Effective Approaches for Low Temperature Polysilicon TFT LCD Post-Mapping Yield Control Problem

Chao-Ton Su, Peng-Sen Wang, and Chun-Chin Hsu

***Abstract*—Low-temperature polysilicon (LTPS) technology has drawn the attention of many display manufacturers because it has several potential advantages over amorphous thin-film-transistor liquid crystal display (TFT LCD). The mapping operation matches one TFT and one color-filter (CF) glass plate together to form one LCD plate. Each plate contains a certain number of cells that are independent devices. The matched LCD cell is good only when the TFT and CF cell match is good. When only a TFT or CF cell is good, there is a yield loss. The sorter is a robot used in LCD manufacturing systems to achieve higher yield in matching TFT and CF plates. This sorter contains several ports that can transfer CF glasses from CF cassettes to match TFT glasses. This is an important determinant for post-mapping yield. This study first proposes a linear programming formulation to optimize the plates-matching problem for the various ports. Next, we propose an algorithm to reduce the number of ways for choosing different matched objects when the number of matched cassettes is large. This algorithm avoids computer overload and provides an excellent solution. The empirical results illustrate the efficiency and effectiveness of the proposed approaches.**

***Note to Practitioners*—Yield is an important competitiveness determinant for thin-film-transistor liquid crystal display (TFT LCD) factories. TFT-LCD contains three major manufacturing sectors: the array, cell and module assembly processes. The yield loss from the cell process is one of the most critical steps. This study first formulates a linear programming for the TFT color-filter plates-matching problem in the cell process and a reduction algorithm then is developed to reduce the computational efforts. Our proposed approach is workable and it does not require a significant investment to produce yield improvement by applying the proposed matching algorithm.**

***Index Terms*—Combinatorial optimization, Hungarian method, liquid crystal display (LCD), matching, yield mapping.**

I. Introduction

During the past 12 years, the market for liquid crystal displays (LCDs) has grown at over 20% on average per annum. This high-performance display is expected to grow rapidly and obtain major market share in the display market. In the 1980s, market demand forced a transition from twisted nematic displays to super twisted nematic displays. This led to today's amorphous silicon and low-temperature polysilicon (LTPS) thin-film-transistor LCD (TFT LCD). LTPS technology has gathered much attention from many display manufacturers because it has several advantages over amorphous displays, e.g., built-in driver circuits, high-definition and high-aperture ratio. LTPS production technology is aimed at manufacturing small and medium sized LCD panels for rapid growth in the digital still cameras (DSC), digital video camcorders (DVC), notebook computers, cellular phones and personal digital assistants (PDA) markets.

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C.-T. Su is with the Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu 300, Taiwan, R.O.C., and also with Quality Research Center, National Tsing Hua University, Hsinchu 300, Taiwan, R.O.C. (e-mail: ctsu@mx.nthu.edu.tw).

P.-S. Wang is with the Department of Management and Information Technology, Southern Taiwan University of Technology, Tainan 710, Taiwan, R.O.C. (e-mail: peng@mail.stut.edu.tw).

C.-C. Hsu is with the Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C. (e-mail: u8833535.iem88g@nctu.edu.tw).

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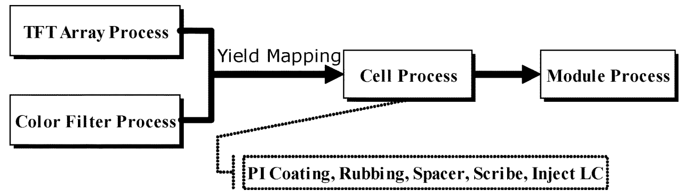

Fig. 1. LTPS TFT LCD process flow.

The manufacturing process [1] for LCDs may be likened to making a sandwich. The bottom substrate is the TFT array. The TFT fabrication process sequence is a series of deposition and etching sequences, as in integrated circuit fabrication. The top substrate is the color filter plate. Color-filter (CF) glasses are usually purchased from outside vendors. Both the TFT plate and CF plate are joined together in what is called a cell assembly process. During cell assembly, the liquid-crystal material is sandwiched between the two substrates and the glass plate is scribed to the individual displays. The final step is module assembly, integrating the drive integrated circuit (IC) onto the substrate to drive the display. A concise LTPS process is shown in Fig. 1.

