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MODELLING THE MATERIAL ALLOCATION SYSTEM FOR TFT-LCD MODULE FACTORIES BASED ON MAKE-TO-STOCK PRODUCTION*

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The TFT-LCD module factories are in charge of the last process of the TFT-LCD supply chain, i.e., assembling LCD panels (produced from the former process in the supply chain) as well as electronic components into TFT-LCD panels or the finished products using TFT-LCD panels. Since the variation of machine processes and production techniques at the former process of the supply chain results in a variety of qualities of LCD panels, the finished products assembled with those LCD panels of different qualities are also of different qualities, according to which they are classified into different grades. This paper models the material allocation system for a TFT-LCD module factory based on the make-to-stock (MTS) production, in which one of the main designs is to allow the flexibility that the finished products of higher grades are able to be downgraded to respond to the drastic variation of customer requirements for each grade of finished products. The system is modelled in detail by an integer programming approach that takes into account not only downgraded products but also the customer requirements for the quality qualification rate and the lower bound of non-dot-defect rate of products, to maximize the total profit of the product portfolio. The model is evaluated by conducting an experimental study for a numerical example, which turns out that the proposed system looks promising as it determines a feasible product portfolio that decreases both the inventory of LCD panels and the volume of unqualified products while maintaining a high profit.

Keywords: TFT-LCD; material allocation; downgraded product; quality qualification rate; lower bound of non-dot-defect rate.

1. Introduction

Thin film transistor liquid crystal display (TFT-LCD) is a kind of advanced displaying device that enjoys many competitive advantages over the others in the flat panel display industry, e.g., lightweight, excellent image, energy saving, among others,

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and hence TFT-LCD has been applied widely to a variety of products, e.g., monitors, notebooks, televisions, etc. In general, the TFT-LCD supply chain is mainly composed of *array*, *cell*, and *module processes* (Chang, 2005). The *array factories* are responsible to stack circuits and components on glass substrates through some cycling steps, and then the *cell factories* take charge of assembling those glasses with color filters into LCD panels. Finally, the *module factories* are in charge of assembling the LCD panels and electronic components (including integrated circuits, printed circuit boards, backlight modules, and so on) into TFT-LCD panels or the finished products using TFT-LCD panels, and inspecting them. In general, the TFT-LCD panel products with common-size active display areas (e.g., 14-inch or 15-inch notebooks) are manufactured with the make-to-stock (MTS) production, in which the demand of products is forecasted and the production is usually finished before customer orders are received. Such a production form is useful as it can effectively make use of machine capacity to increase the product volume and further the total profit.

From the viewpoint of factory management, each of the above three processes has a different concern about production planning. Owing to expensive setup cost of facilities, both array and cell factories aim at maintaining high utilization rates of facilities to ensure production capacity. Different from them, since the material cost in a module factory accounts for more than 60% of the total cost in general (Research and Markets, 2009), the module factory (with similar characteristics as the assembling industry) is more concerned about material planning to reduce the pending time of raw materials. If the material allocation planning and the production planning are made inappropriately, the inventory cost of both the input LCD panels and the TFT-LCD finished products would be increased drastically so that the total profit is decreased. However, from the literature, most of the previous studies on the TFT-LCD industry only focused on the problem of capacity and production planning (e.g., see Chen et al. (2010)), the product combination problem (e.g., see Liang and Fang (2011)), or the available-to-promise order problem (e.g., see Tsai and Wang (2009)), but few previous studies focused on the material allocation for module factories with concerns about the customer requirements for quality qualification.

On the other hand, we consider the input materials of module factories. Among all the input materials of constituting a finished TFT-LCD product in module factories, the most critical material is the LCD panel manufactured by cell factories (the former process of the supply chain), because the quality of LCD panels significantly influences the image-displaying quality of the finished TFT-LCD products. Since cell factories have different machine processes and production techniques, the manufactured LCD panels are of different qualities, so that the finished products assembled with LCD panels of different qualities are also of different qualities, according to which they are classified into different grades. Note that, throughout the rest of this paper, in order to discriminate the quality classification of those LCD panels from that of finished products, *rank* is used to classify the qualities of LCD panels, while *grade* is used for finished TFT-LCD products. However, customers' uncertain demand for each grade of finished TFT-LCD products may not respect its respective volume manufactured by the module factory. Under the MTS production, the difference between customers' demand and the manufactured products for each grade results in a huge loss of the profit due to unfulfilled customer orders and inventory cost.

In light of the above, if we have the flexibility to downgrade higher-grade finished products to fulfil the insufficient volume for lower-grade products, then both unfulfilled orders and inventory cost can be reduced. Although a part of the profit is decremented due to the product downgrade, the cost for unfulfilled orders and inventory cost can be reduced at the same time, and hence it is of interest and of importance to find a compromise among them. As a result, this paper proposes a material allocation system for a TFT-LCD module factory in an MTS production environment with the mechanism of downgrading finished products, i.e., it is allowed that the high-grade products are able to be downgraded to the products of its adjacent lower grade if the volume of the adjacent-grade products is insufficient. The proposed system is based on integer programming to maximize the profit of a product portfolio when the quality ranks of LCD panels, the grades of finished products, and the customer requirements for quality qualification rate and lower bound of non-dot-defect rate of products are taken into account. The experimental results of a representative example show that the proposed model can help module factories quickly determine the released volume for each rank of LCD panels, and effectively downgrade each grade of finished products to fulfill customer orders.

The main contribution of this paper is stated as follows. Our material allocation system considers that the LCD panels manufactured from the former process of the TFT-LCD supply chain have different ranks, and those rank differences lead to a variety of grades of TFT-LCD panel products. In order to fulfill the insufficient product volume of customer orders, our system based upon an integer programming approach has the mechanism of downgrading higher-grade products to replenish the insufficient volume of lower-grade products in TFT-LCD module factories to drastically reduce inventory cost.

The rest of this paper is organized as follows. Section 2 gives some preliminaries of our research. Section 3 gives our proposed mathematical model in detail. Section 4 computes a numerical example and discusses its experimental results. Finally, Section 5 concludes this paper with future work.

2. Preliminaries

This section first gives an overview of the TFT-LCD module process, and then reviews some previous related works.

2.1. *The TFT-LCD module process*

In general, the TFT-LCD module process consists of *mounting*, *assembling*, and *inspection subprocesses*, as illustrated in Figure 1. The *mounting subprocess* takes charge of enabling the electrical conduction of LCD panels (including polarizer sticking and anisotropic conductive film (ACF) adhering), and then the *assembling subprocess* is responsible to assemble these LCD panels with integrated circuits (IC), flexible polymer boards (FPB), and printed wiring boards (PWB) into TFT-LCD panels. Finally, all the finished TFT-LCD panels are inspected and classified into different graded products in the *inspection subprocess*.

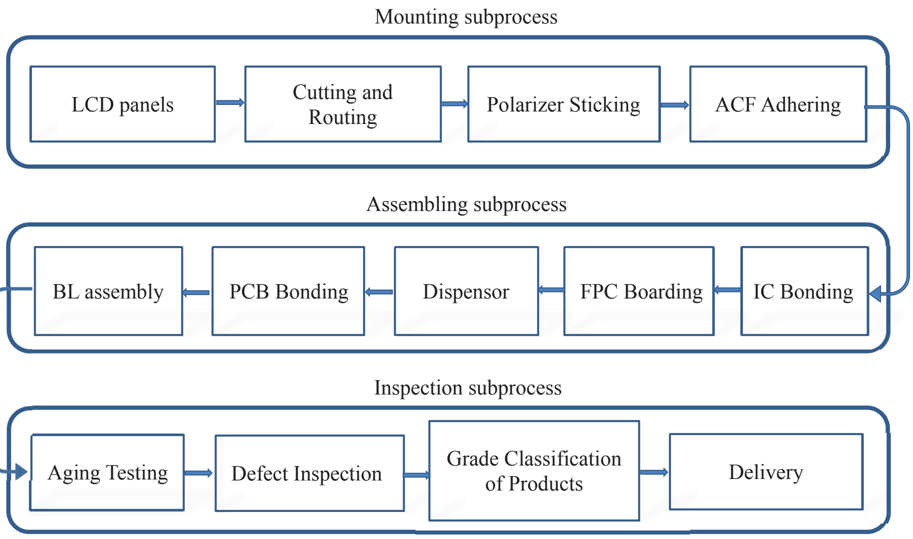

Fig. 1. Illustration of the TFT-LCD module process.

