Korea. Weigert et al. [13] used heuristic algorithms to develop a simulation-based scheduling system which can optimize the processes for a semiconductor backend facility. Wu et al. [14] developed a Drum–Buffer–Rope customization model based on theory of constraints to schedule and control TFT-LCD cell plant. Chen and Pundoor [15] studied four general NP-hard problems related to order assignment and scheduling in a supply chain and proposed fast heuristics for each of them. Liu and Chang [16] presented a Lagrangian relaxation-based approach for production scheduling of flexible flow shops and provided a practical advancement in scheduling FFS's with sequence-dependent setup effects to industrial application. Allahverdi and Soroush [17] defined and emphasized the importance, applications, and benefits of explicitly considering setup times/costs in scheduling research. Sherali et al. [18] developed a quantitative modeling and algorithmic approach for scheduling activities or tasks in order to minimize the setup time in such situations. Yokoyama [19] considered a scheduling model for flow shop production system including machining, setup and assembly operations, and used pseudo-dynamic programming and a branch-and-bound method to obtain a near-optimal scheduling. Load balancing method was also used in this research to determine lot release time and start fab to balance equipment loading in each of the twin fabs. Farkas et al. [20] developed a heuristic workload balancing procedure to avoid excessive capacity over or under utilization. The results showed that both workload balancing and capacity utilization of the system was improved.

Chen et al. [21] developed an infinite capacity requirements planning system that considers the capability and dedication of equipment to efficiently balance the equipment workload among multiple fabs. Toba et al. [22] proposed a load balancing method which balanced all processing operations of products among multiple semiconductor wafer fabs by using predictive scheduling results.