Yield control is an important factor for a TFT LCD manufacturing firm to gain a competitive edge. Significant yield losses range from 5% to 25% for the TFT LCD manufacturing process. This loss occurs in three major manufacturing sectors: the array, cell and module assembly processes. The post-mapping yield loss from the cell process is one of the most critical steps. There are two options for post-mapping yield improvement. The first is to improve the TFT and/or CF plate yield. This approach requires improvement in the manufacturing processes, technology, tooling, etc., and may be costly and have technological constraints. For example, Kim and Choi [2] developed a megasonic cleaner to remove very small particles from the LCD panels to improve the manufacturing yield rate. The second option is to use a judicious mapping policy to optimize yield mapping. This approach could be very efficient and does not alter the cell process or add equipment. The matching technique plays an important role in TFT and CF yield matching. The objective of this study is to minimize the yield loss through a matching process that obtains a greater number of acceptable LCD panels to improve the cell process yield.

II. Yield Mapping

A. Mapping Process

The cell mapping process combines one TFT and one CF plate to form both sides of a LCD. This mapping process has a one-to-one match between the relative cell positions on both plates. A matched LCD cell is "good" only when both the CF and TFT cells are "good". When only the TFT or CF cell is good, there is a yield loss. The cell status (good or bad) for either a TFT or a CF cell is known by inspection before the mapping operation commences. The selected yield-matching CF glass in a TFT product can have a critical impact on cell process yield improvements. For example, in Fig. 2, the number of panels per substrate is six. The CF glass goes through rotation and reverse then moves to cover a TFT glass. Both the TFT and CF glass contain a defective cell. Only one bad panel is produced in Fig. 2(b), while Fig. 2(a) has two bad panels.

The mapping process involves two sequential stages: cassettes matching and plates matching. Assume that the ith and jth sample cassettes from the TFT and CF queue lines are selected. The ith TFT and jth sample CF cassettes are then matched. This is the

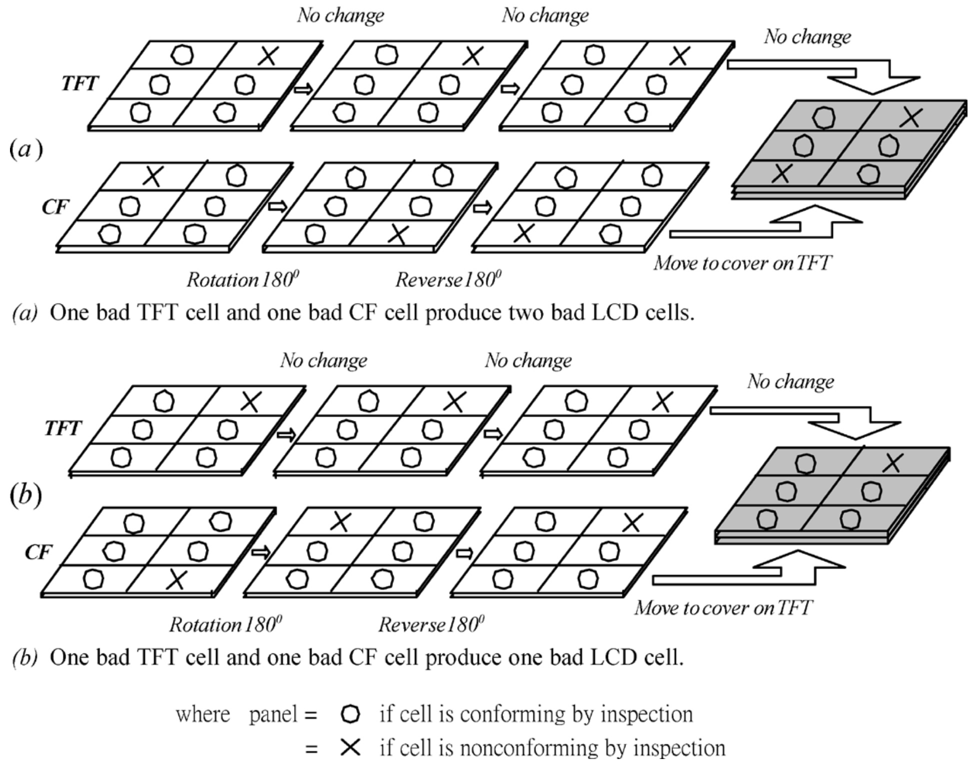

Fig. 2. Cell mapping process.

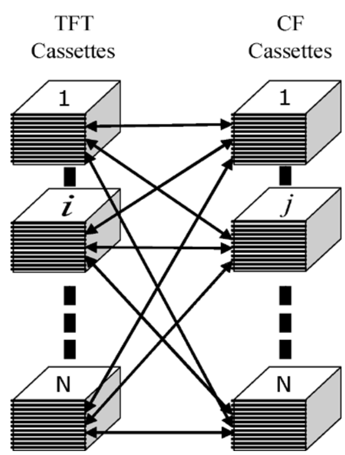

Fig. 3. Cassette matching (A sample has one cassette).