Our system for the TFT-LCD module process based on the MTS production is illustrated in Figure 2, in which five ranks of LCD panels are transformed into three types of products (each with two grades respectively), and then delivered to three customers according to their required quality specifications and demand for products. The input of the system is the LCD panels manufactured by cell factories. Since cell factories have different machine processes and manufacturing techniques, the manufactured LCD panels have different qualities, according to which they are classified into different ranks (e.g., ranks 1–5 in Figure 2). Based on the MTS production, the actual demand of each type of products for next term or season is forecasted according to the previous historical data, so the required released volume of each rank of LCD panels and the processes that will be applied to the production are determined in the beginning of production. In our system, LCD panels of different ranks are transformed into finished products after mounting process, assembling process and inspection (see Figure 2). Under considering the existing product inventory, we can determine the output volume of each type of products. Note that a module factory may manufacture not only one type of products, e.g., there are three types of products (Types A, B and C) in Figure 2. Since the manufactured products are of different quality, they are classified into different grades, e.g., each type of products are divided into grades 1 and 2 in Figure 2. Hence, the actual fill rate of customer orders is influenced by both the released volume of ranked LCD panels and the allocation of graded products under a variety of customer requirements. In light of the above, the material allocation system is very complicated.

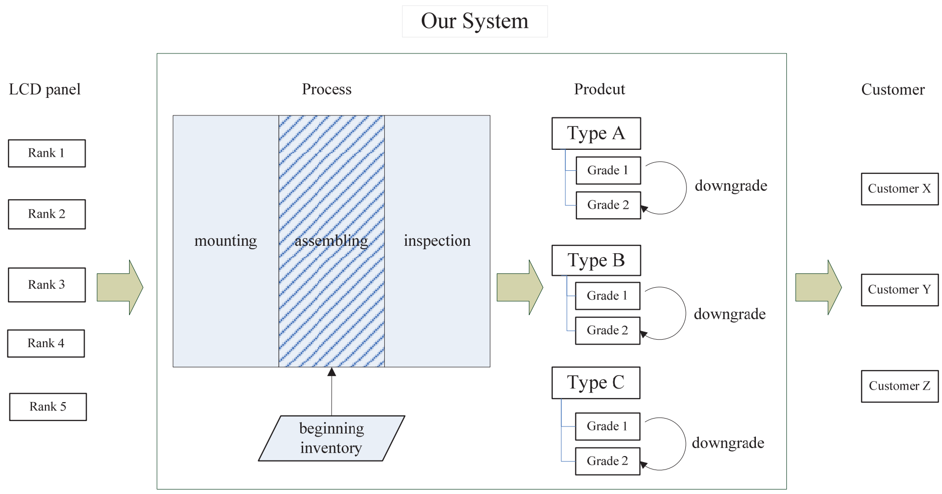

Fig. 2. Illustration of our system for the TFT-LCD module process based on the MTS production.

For the same grade of products, since the customers have different requirements for quality qualification, the products have different acceptance rates when customers inspect the products. These products that are not accepted by the customers with strict quality specifications lead to a loss of the total profit. Especially, because the customers' demand is uncertain and our production is based on MTS, it is common that the volume of accepted products for each grade may not satisfy customers' actual demand. To alleviate the problem, this paper considers to make good use of those unsatisfied products. Since the manufactured higher-grade products have stricter standards for quality qualification, they may pass the looser standards of lower-grade products. As a result, we allow to downgrade those unsatisfied higher-grade products to supply the shortage of lower-grade products. Based on maximizing the total profit of the module factory, an important issue for production managers is to investigate how to plan the volume of released LCD panels and apply the mechanism of downgrading products to increasing the customers' order fill rate and eliminating the exceeded products.

2.2. *Related work*

To the best of our understanding, there is no previous work on modelling the material allocation system for TFT-LCD module factories with the mechanism of downgrading products. Therefore, the other related works on the TFT-LCD industry are introduced in this subsection. Most of the previous studies on the TFT-LCD industry focused on the problem of capacity and production planning, the product combination problem, and the available-to-promise order problem. Hence, the three lines of research are introduced respectively as follows.

For capacity and production planning, Chen et al. (2010) proposed a mixed integer linear programming model to plan and expand the capacity for TFT-LCD manufacturing, and utilized a shadow-price-based heuristic to find a near-optimal solution for their optimization problem. Jeong et al. (2001) developed a two-stage scheduling system between TFT-LCD cell and module processes, with sequencial dependence between setup time and parallel machines, to minimize the mean flow time and maximize the production progressiveness. Lin et al. (2007) used a three-phase method, which contains capacity configuration, capacity expansion and capacity exploitation, to solve the strategic capacity and product mix problems for the TFT-LCD industry. Lin et al. (2011) used a two-stage stochastic programming model for strategic capacity planning problems in TFT-LCD module factories under demand uncertainties. Shin and Leon (2004) developed two algorithms based on the MULTIFIT method and tabu search to solve the parallel machine-scheduling problem with family setup times and due dates in TFT-LCD module factories. Shin and Kang (2010) proposed a dispatching algorithm for rework processes in TFT-LCD module factories, and measured its performance by six diagnostic indicators. Wang et al. (2007) considered a variety of important factors of resource planning to propose a genetic algorithm to solve the resource portfolio problem in semiconductor testing markers. Wang and Su (2006) applied the Hungarian method to improving the TFT-LCD cell process to yield for matching TFT and CF plates.

For product combination problem, Chen and Hong (2000) studied the product mix planning problems with time bucket selection, mix optimization, and bottleneck planning in semiconductor foundry plants based on integer programming and heuristic procedures. Chung et al. (2005a,b) applied an analytic hierarchy process (AHP) and an analytic network process (ANP) to maximize the manufacturing efficiency for a semiconductor fabricator with concerns about the aspects of product mix, equipment efficiency, as well as finance. Lin et al. (2009) indicated that the traditional material requirement planning (MRP) is not suitable for the TFT-LCD industry due to a variety of customer requirements, and addressed a critical material planning (CMP) problem that considers customer preference factors and the purchase quantity ratio based on a network graph method. Lin et al. (2004) constructed a hierarchy planning model, which includes order management, midterm sales, and operations planning for the TFT-LCD production chain, and discussed the allocation of critical resources. Lo et al. (2008) provided a three-level hierarchical forecasting (HF) method that consists of five steps for the LCD monitor market to help LCD manufactures and brand owners to forecast the future market demand accurately. Wang et al. (2007) proposed a mixed integer linear programming model that maximizes the net profit under resource limitations, order fulfillment, and inventory costs for the TFT-LCD industry. Liang and Fang (2011) evaluated the supplier productivity and quality performance in the TFT-LCD industry by a DEA method with the constraint of grey system entropy weights.

For the available-to-promise order problem, Jeong et al. (2002) indicated that the ATP process is very complicated owing to the complexity of supply chain and information integration, and hence proposed a model of estimating the promising delivery date and planning the unused capacity at the shop floor for the TFT-LCD manufacturing supply chain. Lin et al. (2010) highlighted several special production characteristics in the TFT-LCD industry, and built a model that links available material resources and capacity to enhance the responsiveness of order fulfillment processes. Tsai and Wang (2009) constructed a generic three-stage multi-site ATP mechanism that maximizes the assignment of the orders for the maximal profit for TFT-LCD module factories with assemble-to-order manufacturing.

3. Modelling the Material Allocation System for a TFT-LCD Module Factory

In this section, our model for the material allocation system for a TFT-LCD module factory is given in detail. We first introduce the classification of finished products, then the mechanism of downgrading products, and finally the mathematical model for our material allocation system.