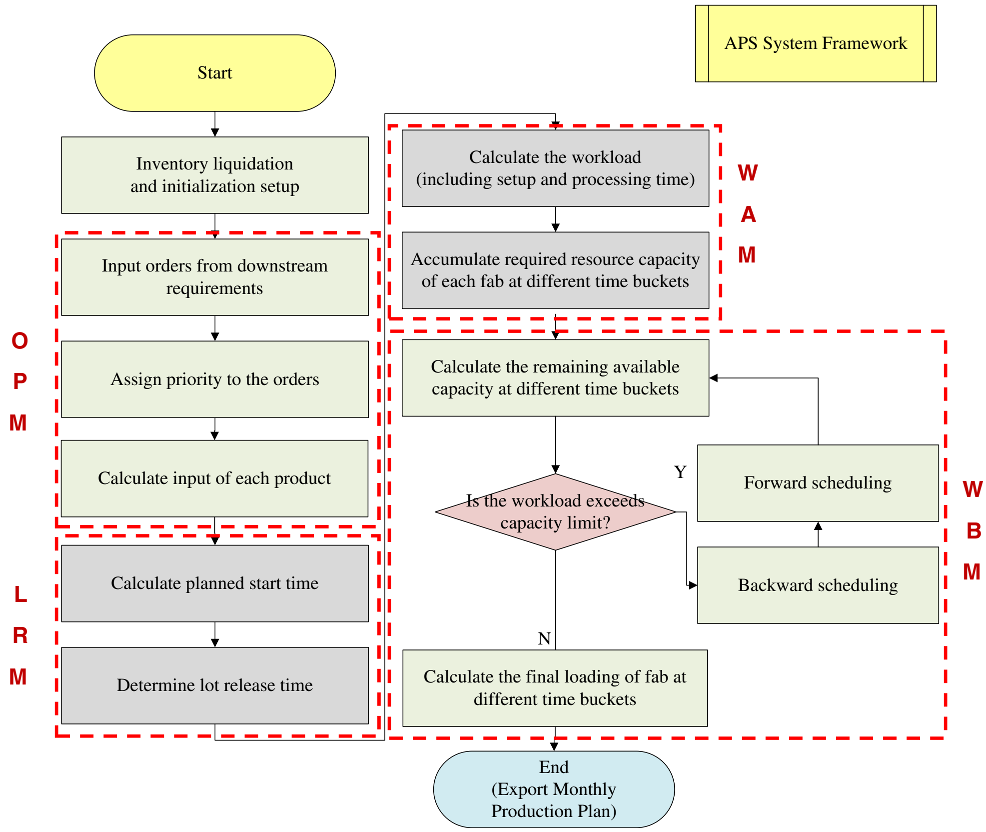

Fig. 5 The framework of APS system

Chen et al. [23] constructed the mathematical programming model of capacity planning, the rates of capacity utilization and customer order fulfillment are found to be effectively enhanced by adding new masks to increase production flexibility. Ou-Yang and Hon [24] proposed an integrated APS and enterprise resources planning (ERP) framework to support the collaboration among these systems. It applied the concept of Web service and agent collaboration to support the issues such as workflow integration and collaboration encountered during the integration period. Lin et al. [25] proposed a capacity and product mix planning decision model with three phases to balance the difference between total supply capacity and total demand forecast for TFT array multi-plant to maximize contribution margin. Lin and Chen [26] proposed a monolithic model of the multi-stage and multi-site production planning problem, combining two different time scales, i.e., monthly and daily time buckets. Through optimization procedures, the information on production and procurement in the multi-plant network was derived. Chen et al. [27] proposed an infinite capacity requirements planning system to calculate the required number of machines to balance the equipment loading for twin wafer fabrication plants with shared equipment. Wang et al. [28] presented a patent of system and method of multi-objective capacity planning in panel industry.

3 Methodology

The APS system was developed using Microsoft VBA for the application of one 4.5-generation CF fab with two production lines in north Taiwan. It can be divided into four major modules: order priority module (OPM), lot release module (LRM), workload accumulation module (WAM), and workload balance module (WBM). Figure 4 shows the major functions of these modules, and Fig. 5 depicts the framework of APS system bases on these modules.

At the beginning, APS manages the material supply by computing the available inventory of glass substrates classified by material types and accumulating the requirements of these glass substrates from the orders on hand. If the remaining is less than the safety stock of certain material, APS will trigger a purchase order to material vendor, based on material requirements planning, to ensure the continuous supply of glass substrates.

When one CF fab with multiple lines receives orders, it needs to determine each order's release time according to the order due date and the characteristics of the production line that is assigned to process the order. OPM sorts the customer's orders from downstream requirements and assigns the priority to each order according to different dispatching rules. Least Due Date or Least Slack (slack is calculated as the difference between time to due date and the

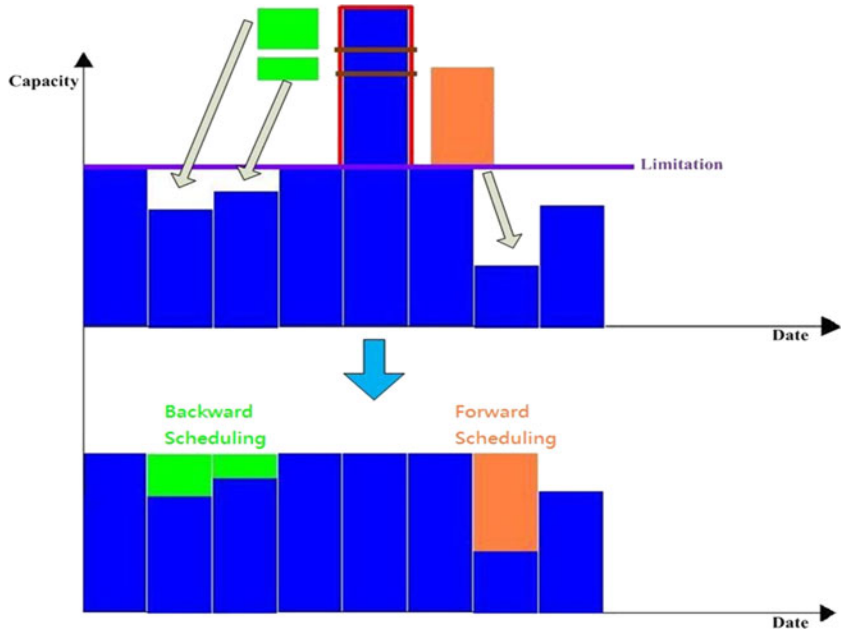

Fig. 6 Work balance on the basis of backward and forward scheduling

remaining processing time) are two common rules widely used. The highest priority is assigned to rush orders at OPM. It is important to control the percentage of rush orders to be less than 20 %, as a rule of thumb, as increasing number of rush orders decrease the production efficiency of real rush orders.

LRM is then used to calculate each order's planned start time by backward scheduling and determine each order's release time. The expected loading of each line needs to be estimated by rough "pre-accumulation," and a line is selected to process the order to "optimize" the workload balance. Least Line Loading policy is commonly used to assign each order to the line with minimum loading.