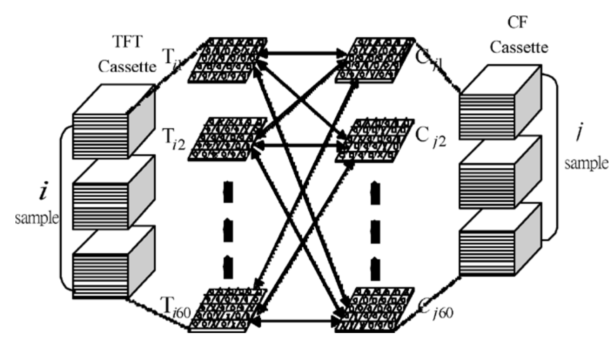

Fig. 4. Plates matching (A sample has three cassettes and each cassette contains 20 plates).

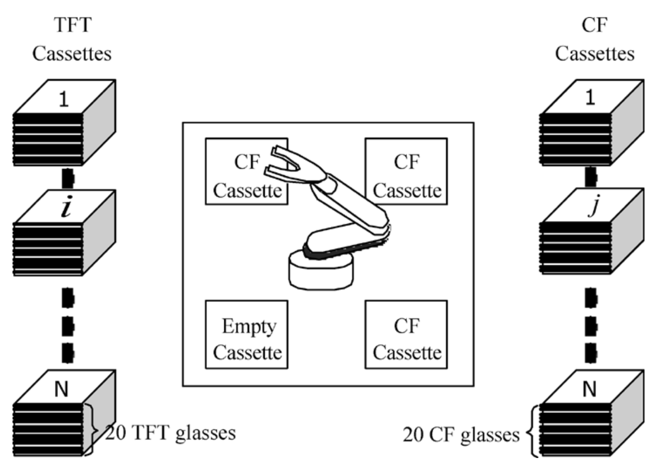

Fig. 5. Mapping by using a sorter with 4 ports.

"cassettes-matching" step. If each sample contains only one cassette, this is "cassette matching" as illustrated in Fig. 3. The next step involves matching the plates from the ith sample TFT cassette and the jth sample CF cassette to form LCD plates. Assume that 60 plates from the TFT and CF lines are numbered $T_{i1}, T_{i2}, \ldots, T_{i60}$ and $C_{j1}, C_{j2}, \ldots, C_{j60}$, respectively. The plate-matching process chooses one TFT plate (T_{ik}) and one CF plate (C_{jl}) to form a matched LCD plate. This step is called "plates matching" as illustrated in Fig. 4. Similarly, if each sample contains only one cassette, this is "plate matching".

B. Mapping Using a Sorter

The sorter (as shown in Fig. 5) is a robot used in LCD manufacturing systems to achieve higher yield for matching TFT and CF plates. This sorter usually contains s ports that can transfer (load/unload) CF glasses from $(s-1)$ CF cassettes into an empty cassette to match an indicated TFT cassette. The indicated TFT cassette and the empty CF cassette (filled with 20 CF glasses with the slot order