3.1. *Classification of finished products*

In TFT-LCD module factories, the finished products are conventionally divided into *standard products* and *substandard products*. The *standard products* are the finished products that satisfy customer requirements for product quality specifications, according to which standard products are further divided into different grades, and each grade of standard products is sold at a different normal price. On the other hand, the *substandard products* are those dissatisfied finished products, and they may be sold at a lower price.

In order to satisfy various customer requirements for product quality specifications so as to fill orders immediately and enlarge the total profit, it is of importance to conduct appropriate inspections and allocation for each grade of products. That is, before delivering to customers, many quality-inspection items for products are needed to be performed when production managers are planning the allocation of each grade of products. Almost all the quality-inspection items are concerned about the image-displaying quality of products, in which customers put more emphasis on the item of inspecting the dot-defect quantity for each batch of products. Dot defects include bright dot defects and dark dot defects, in which the bright dot defect is bright or visible and can always be seen on an all-black background, while the dark dot defect is dark and can always be seen on an all-white background. Note that the inspection is conducted for each patch of products, because any product cannot be manufactured individually under cost consideration.

For simplicity, we roughly classify the quality-inspection items for a batch of products in a module factory into two categories: the most crucial item is to inspecting the non-dot-defect rate, while the other items are related to image-displaying functions (such as aging, reliability, and so on). Correspondingly, the customer requirements for product quality specifications are simplified to be composed of *a lower bound of non-dot-defect rate* and *a quality qualification rate*. Note that the lower bound of non-dot-defect rate is the customer's least accepted threshold value for non-dot-defect rates, while the quality qualification rate is the passing rate of the quality-inspection items related to the image-displaying functions. In general, customers are cooperated with the module factory to set up the production processes and the released material of each rank together. Therefore, when a customer requests a specific quality qualification of products, the module factory inspects this batch of products, and corrects the unqualified products until the lower bound of non-dot-defect rate and the quality qualification rate are achieved. As a result, in practice, the manufactured volume of each grade of products multiplied by the quality qualification rate and the non-dot-defect rate requested by the customer is the actual volume of the products that pass the inspection items of quality qualification.

The two quality-inspection specifications (i.e., the above simplified product quality specifications for the non-dot-defect rate and the quality qualification rate) requested by customers are the parameters used for downgrading products, and can quickly and effectively assist the module factory in classifying the qualities of finished products. Since different customers have different requirements for the two quality-inspection specifications, not all the finished products can be accepted by a variety of customers, and the products dissatisfying customers are sold at low prices and lead to the loss of the total profit. Therefore, for production managers, it is of importance to eliminate the dissatisfying products from the aspect of satisfying customers' demand. As consequence, the objective of this paper is to propose a material allocation system of graded products with mechanism of downgrading products to maximize the total profit so that customer requirements for the two quality specifications are satisfied, based on the released LCD panels of different ranks to manufacture products and reallocate the dissatisfied products.

The flowchart of the process of transforming the input materials (mainly, LCD panels) into standard products in our allocation system is illustrated in Figure 3. The process is based upon a two-phase procedure to identify standard products (which are the main source of the total profit) according to quality qualification rate and lower bound of non-dot-defect rate, and then is to conduct the mechanism of downgrading products to increase the amount of lower-grade standard products. The process is stated in detail as follows. See also Figure 3. After transforming the input LCD panels into finished products of different grades, the first phase of the process is to inspect and correct the finished products to satisfy each customer's requested quality qualification rate. If a product passes the inspection, it is called *qualified product*; otherwise, *unqualified product*. Note that the actual volume of the qualified products can be calculated as the manufactured volume of products multiplied by the quality qualification rate requested by the customer.

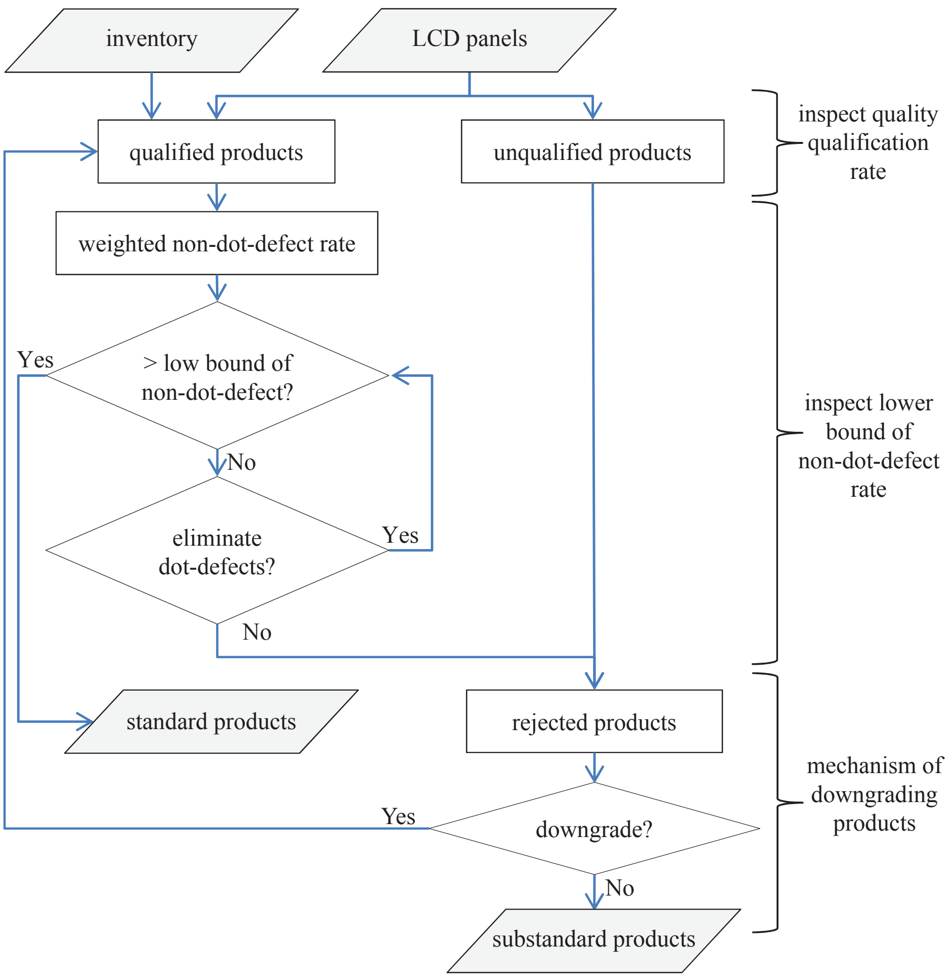

Fig. 3. The flowchart of the process of transforming the input materials into standard products in our material allocation system.

Then, for each batch of qualified products (including qualified inventory), the products are of various qualities, which affect their actual dot-defect quantity, so the second phase of the process is to inspect the quantity of dot defects with a *weighted non-dot-defect rate*, which is the weighted mean of the non-dot-defect rates of all product grades of this patch of products with their actual qualified product volumes as the weights. If the weighted non-dot-defect rate for this batch of products is greater than the customer's requested lower bound of non-dot-defect rate, then they are called *standard products* and are sold at a normal price; otherwise, they are revised (by eliminating some dot-defect products) until they can achieve the required lower bound. The remaining products are viewed as *rejected products*. On the other hand, the unqualified products at the first phase are viewed as rejected products as well. Finally, we try to downgrade those rejected higher-grade products to qualified lower-grade products. If the rejected products satisfy customers' required quality qualification rate and the lower bound of non-dot-defect rats for lower-grade standard products, then they are downgraded to lower-grade standard products; otherwise, they are viewed as *substandard products* and are sold at a low price.

For module factories, the LCD panels are the most main materials of the TFT-LCD products. Owing to variation of production machines or manufacturing techniques, the LCD panels from cell factories have different qualities, in which the products assembled with higher-quality LCD panels enjoy better image-display quality and have fewer dot defects, so that they have a higher probability to satisfy customer requirements for quality specifications. Therefore, different qualities and released volume of LCD panels remarkably influence the fill rate of customer orders. Since each customer has a different specification for quality qualification of products, the finished products are classified into different grades, and the higher-grade products have stricter qualify specification for image display and lower quality qualification rate. The products that do not satisfy customers' quality specifications are called unqualified products, and may reduce the profit of products, because they are usually sold to other customers at a low price. In fact, the higher-grade products have stricter quality specification, which may satisfy the looser quality specification of lower-grade products. Hence, this paper allows to downgrade unqualified higher-grade products to lower-grade products.