After the order is released by LRM, the APS system then uses WAM to accumulate the required resource capacity (including setup time and processing time) along product's routine at different time buckets. The calculation of available capacity needs to take into account practical conditions with time window constraints including scheduled downtime such as maintenance and unscheduled downtime such as water shortage or power outage. CF is manufactured in a flow shop environment consisting of a sequence of multiple machines. There exists sequence-dependent setup time when a machine has finished an order and start to process another order of different product type. The length of the setup time depends on the type of order that has just finished the processing and the type of the next order that will start the processing. The setup or changeover includes the change of photoresists and masks. It is a trade-off to select the order for next processing considering order due date and the order type sequence that can minimize the sequence-dependent setup time, as both on-time delivery and equipment utilization are important. Better WAM can result in less capacity loss due to line change. Every production step's average cycle time is used in WAM to estimate the time bucket of capacity loading. It is noted that the accuracy of the cycle time estimation affects the performance of APS and it can be estimated by experience or system simulation.

WBM is then used to balance the loading if the workload is unbalanced, indicating that the required accumulated capacity exceeds the available capacity over the planning time horizon. WBM pre-accumulates workload during feasible time buckets and evaluates the expected utilization and resource loading. A lot's start processing time at each production step is selected to get the best workload balance. In WBM, both backward scheduling and forward scheduling are used. Backward scheduling assumes that a job can be finished on time (i.e., just meeting due date) and calculates its latest start time (LST) by subtracting cycle time from its due date. If LST is earlier than time now, it is not feasible and therefore the job can be started from time now. Forward scheduling is then used to start a job at time now and calculates its schedule finished time (SFT) by adding cycle time to time now. When LST is earlier than time now or SFT is later than due date, it indicates more resources need to be allocated to process the job to reduce the lead time (e.g., two identical machines processing the same order simultaneously resulting in half lead time but with the same total processing time) and to avoid late delivery. Material's earliest available time (also called ready time) is another important