However, not all the unqualified products can be accepted by the customers with loose quality specification of products. Only when the required volume of the grade of the products with looser quality specification is greater than that with stricter qualify specification, the excess volume of the latter grade of products can be downgraded to supply the former grade of products. For example, consider two grades of products in Figure 4, where the grade-1 products have a stricter quality specification than the grade-2 products, and their quality qualification rates are 65% and 85%, respectively. Assume that we manufacture 100 pieces of products for each grade. Then, there are 65 pieces of qualified products and 35 pieces of unqualified products for grade-1 products, while there are 85 pieces of qualified products and 15 pieces of unqualified products for grade-2 products.

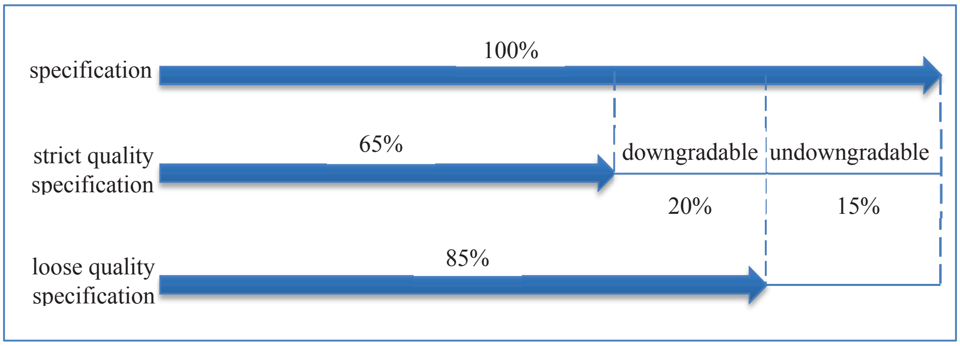

Fig. 4. The quality qualification rate for graded products.

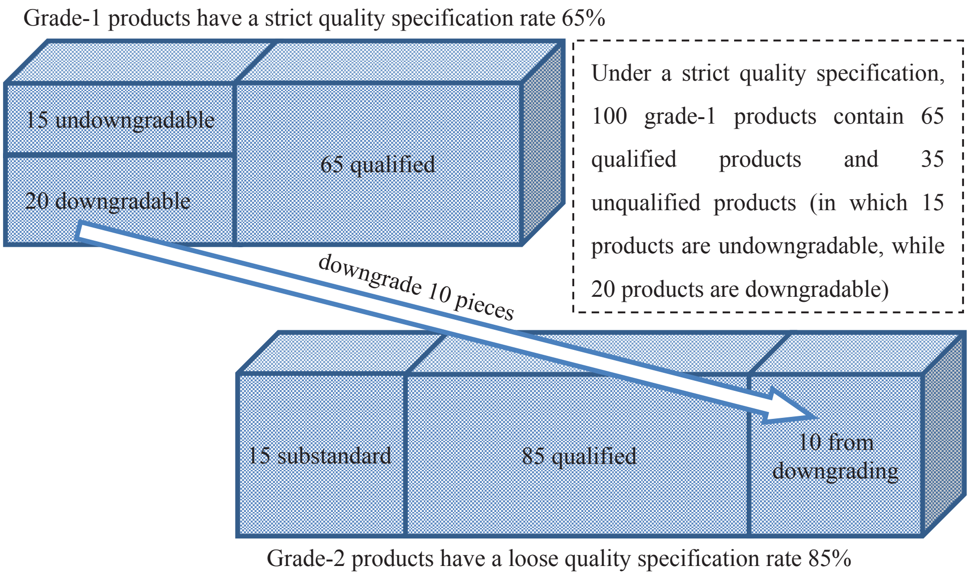

Fig. 5. Illustration of downgrading unqualified grade-1 products to qualified grade-2 products.

Here we suppose that the percentage of downgradable unqualified products is equal to the difference of quality qualification rates of the two graded products, i.e., there are 20 pieces of unqualified grade-1 products ($100 \times (85\% - 65\%)$) can be downgraded to qualified grade-2 products. Note that in practice, the volume of downgradable unqualified products is also estimated according to the difference of the two rates. Hence, the qualified grade-2 products have 105 pieces in total (85+20). But the customer may not demand so many pieces of grade-2 products. Suppose that the customer requires 65 pieces of qualified grade-1 products and 95 pieces of qualified grade-2 products. Then, only 10 pieces of unqualified grade-1 products are downgraded to qualified grade-2 products. As shown in Figure 5, it turns out that for grade-1 products, there are 65 pieces of qualified products, 15 pieces of undowngradable substandard products, and 20 downgradable products, in which only 10 pieces are downgraded to qualified grade-2 products, while the other 10 pieces are downgradable substandard grade-1 products but not downgraded (which are called *surplus* in the rest of this paper).

In addition to the quality qualification inspection, the inspection of dot defects of TFT-LCD products is concerned as well. For the qualified products, we calculate the weighted non-dot-defect rate that considers all grades of qualified products. If the rate is not greater than the lower bound of non-dot-defect rate, we eliminate some dot-defect products until the lower bound is achieved. As illustrated in Figure 6, the volume of qualified products may be reduced to a smaller volume of standard products, consisting of non-dot-defect and dot-defect products. Either of the non-dot-defect and dot-defect products can be sold at a normal price, downgraded to qualified lower-grade products, or remaining as a surplus.

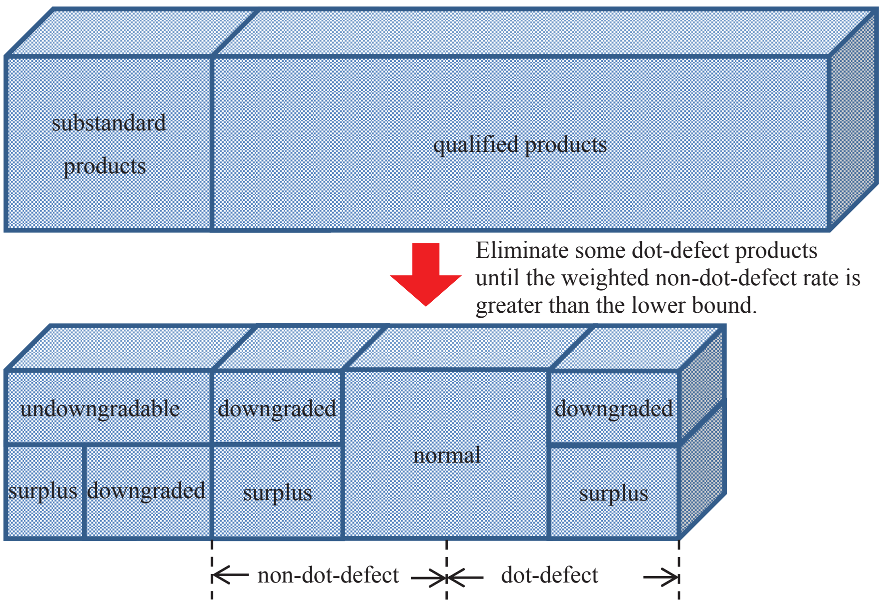

Fig. 6. The planning of qualified products with a lower bound of dot-defect rate.

3.2. *A mathematical model of the material allocation problem*

The main operational objective of module factories based on the MTS production is to acquire a high profit. Such an objective should be able to be achieved by quickly planning the released volume of various ranks of LCD panels, producing as many higher-revenue standard products as possible, and effectively downgrading unqualified higher-grade products to reduce the quantity of unqualified products and the inventory of LCD panels. As a result, we construct a mathematic model based on integer programming that takes into account different ranks of LCD panels, the production information of products, and the customer requirements for quality qualification rate and lower bound of non-dot-defect rate. In what follows, we first list the assumptions behind our material allocation system with mechanism of downgrading products, then depict the notation of our model, and finally formulate our integer programming model.