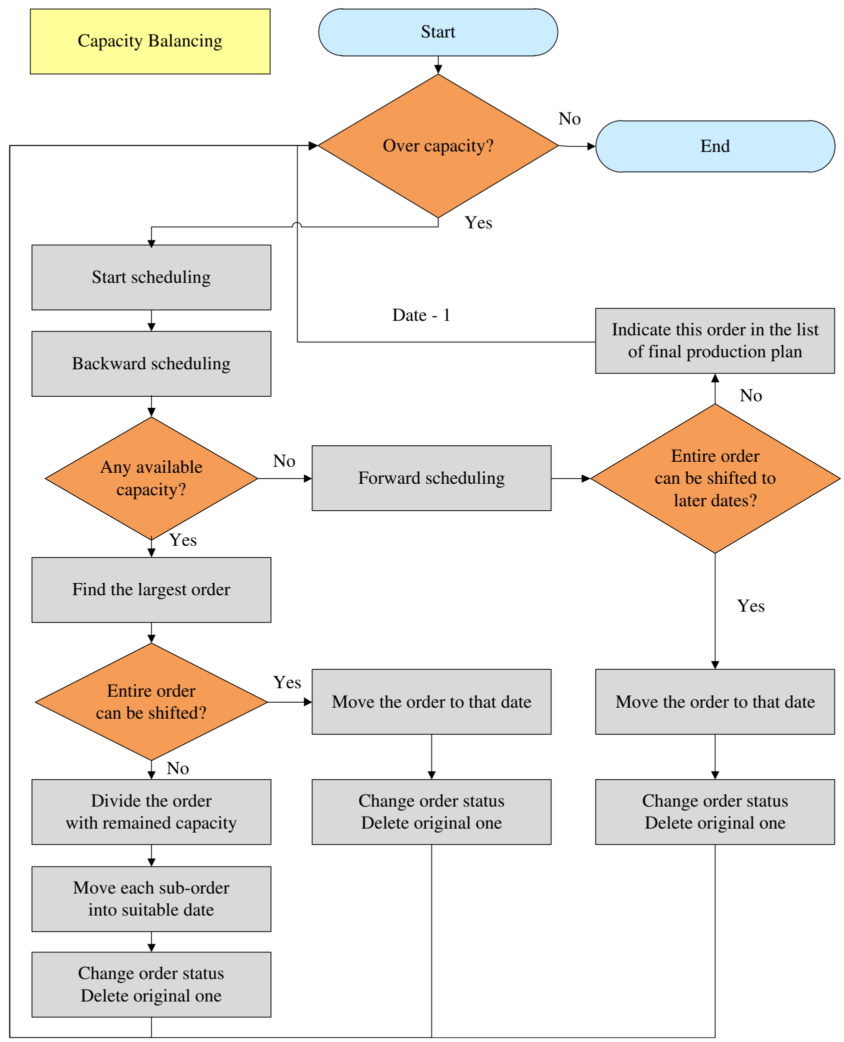

Fig. 7 Backward and forward scheduling for capacity balancing in WBM

factor that needs to be taken into account. The maximum of material ready time, LST, and time now is the time that an order can start the processing.

As shown in Fig. 6, WBM predicts the overloading of resource in the planning time horizon by pre-accumulation. When this happens, WBM first shifts the overloaded order

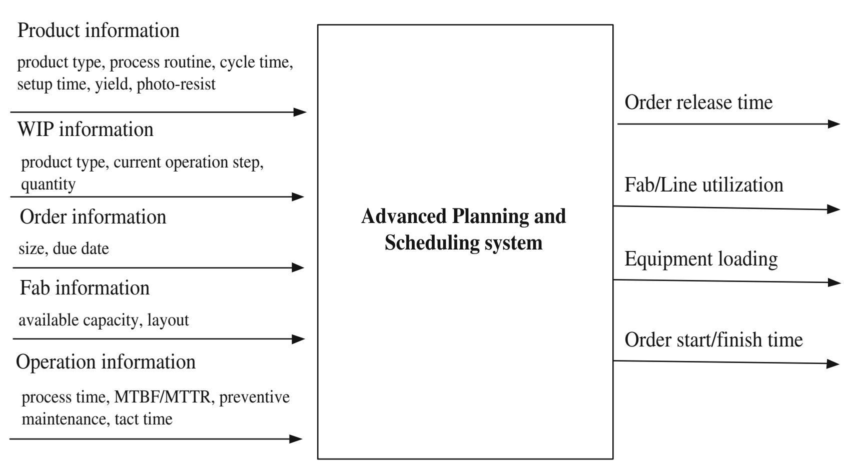

Fig. 8 Input and output of APS system

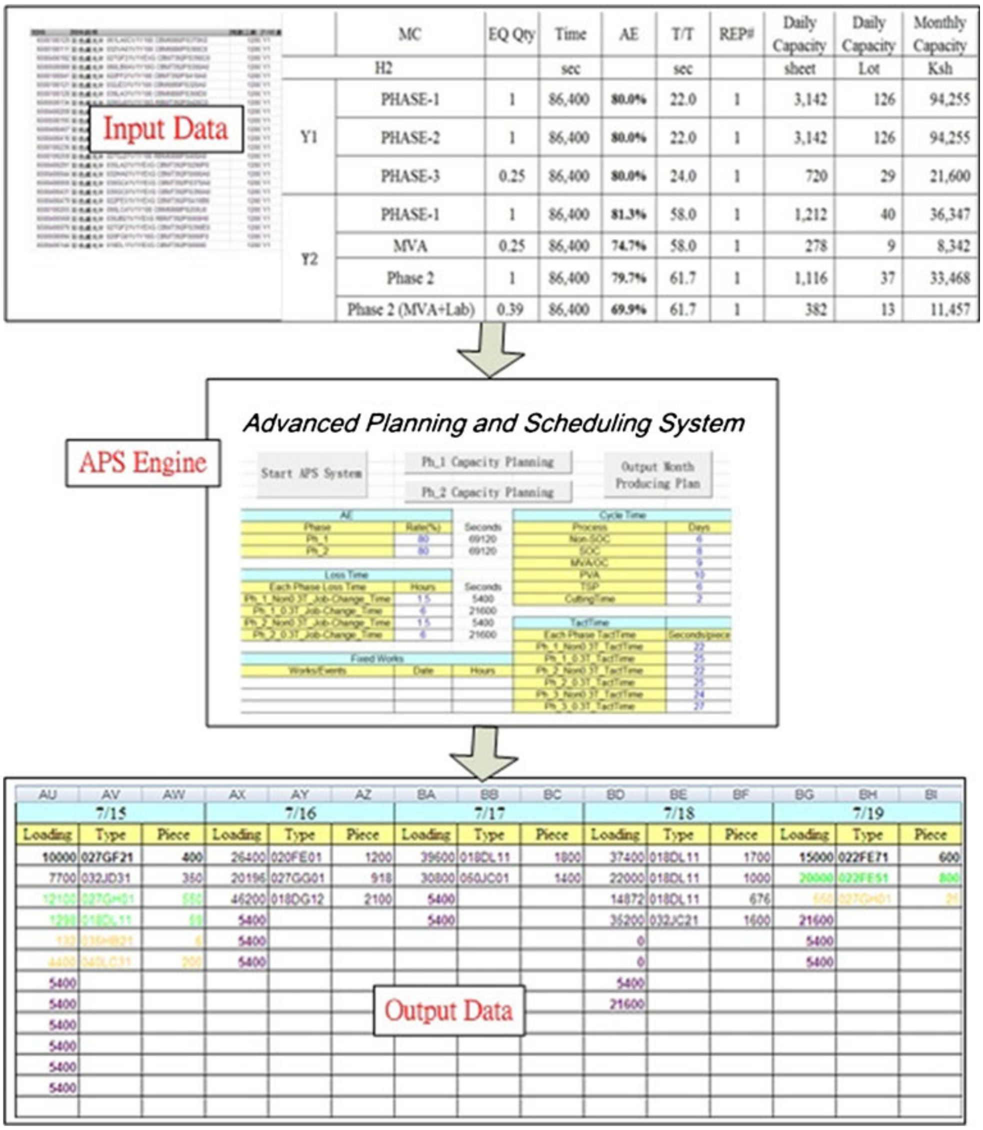

Fig. 9 User interface of APS system

to earlier time slots, by checking the resource availability from the time slot that overloading occurs backward to time now. The adjustment will not influence the orders that have been already scheduled to resources to avoid complication. If there is no feasible available resource, WBM will check forward and look for future available resource. This "look-ahead" balance mechanism can reduce equipment idleness and increase resource utilization. Figure 7 illustrates the detailed procedure of backward and forward scheduling used in WBM.

Figure 8 illustrates the input and output of APS system. The input data include size of order, order due date, available capacity, product type, process routine, process time, cycle time, setup time, yield, photoresist, tact time, preventive maintenance, mean

Table 1 The four product types considered in this study and their process routines

Product type	Type	Process route	Number of steps	Cycle time (in day)
A	Non-SOC	BM→R→G→B→ITO	5	6
B	SOC	BM→R→G→B→ITO→PS	6	8
C	MVA	BM→R→G→B→ITO→MVA→PS	7	9
D	PVA	BM→R→G→B→OC→ITO→VAD→PVA→PS	9	10