3.2.1. *Assumptions*

The main assumptions behind our concerned problem are stated as follows:

- The module factory is based on the MTS production.
- The upper bound of forecasted demand for each grade of products is known.
- Only the material allocation of LCD panels is concerned.
- The beginning inventory and the schedule of the volume arriving at the module factory for LCD panels are known.
- The customer requirements for each grade of products consists of quality qualification rate and lower bound of non-dot-defect rate, and the two rates of each graded product are assumed to be known.
- The quality qualification rate of a product is related to the grade of the product and the rank of the used LCD panel, but the lower bound of non-dot-defect rate of a product is only associated with the grade of the product.
- For each grade s, the grade-s products have stricter quality qualifications than the grade-$(s+1)$ products. In our system, the grade-s products are downgradable to the grade-$(s+1)$ products, but cannot be downgraded to the other lower-grade products. Note that in the MTS production environment, the operational objective of a module factory is generally to maximize the total profit. If the grade-s products are downgradable to the other lower-grade products rather than the grade-$(s+1)$ products, the total profit would be reduced too much, because the manufacturing cost of higher-grade products is usually greater than that of lower-grade products.

3.2.2. *Notation*

The notation used in our mathematical model is given as follows.

Indices:

- p denotes the product type ($p = 1, 2, 3, \cdots, P$).
- s denotes the index to one of the S_p grades of type-p products ($s = 1, 2, 3, \cdots, S_p$).

- r denotes the index to one of the R ranks of LCD panels ($r = 1, 2, 3, \cdots, R$).
- t denotes the index to one of the T planning periods ($t = 1, 2, 3, \cdots, T$).

Parameters:

- $pr_{p,s}$ is the revenue of normal grade-s type-p products.
- $ci_{p,s}$ is the revenue of substandard grade-s type-p products.
- $mc_{p,s}$ is the manufacturing cost for grade-s type-p products.
- $lq_{p,r}$ is the material cost of rank-r LCD panels for type-p products.
- $hc_{p,r}$ is the inventory cost of rank-r LCD panels for type-p products.
- $ar_{p,r,t}$ is the arrival volume of rank-r LCD panels for type-p products at period t.
- $pfb_{p,s}$ is the upper bound of the forecasted demand for grade-s type-p products.
- $ug_{p,s,r}$ is the quality qualification rate for grade-s type-p products using rank-r LCD panels.
- $bd_{p,r}$ is the non-dot-defect rate of type-p products (of all grades) using rank-r LCD panels.
- $zbd_{p,s}$ is the lower bound of non-dot-defect rate of grade-s type-p products.
- $\alpha_{p,s,r}$ is the ratio of undowngradable products for grade-s type-p products using rank-r LCD panels, which determines the undowngradable volume from the grade-s products to the grade-$(s+1)$ products. The calculation of this ratio is concerned with the quality qualification rate of adjacent lower-grade products ($s < S_p$), but the products of the lowest grade ($s = S_p$) do not have the quality qualification rate of adjacent lower-grade products, and hence, the ratio in this case applies the quality qualification rate of its own grade. It is determined as follows:

$$\alpha_{p,s,r} = \begin{cases} 1 - ug_{p,s+1,r}, & \text{if } s < S_p; \\ 1 - ug_{p,s,r}, & \text{if } s = S_p. \end{cases}$$

- δ_s is a 0-1 variable used to determine whether the grade-s products can be downgraded to the grade-$(s+1)$ products. The variable is defined as follows:

$$\delta_s = \begin{cases} 0, \text{ if } s = S_p; \\ 1, \text{ if } s < S_p. \end{cases}$$

  That is, if the grade s of the product is the lowest ($s = S_p$), then the product cannot be downgraded; otherwise ($s < S_p$), it can.

Decision variables:

- $HP_{p,r,t}$ is the accumulated inventory of rank-r LCD panels for type-p products at period t, and $HP_{p,r,0} = 0$.
- $SPX_{p,s,r,t}$ is the input volume of rank-r LCD panels for grade-s type-p products at period t.

- $VQ_{p,s,r,t}$ is the volume of undowngradable substandard products for grade-s type-p products using rank-r LCD panels at period t.
- $NV_{p,s,t}$ is the downgraded volume of grade-s type-p products without any dot defects (a.k.a., non-dot-defect products) at period t.
- $HV_{p,s,t}$ is the downgraded volume of grade-s type-p products with dot defects (a.k.a., dot-defect products) at period t.
- $SUVQ_{p,s,r,t}$ is the accumulated surplus of substandard product for grade-s type-p products using rank-r LCD panels at period t, and $SUVQ_{p,s,r,0} = 0$.
- $SUNV_{p,s,t}$ is the accumulated surplus of non-dot-defect products for grade-s type-p products at period t, and $SUNV_{p,s,0} = 0$.
- $SUHV_{p,s,t}$ is the accumulated surplus of dot-defect products for grade-s type-p products at period t, and $SUHV_{p,s,0} = 0$.
- $DVQ_{p,s,r,t}$ is the volume of downgrading substandard products for grade-s type-p products using rank-r LCD panels at period t, and $DVQ_{p,0,r,t} = 0$.
- $DNV_{p,s,t}$ is the volume of downgrading non-dot-defect products for grade-s type-p products at period t, and $DNV_{p,0,t} = 0$.
- $DHV_{p,s,t}$ is the volume of downgrading dot-defect products for grade-s type-p products at period t, and $DHV_{p,0,t} = 0$
- $PQ_{p,s,t}$ is the delivered volume of grade-s type-p products at period t.

3.2.3. *Mathematical model*

The objective function of our model is to maximize the total profit of a product portfolio, which is conventionally influenced by the revenue of standard products, the revenue of substandard products (which includes not only the total quantity of undowngradable products over the planning period, but also the available downgraded surplus of substandard products at the end of period, non-dot-defect products, and dot-defect products), as well as the material cost and stock cost of LCD panels. Note that the stock cost considers only the volume of the LCD panel inventory at the end of the whole planning period, at which most module factories take stock routinely. The objective function of our model is expressed as follows:

$$
\begin{aligned}
&\text{Maximize } Z = \\
&\sum_{p=1}^{P}\sum_{s=1}^{S_p}\sum_{t=1}^{T} PQ_{p,s,t} \cdot (pr_{p,s} - mc_{p,s}) \\
&+\sum_{p=1}^{P}\sum_{s=1}^{S_p}\left[\sum_{r=1}^{R}\left(\sum_{t=1}^{T} VQ_{p,s,r,t} + SUVQ_{p,s,r,T}\right) + SUNV_{p,s,T} + SUHV_{p,s,T}\right] \\
&\cdot(ci_{p,s} - mc_{p,s}) - \sum_{p=1}^{P}\sum_{s=1}^{S_p}\sum_{r=1}^{R}\sum_{t=1}^{T} SPX_{p,s,r,t} \cdot lq_{p,r} - \sum_{p=1}^{P}\sum_{r=1}^{R} HP_{p,r,T} \cdot hc_{p,r} \quad (3.1)
\end{aligned}
$$

For the constraints of the input materials, the released volume of LCD panels is concerned with the demand of products. Since we focus on the module factory based on the MTS production, the demand of each grade of products is forecasted and is usually finished before receiving customer orders. In addition, note that the accumulated inventory for higher-rank LCD panels at each period can help to reduce the inventory of other lower-rank LCD panels. The corresponding constraints are represented as follows:

$$\sum_{t=1}^{T} PQ_{p,s,t} = pfb_{p,s} \tag{3.2}$$

$$HP_{p,r,t-1} + ar_{p,r,t} - \sum_{s=1}^{S_p} SPX_{p,s,r,t} = HP_{p,r,t} \tag{3.3}$$

For inspecting unqualified products, to decrease the inventory so as to effectively reduce the production cost, we calculate the volume of undowngradable products according to the quality qualification rate of each grade of products, and downgrade the downgradable products to satisfy the demand of lower-grade products if the demand of adjacent lower-grade products is not satisfied. The corresponding constraints are represented as follows:

$$SPX_{p,s,r,t} \cdot \alpha_{p,s,r} = VQ_{p,s,r,t}, \forall p, s, r, t \tag{3.4}$$

$$\begin{aligned} &SUVQ_{p,s,r,t-1} + SPX_{p,s,r,t} \cdot (ug_{p,s+1,r} - ug_{p,s,r}) - DVQ_{p,s,r,t} \\ &= SUVQ_{p,s,r,t}, \qquad \forall p, s, r, t \end{aligned} \tag{3.5}$$

Specifically, Constraint (3.4) calculates the volume of undowngradable substandard products, while Constrain (3.5) calculates the volume of the surplus of substandard product by deducting the volume of downgrading substandard products from the volume of downgradable substandard products (including the inventory volume and the downgraded volume from adjacent higher-grade products). Note that, since the required volume of the product grade with looser quality specification is greater than that with stricter qualify specification, the excess volume of the latter-grade products can be downgraded to supply the former-grade products, and hence the downgraded volume is $SPX_{p,s,r,t} \cdot (ug_{p,s+1,r} - ug_{p,s,r})$.

For inspecting qualified products, to consider the practical situation that customers emphasize the quantity of non-dot defects of delivered products, we construct the mechanism of downgrading non-dot-defect products and dot-defect products, respectively, and calculate the exact accumulated downgraded volume after modifying the volume of delivered products to satisfy customers' demand at each period. Constraints (3.6) and (3.7) represent the downgraded volume for non-dot-defect products, while Constraints (3.8) and (3.9) indicate the downgraded volume for dot-defect products. Those constraints are shown as follows:

$$SUNV_{p,s,t-1} + \left(\sum_{r=1}^{R} DVQ_{p,s-1,r,t} \cdot bd_{p,r} + DNV_{p,s-1,t}\right) + \sum_{r=1}^{R} SPX_{p,s,r,t} \cdot ug_{p,s,r} \cdot bd_{p,r} - PQ_{p,s,t} \cdot zbd_{p,s} = NV_{p,s,t}, \forall p, s, t \quad (3.6)$$

$$NV_{p,s,t} - DNV_{p,s,t} \cdot \delta_s = SUNV_{p,s,t} \forall p, s, t \quad (3.7)$$

$$SUHV_{p,s,t-1} + \left[\sum_{r=1}^{R} DVQ_{p,s-1,t} \cdot (1 - bd_{p,r}) + DHV_{p,s-1,t}\right] + \sum_{r=1}^{R} SPX_{p,s,r,t} \cdot ug_{p,s,r} \cdot (1 - bd_{p,r}) - PQ_{p,s,t} \cdot (1 - zbd_{p,s}) = HV_{p,s,t} \forall p, s, t \quad (3.8)$$

$$HV_{p,s,t} - DHV_{p,s,t} \cdot \delta_s = SUHV_{p,s,t} \forall p, s, t \quad (3.9)$$

All the values of decision variables are nonnegative, as constrained as follows:

$$HP_{p,r,t} \geq 0, SPX_{p,s,r,t} \geq 0, VQ_{p,s,r,t} \geq 0, SUVQ_{p,s,r,t} \geq 0, SUNV_{p,s,t} \geq 0,$$
$$SUHV_{p,s,t} \geq 0, DVQ_{p,s,r,t} \geq 0, DNV_{p,s,t} \geq 0, DHV_{p,s,t} \geq 0, PQ_{p,s,t)} \geq 0, \forall p, s, r, t$$

4. Experimental Study

In this section, we conduct the experimental study on a numerical example detailed as follows. Consider a module factory based the MTS production that produces three kinds of TFT-LCD products: television, notebook and monitor, where each product is assembled by a LCD panel with a medium common-size active display area (14-inch size and true SXGA resolution (1280 × 1024 pixels)). Each kind of products has three grades of quality qualification, where the products of lower-numbered grade (resp., higher-numbered grade) have stricter quality qualification and can be downgraded to products of higher-numbered grade (resp., lower-numbered grade), and each kind of products can be manufactured by using one of four ranks of LCD panels.

In this example, we plan to fill six customer orders respectively in a week. The total volume of products in these six orders is about 300,000 pieces a week (i.e., 1.2 million pieces a month), which are assumed according to the real production volume from a module factory in Taiwan that is of a small or medium size as compared with other factories. In addition, to ensure our instance to closely satisfy the real situation of TFT-LCD module process, the assumptions of the production information for each rank of LCD panel (such as the acceptance rate, non-dot-defect rate, and volume arrived) are also referred to this real factory. The production information of products and their acceptance rates when using each rank of LCD panels are shown in Tables 1 and 2. The information of using each rank of LCD panels to manufacture each kind of products is shown in Table 3, and the beginning inventory and the schedule of LCD panels arriving at the module factory each day are listed in Table 4.

Table 1. The production information of all products.

Product	p =1 (TV)			p =2 (TV)			p =3 (Notebook)		
Grade	s =1	s =2	s =3	s =1	s =2	s =3	s =1	s =2	s =3
Upper bound of demand	24000	21000	17000	17000	16000	12000	20000	18000	13000
Cost	120	100	80	100	80	60	55	35	25
Standard revenue	200	175	150	180	150	110	110	80	55
Substandard revenue	170	140	100	140	120	90	90	65	50
Product	p =4 (Notebook)			p =5 (Monitor)			p =6 (Monitor)		
Grade	s =1	s =2	s =3	s =1	s =2	s =3	s =1	s =2	s =3
Upper bound of demand	22000	18000	14000	21000	17000	14000	20000	18000	13000
Cost	50	35	25	44	31	20	40	29	17
Standard revenue	105	78	59	90	68	55	85	69	45
Substandard revenue	85	62	44	78	53	35	68	49	29

Table 2. The acceptance rates of the products assembled with each rank of LCD panels.

Product	p =1 (TV)			p =2 (TV)			p =3 (Notebook)		
Grade	s =1	s =2	s =3	s =1	s =2	s =3	s =1	s =2	s =3
Quality qualification rate r =1	92%	97%	100%	85%	90%	100%	90%	92%	100%
Quality qualification rate r =2	85%	95%	98%	78%	85%	95%	84%	88%	95%
Quality qualification rate r =3	82%	87%	90%	74%	80%	90%	78%	84%	92%
Quality qualification rate r =4	75%	79%	82%	65%	75%	85%	75%	80%	86%
Lower bound of non-dot-defect rate	90%	85%	80%	90%	85%	80%	95%	90%	85%
Product	p =4 (Notebook)			p =5 (Monitor)			p =6 (Monitor)		
Grade	s =1	s =2	s =3	s =1	s =2	s =3	s =1	s =2	s =3
Quality qualification rate r =1	90%	95%	100%	93%	96%	100%	90%	94%	100%
Quality qualification rate r =2	88%	92%	95%	85%	92%	96%	85%	90%	95%
Quality qualification rate r =3	84%	90%	90%	82%	88%	91%	82%	85%	90%
Quality qualification rate r =4	79%	85%	88%	79%	83%	85%	77%	81%	84%
Lower bound of non-dot-defect rate	90%	85%	70%	90%	85%	64%	90%	70%	45%

Table 3. The production information of LCD panels.

Product	p =1 (TV)				p =2 (TV)				p =3 (Notebook)			
Rank	r =1	r =2	r =3	r =4	r =1	r =2	r =3	r =4	r =1	r =2	r =3	r =4
Non-dot-defect	95%	80%	75%	50%	90%	80%	70%	50%	90%	85%	80%	70%
Cost	900	800	600	400	900	800	600	400	900	800	600	400
Stock	100	100	100	100	100	100	100	100	100	100	100	100
Product	p =4 (Notebook)				p =5 (Monitor)				p =6 (Monitor)			
Rank	r =1	r =2	r =3	r =4	r =1	r =2	r =3	r =4	r =1	r =2	r =3	r =4
Non-dot-defect	95%	80%	70%	60%	90%	80%	75%	50%	95%	80%	65%	60%
Cost	900	800	600	400	900	800	600	400	900	800	600	400
Stock	100	100	100	100	100	100	100	100	100	100	100	100

Table 4. The schedule of the volume of LCD panels arrived at the module factory.