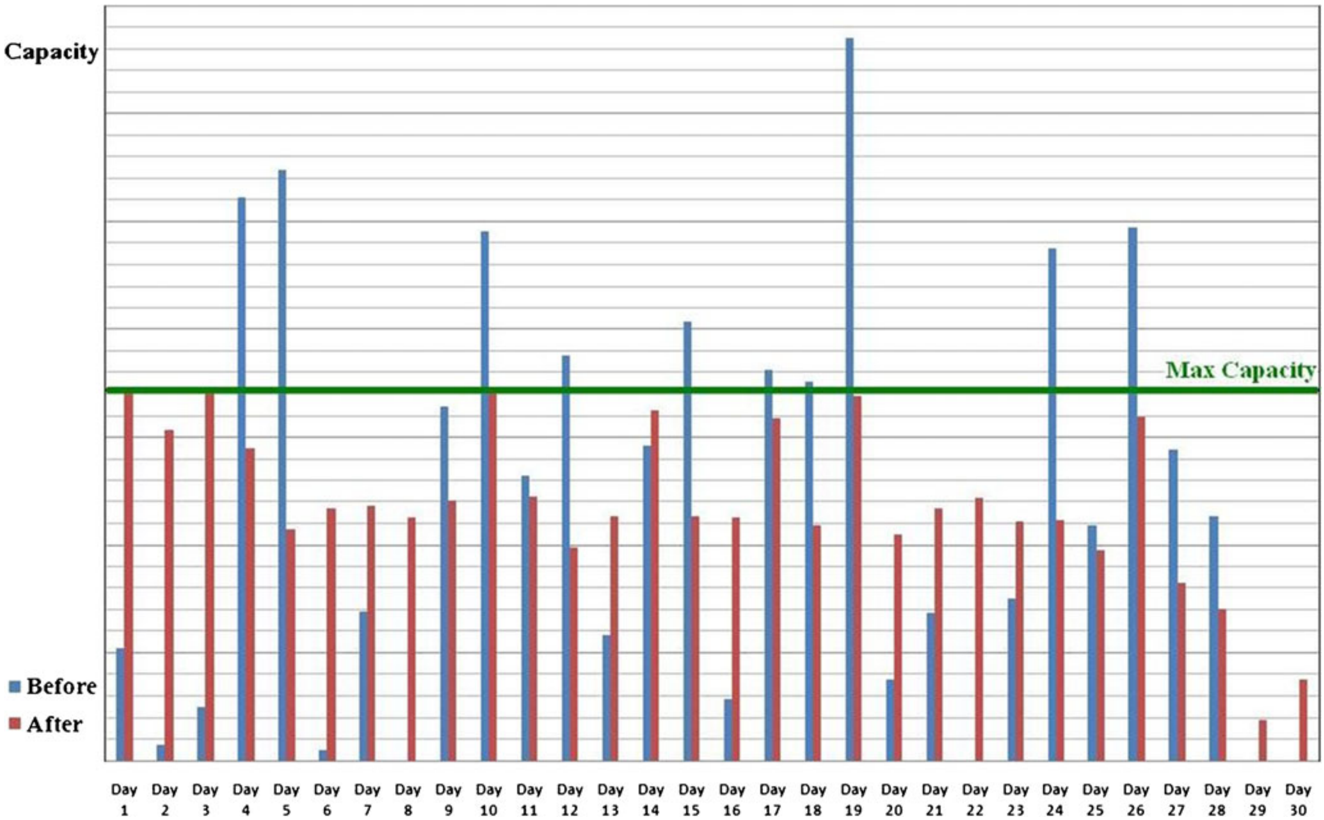

Fig. 10 A comparison of daily capacity plan before and after WBM

time to repair, mean time between failure, and WIP. Input data (e.g., process routines or product types) need to be continuously updated in response to either new orders or order modification. The output of the system includes equipment loading, fab utilization, line utilization, order release time, and order start/finish time. Industrial data from a real CF fab were collected and used to validate and evaluate the performance of APS. Historical production data were used to estimate the cycle time and waiting time at each production step.

Figure 9 shows the Microsoft Excel-based user interface of APS. APS reads in the data in the database of ERP system through input user interface and generates schedule and utilization results that can be saved in the database through the output interface. Production controller can use APS to efficiently generate feasible schedule and adjust schedule, if necessary. APS can be used for quick rescheduling due to its speed.

4 Experiments and results

This section uses experiments to demonstrate the efficiency and effectiveness of APS. Industrial data from real CF fab were collected and used to evaluate the performance of APS.

There are four typical product types: A, B, C, and D representing spacer on color filter (SOC), non-SOC, MVA, patterned vertical alignment (PVA), respectively. It is noted that SOC indicates spacer on color filter, and PVA means patterned vertical alignment. These products have numbers

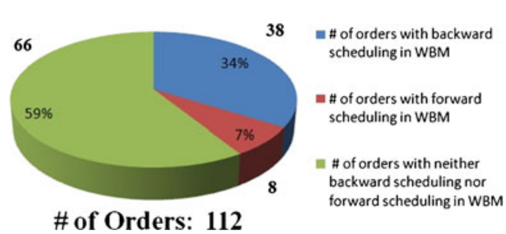

Fig. 11 The numbers of orders with backward scheduling and forward scheduling in an experiment of APS

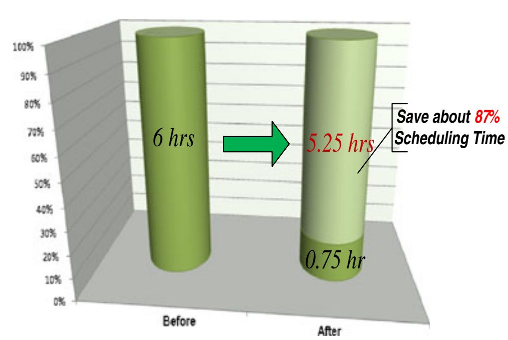

Fig. 12 A comparison of scheduling time before and after APS

of steps ranging from 5 to 9 and cycle times of 6 to 10 days. The cycle time, number of steps, and routing of each product type is shown in Table 1.