Product	Rank	Period							
		0	1	2	3	4	5	6	7
1	1	8000	1600	5000	1500	2000	0	3500	1000
	2	6500	1300	1000	3000	1000	2000	1000	1400
	3	5000	1300	1000	1000	0	2500	0	2000
	4	3000	1000	1100	1000	0	1000	2000	0
2	1	6300	1500	0	2000	1500	1500	0	900
	2	5800	1500	1000	0	1000	1000	1300	0
	3	5500	1000	0	1500	1000	1000	1400	0
	4	5000	1000	0	1500	0	0	0	900
3	1	6100	1000	2000	1000	1500	1500	1700	3200
	2	5200	1000	1000	2000	0	1400	1300	1000
	3	4800	1600	0	1600	2000	0	1500	0
	4	3500	1000	0	1500	0	2000	1200	0
4	1	6200	2000	2500	2000	0	2500	0	2000
	2	4800	4300	0	1500	2000	1500	0	1200
	3	4200	1500	2500	1000	1000	0	1500	0
	4	3200	1200	1000	1400	0	0	2800	0
5	1	6200	1000	2000	0	1200	2200	0	3000
	2	5000	1500	2000	1500	0	0	2000	1200
	3	4200	1200	2400	0	0	1500	3500	0
	4	3200	1000	0	2000	2200	0	2500	0
6	1	5900	1000	2000	2000	2200	2000	1000	0
	2	4200	2000	1500	0	1500	0	2200	1200
	3	4500	1000	1000	1000	0	1000	1300	1400
	4	4200	1800	2000	0	1100	1000	0	1500

We adopt the IBM ILOG CPLEX Optimizer to solve the material allocation model using the above example. The experiment runs on an Intel Core i5-2400 PC (@3.10GHz) with 2 GB memory. The average executing time of solving the example is about 0.1055 second. The experimental results include the material allocation schedule, the experimental result of unqualified products, and the experimental result of qualified products in Tables 5, 6, and 7, respectively. From Table 5, the volume of products delivered to customers and the released volume of each rank of LCD panels for different grades of products are obtained, and it is obvious to see that the demand of the products with higher-revenue grade is filled while maximizing the total profit. As far as the products with downgradable characteristics and different profits are concerned, this material schedule can help the managers to release the LCD panels effectively, with the minimal stock of LCD panels and the maximal total profit of the product portfolio.

Conventionally, unqualified products are sold to other customers at a low price. Through our mechanism of downgrading products, the quantity of unqualified products is reduced to 11974, the volume of undowngradable products is 32025, and the surplus of enable downgraded products is 1194 (see Table 6). From Table 7, since customers emphasize the quantity of dot defects of qualified products, conventionally the qualified products which do not satisfy the requirements for upper bound of non-dot-defect rate are modified to meet the standard, and the surplus of eliminated products are viewed as substandard products and are sold at a low price. But through the mechanism of downgrading products, for the surplus, the volume

Table 5. The material allocation schedule.

Product	p =1 (TV)			p =2 (TV)			p =3 (Notebook)		
Grade	s =1	s =2	s =3	s =1	s =2	s =3	s =1	s =2	s =3
LCD panel r =1	0	15661	6939	10749	2951	0	18000	0	0
LCD panel r =2	15171	2029	0	0	11600	0	12900	0	0
LCD panel r =3	12800	0	0	8393	3007	0	11500	0	0
LCD panel r =4	9100	0	0	8400	0	0	9200	0	0
Total LCD panel	37071	17690	6939	27541	17559	0	51600	0	0
Product payment	24000	21000	8859	17000	15551	1756	20000	18000	0
Upper-bound demand	24000	21000	17000	17000	16000	12000	20000	18000	13000
Product	p =4 (Notebook)			p =5 (Monitor)			p =6 (Monitor)		
Grade	s =1	s =2	s =3	s =1	s =2	s =3	s =1	s =2	s =3
LCD panel r =1	17200	0	0	0	15600	0	16100	0	0
LCD panel r =2	15300	0	0	13198	2	0	12600	0	0
LCD panel r =3	11700	0	0	12800	0	0	11200	0	0
LCD panel r =4	9600	0	0	10900	0	0	11600	0	0
Total LCD panel	53800	0	0	36898	15602	0	51500	0	0
Product payment	20000	18000	0	21000	17000	5195	20000	18000	0
Upper-bound demand	22000	18000	14000	21000	17000	14000	20000	18000	13000

Table 6. The experimental results of unqualified products.

Product	Grade	Undowngradeable	Downgradedable	
			Surplus	Downgraded
p =1	s =1	4333.5416	0	2276.9853
	s =2	40.5833	0	469.8264
	s =3	0	0	0
p =2	s =1	4853.3651	0	593.5519
	s =2	880.7468	0	1755.8882
	s =3	0	0	0
p =3	s =1	6668	730	360
	s =2	0	0	0
	s =3	0	0	0
p =4	s =1	4694	0	2215
	s =2	0	0	0
	s =3	0	0	0
p =5	s =1	4444.8750	0	2127.8906
	s =2	0.0625	0	624.0625
	s =3	0	0	0
p =6	s =1	6110	0	1550.7827
	s =2	0	463.9976	0
	s =3	0	0	0
Total quantity		32025.1743	1193.9976	11973.9876

of non-dot-defect products is downgraded by 44640 and the volume of dot-defect products is downgraded by 12037, meaning that these surplus of products can be eliminated effectively.

Finally, we conduct the performance analysis for the downgradable mechanism, and the comparative results between the downgradable and undowngradable mechanisms is shown in Table 8. From Table 8, the optimal solution of the downgradable mechanism has a higher profit, which is increased by 172,665 $(= 14,164,253 - 13,991,588)$, and can deliver more product volume by 10,326 $(= 247,361 - 237,035)$ than the undowngradable mechanism. In addition, the pro-

Table 7. The experimental results of qualified products.

Product	Grade	Non-dot-defect		Dot-defect	
		Surplus	Downgraded	Surplus	Downgraded
p =1	s =1	0	0.6666	3466.875	0
	s =2	0	0	0	1389.1776
	s =3	0	0	0	0
p =2	s =1	0	0	3806.772	0
	s =2	0	0.65	1251.578	0
	s =3	0	0	0.5381	0
p =3	s =1	1647.2	15149.4	4554.8	0
	s =2	0	0	0	0
	s =3	0	0	0	0
p =4	s =1	3950.8	13156.4	5155.2	1612.1
	s =2	0	0	0	0
	s =3	0	0	0	0
p =5	s =1	0	2252.4375	4860.0625	2213.1719
	s =2	0	2815.1	0	1755.55
	s =3	0	0	0	0
p =6	s =1	4396.5015	11265.7985	2529.5404	5057.5608
	s =2	0	0	0	0
	s =3	0	0	0	0
		9994.5015	44640.4526	25625.366	12027.5603

Table 8. The comparison between downgradable and undowngradable mechanisms.

Mechanism	Optimal solution	Standard	Substandard					
			Qualified				Unqualified	
		Payment	non-dot-defect		dot-defect			
			surplus	enable to downgrade	surplus	enable to downgrade	surplus	enable to downgrade
Downgraded (1)	14164253	247361	9995	44640	25625	12028	33219	11974
Non-downgrade (2)	13991588	237035	8464	0	26140	0	44561	0
Difference (1)-(2)	172665	10326	1531	44640	-515	12028	-11342	11974

posed downgradable mechanism can effectively downgrade the products which are not satisfied by customers to other lower-grade products as demand. From Table 8, the total volume of downgraded products is 68642 (= 44640 + 12028 + 11974), where the total volume of downgrade products includes non-dot-defect products (= 44640), dot-defect products (= 12028), and qualified products (= 11974). The downgradable function can reduce the surplus of products, and the surplus of substandard products is reduced by 11520 (= 1531 − 515 − 12536) as compared to undowngradable mechanism, where the surplus of substandard products includes the unqualified surplus (= 1531), the qualified surplus of non-dot-defect products (= −515), and the surplus of dot-defect products (= −12536).

Based upon the above experimental results, some recommendations from the viewpoint of the managers in module factories are provided as follows. First, in the situation where the finished products can be downgraded, for different-grade products with the same revenue (e.g., in Table 1, the grade-3 type-2 products and the grade-1 type-3 products have same revenue), the demand of higher-grade products should be satisfied with the highest priority, so as to raise the volume of downgradable products and further to increase the total volume of qualified products. Second, the number of product grades should be increased. In general, the gap of the quality specification between two adjacent-grade products of the same type would be small if the number of product grades is incremented. A shorter gap can increase the volume of unqualified products downgraded to qualified products so as to reduce the volume of substandard products.

5. Conclusion

In module factories, it is specific and significant to investigate the problem of allocating different ranks of critical materials (LCD panels) and allocating a variety of grades of products to acceptable customers, who have different requirements for product quality specifications. The reason of resulting in different grades of products is that the LCD panels manufactured from the former cell process of the TFT-LCD supply chain have different qualities. As the customers have different requirements for quality qualification of products, the products of the same grade could be rejected, and conventionally the factories deal with them by selling them at a lower price so that the total profit is reduced and the inventory cost of LCD panels is increased. We observe that some of the products rejected by customers have strict quality specifications and may be accepted by the customers with looser quality specifications, and therefore we apply a mathematic method that takes into account the downgradable characteristics of products, customers' product specifications (quality qualification rate and lower bound of non-dot-defect rate), acceptance rate of each grade of products using different ranks of LCD panels, as well as revenue of each grade of products, to design a material allocation system that consolidates the mechanism of downgrading products. Our system can help the production managers to effectively release different ranks of LCD panels, to produce the products while maximizing the total profit of the product portfolio, and quickly determine the volume of downgrading the products which do not satisfy customers' quality specifications, so that both the production cost and inventory of LCD panels are reduced.

The main conclusions of this paper are listed as follows: First, a proper mechanism of downgrading products has been proposed to effectively allocate the rejected products to other acceptable customers at the same grade or downgrade them to qualified lower-grade products as demand. It can reduce the production cost and fill most of the demand of higher-revenue products in the MTS production environment. Second, the proposed mechanism of downgrading products can immediately affect the planning of the released volume of LCD panels, and adjust different grades of products to satisfy most of the customer requirement for quality specifications while minimizing the volume of low-rank LCD panels. Third, in practice, customers are concerned about two parameters of product quality specifications: quality qualification rate and lower bound of non-dot-defect rate. Our material allocation system incorporates the two quality specifications, and quickly and effectively helps the production managers to identity and calculate the downgraded volume of products, and immediately fill the orders of customers with various requirements for product quality. Last, as the operational objective of module factories is to maximize the profit of the module factory, our proposed model copes with various revenues and production costs of products, and finds the optimal product portfolio while maximizing the total profit.

In the future, we intend to extend our work along the following three lines. First, the objective function of the model could include the loss cost due to the uncertainty of customers' demand. Our work assumes that all the products are sold out over the planning period. However, since the customers' demand for each grade of products can be forecasted in the MTS production environment, the production in our model might be over-estimated or under-estimated, so that the stock cost is increased. Hence, the uncertainty of customers' demand should be considered in the future. Second, our model based upon the MTS production is more suitable for the TFT-LCD panel products with common-size active display areas in the module factories. In the future, the other production forms for diversified customized products could be adopted, e.g., the assemble-to-order (ATO) or make-to-order (MTO) production. Third, metaheuristic approaches for large-scale problems concerned in this work could be developed. Our proposed model based on integer liner programming (ILP) can produce exact optimal solutions but is restricted to small-scale or medium-scale problems. Solving a large-scale problem by ILP could take more than 12 hours. Therefore, it would be of interest to develop a metaheuristic approach for large-scale problems, though it may not always produce the optimal solutions.

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References

Chang, S. (2005). The TFT-LCD industry in Taiwan: Competitive advantages and future developments. *Technology in Society*, 27, 199-215.

Chen, T. L, J. T Lin, and S. C Fang. (2010). A shadow-price based heuristic for capacity planning of TFT-LCD manufacturing. *Journal of Industrial and Management Optimization*, 6, 209-239.

Chen, Y. C and I. H Hong. (2000). A methodology for product mix planning in semiconductor foundry manufacturing. *IEEE Transactions on Semiconductor Manufacturing*, 13, 278-285.

Chung, S. H, A. H. I Lee, and W. L Pearn. (2005a). Analytic network process (ANP) approach for product mix planning in semiconductor fabricator. *International Journal of Production Economics*, 96, 15-36.

Chung, S. H, A. H. I Lee, and W. L Pearn. (2005b). Product mix optimization for semiconductor manufacturing based on AHP and ANP analysis. *International Journal of Advanced Manufacturing Technology*, 25, 361-369.

Jeong, B, S Kim, and Y Lee. (2001). An assembly scheduler for TFT-LCD manufacturing. *Computers & Industrial Engineering*, 41, 37-58.

Jeong, B, S Sim, H Jeong, and S Kim. (2002). An available-to-promise system for TFT LCD manufacturing in supply chain. *Computers & Industrial Engineering*, 43, 720-729.

Liang, Y.-C and N Fang. (2011). Supplier productivity and quality performance evaluation in the TFT-LCD industry. *Asia-Pacific Journal of Operational Research*, 28, 787-802.

Lin, J. T, T. L Chen, and W. J Chen. (2007). Capacity and product mix planning problem for TFT array multi-plant. *Journal of the Chinese Institute of Industrial Engineers*, 24, 209-239.

Lin, J. T, T. L Chen, and C. C Huang. (2004). A hierarchical planning model for TFT-LCD production chain. *International Journal of Electronic Business Management*, 2, 59-68.

Lin, J. T, T. L Chen, and Y. T Lin. (2009). Critical material planning for TFT-LCD production industry. *International Journal of Production Economics*, 122, 639-655.

Lin, J. T, I. H Hong, C. H Wu, and K. S Wang. (2010). A model for batch available-to-promise in order fulfillment processes for TFT-LCD production chains. *Computers & Industrial Engineering*, 59, 720-729.

Lin, J. T, C. H Wu, T. L Chen, and S. H Shih. (2011). A stochastic programming model for strategic capacity planning in thin film transistor-liquid crystal display (TFT-LCD) industry. *Computers & Operations Research*, 38, 991-1007.

Lo, S. L, F. K Wang, and W. J Lin. (2008). Forecasting for the LCD monitor market. *Journal of Forecasting*, 27, 341-356.

Research and Markets. (2009). *Global and China large-size TFT-LCD* (Tech. Rep. No. 1061705). Research and Markets. Available online: http://www.researchandmarkets.com/reports/1061705/global_and_china_large_size_tft_lcd_industry

Shin, H. J and Y. H Kang. (2010). A rework-based dispatching algorithm for module process in TFT-LCD manufacture. *International Journal of Production Research*, 48, 915-931.

Shin, H. J and V. J Leon. (2004). Scheduling with product family set-up times: an application in TFT LCD manufacturing. *International Journal of Production Research*, 42, 4235-4248.

Tsai, K and S Wang. (2009). Multi-site available-to-promise modeling for assemble-to-order manufacturing: an illustration on TFT-LCD manufacturing. *International Journal of Production Economics*, 117, 174-184.

Wang, F. K, T Du, and F. C Wen. (2007). Product mix in the TFT-LCD industry. *Production Planning & Control*, 18, 584-591.

Wang, K. L, S. M Wang, and S. J Yang. (2007). A resource portfolio model for equipment investment and allocation of semiconductor testing industry. *European Journal of Operation Research*, 179, 390-403.

Wang, P. S and T. C Su. (2006). An optimal yield mapping approach for the small and medium sized liquid crystal displays. *International Journal of Advanced Manufacturing Technology*, 27, 985-989.