Figure 10 shows the daily capacity plan of one month. The green line indicates the maximum daily available capacity, and the blue lines represent the daily required capacity plan based on OPM, LRM, and WAM. The date of capacity requirement is calculated by subtracting the average cycle time from order due date. The infinite capacity plan is relatively easy to estimate by accumulating the required capacity according to the required date. In many cases, production controller may provide this infinite capacity planning result without systematically going further to implement the WBM of APS, due to the complexity in adjustment and the limitation in planning time. Shop floor manager can use this infinite capacity plan as a rough reference (due to its over-capacity requirements) and first process orders with higher priority on the basis of available capacity that is a practical constraint.

The red lines represent the daily required capacity generated by APS implementing all OPM, LRM, WAM, and WBM. It is obvious that this finite capacity planning results are feasible and reasonable, since the required capacity is no more than the available capacity. Therefore, shop floor manager can follow this capacity plan and make adjustment only when shop floor uncertainty occurs. In summary, Fig. 10 demonstrates the unbalance and balance of capacity plan before and after implementing APS.

Figure 11 illustrates the number of orders with backward scheduling and forward scheduling in an experiment of APS in 1 month. There are a total of 112 orders. After WAM, 66 orders (59 %) can start the processing on their originally planned latest start dates, but there are 46 orders (41 %) whose required capacity exceeds the available capacity of the dates that these orders planned to start the processing. With WBM, 38 orders (34 %) can be processed earlier by backward scheduling without delaying their due dates or influencing the other orders. On the other hand, eight orders (7 %) need to be processed after their latest start dates by forward scheduling. Shop floor managers can use overtime, backup capacity, or splitting an order to be simultaneously processed on multiple equipment to speed up the processing of these orders to meet their order due dates.

Originally, it takes about 6 h for an experienced CF production controller to manually generate a production schedule, including much work such as data collection and verification, check for material readiness, check for equipment unavailability, confirmation of equipment takt time, estimation of equipment loading, plan for the minimization of capacity loss, calculation of each order’s latest start time, and equipment workload balance. This is difficult and it becomes even more difficult when rescheduling is required within a short period of time, e.g., 10 min, due to urgent shop floor uncertainty. When the experienced production controller becomes unavailable (e.g., due to taking days off, job rotation, or resignation), it takes at least more than 10 h for an inexperienced production controller to take over this scheduling job, and generally the resulting schedule is with poor solution quality, if it is not infeasible.

With APS, it takes less than 1 min to go through all OPM, LRM, WAM, and WBM to generate a feasible schedule. Production controllers, either with or without sufficient experience, can manually adjust this schedule for further improvement and the required time is up 40 min, depending on the level of adjustment. The above are applicable to either scheduling or rescheduling. This leads to a saving of 87 % scheduling time, as shown in Fig. 12. The initial schedule generated by APS is with good quality and is robust, compared to manual operations highly depending on the experience of production controllers.

5 Conclusions and future research

This research develops an APS for one 4.5-generation CF fab with two production lines in north Taiwan. It includes four main modules to assign priority to orders, to determine lot release time, to accumulate workload, and to balance workload. Both forward scheduling and backward scheduling are used for workload balance and capacity loss can be controlled by taking into account the sequence-dependent setup times. Preliminary results show that APS can result in good and robust schedules in less than 87 % of scheduling time, compared to manual scheduling. Both scheduling speed and solution robustness are important when rescheduling is needed in uncertain shop floor environments. With APS, better scheduling/rescheduling results can lead to higher throughput and shorter lead time. These in turn increase the productivity and competitiveness of the studied CF fab.

This research can be extended to several directions. First, it is of interest to systematically compare the performance of APS with experienced production controllers. Currently, production controllers take the output of APS as initial solution and make manual adjustment on the basis of experience. A systematic comparison can be conducted to compare the initial solutions of APS and these production controllers. Second, there is a need to improve the work balance adjustment in WBM by applying heuristics such as genetic algorithm or grouping genetic algorithm. Third, this APS can be extended to multiple CF fabs with multiple lines. Furthermore, similar algorithms can be applied to the other manufacturing sectors of TFT-LCD supply chain, such as array fab and cell factory.

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