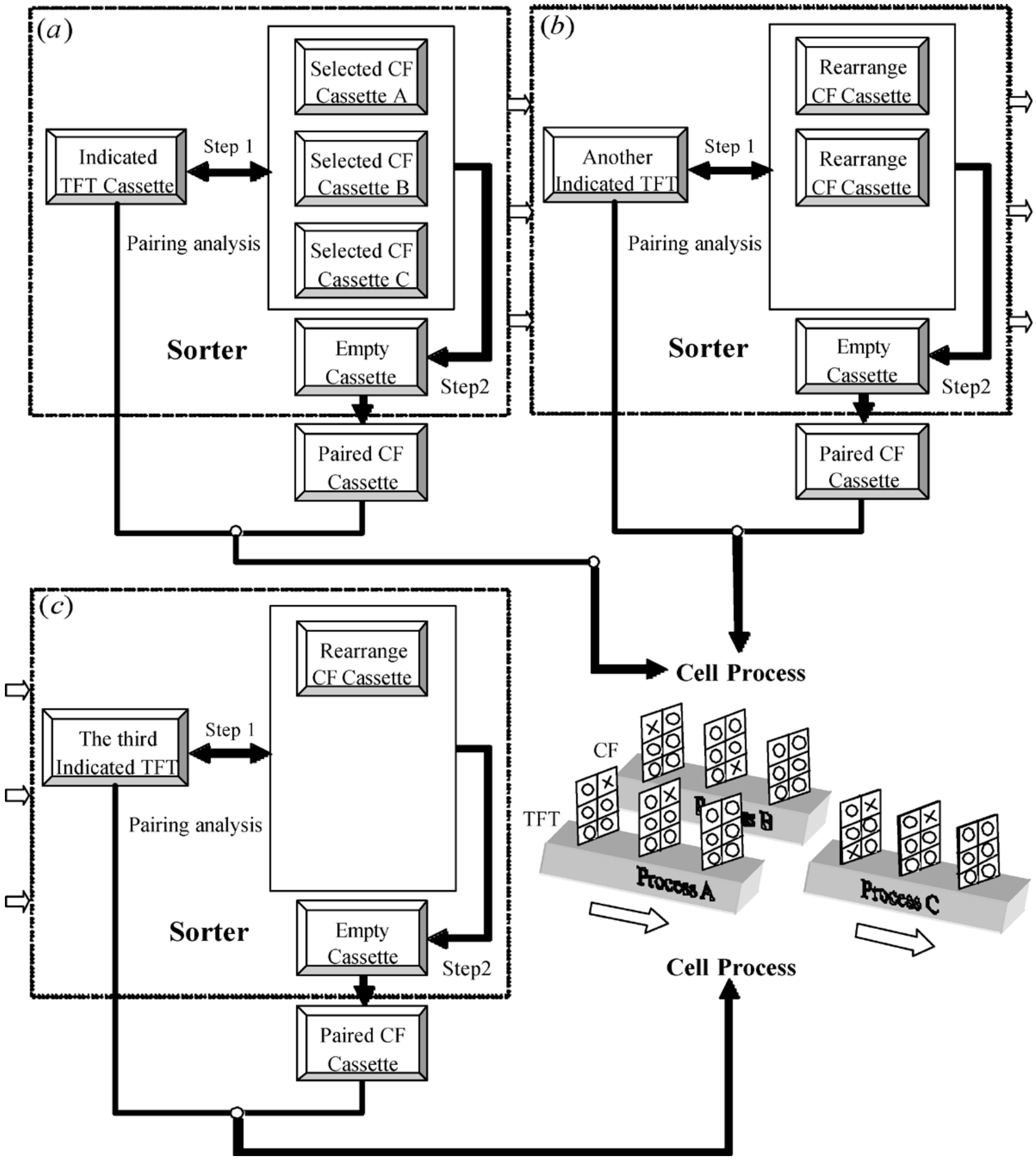

Fig. 6. Sorter transfers CF glasses from CF cassettes into empty cassettes to match indicated TFT cassettes.

the same as the matched TFT cassette glasses) will be transferred onto a loader for PI coating in the cell process. After the sorter transfers the remaining 40 CF glasses onto two other CF cassettes, one cassette becomes an empty cassette. The sorter transfers CF glasses from two CF cassettes onto the empty cassette to match another TFT cassette. The sorter then transfers the remaining 20 CF glasses onto an empty cassette to match the third TFT cassette. These steps are shown schematically in Fig. 6.

III. Proposed Approaches

A. Proposed LP Formulation for Solving the Plates-Matching Problem

Linear programming (LP) involves restrictions or constraints for determining optimal solutions to problems. An assignment problem is a special type of linear programming problem. The usual assignment problem is given the same number of jobs and machines. In each assignment, assigning the job to the machine, has a fixed profit. This problem assigns each machine a unique job such that the sum of the profit from the machines is maximum. Without loss of generality, we will refer to jobs as TFT plates, machines as CF plates, and the profit as the matching yield for the TFT and CF plate. Therefore, plates matching can be formulated as a linear programming problem. The notations are defined before the LP formulation as follows:

N pair quantities of TFT and CF cassettes in queue;

r plate quantities of cassette (typically $r = 20$);

s number of sorter ports;

f_{ikjl} mapping function represents the matching yield for the kth plate from the ith sample TFT cassette and the lth plate from the jth sample CF cassette. Let two ordered n-tuples $p = (p_1, p_2, \ldots, p_n)$ and $\mathrm{q} = (q_1, q_2, \ldots, q_n)$ represent TFT plate and corresponding CF plate panels (after rotation and reversing). Where $p_1, p_2, \ldots, p_n, q_1, q_2, \ldots, q_n = 0$ (bad panel) or 1 (good panel). Then, $f_{ikjl} = p \cdot \mathrm{q} = p_1 q_1 + p_2 q_2 + \cdots + p_n q_n$;

ϕ_{ij} optimal matching yield from the ith sample TFT cassette and the jth sample CF cassette. This value is the result from the plates-matching LP solution;

x_{ikjl} =1 when the kth plate from the ith sample TFT cassette is matched with the lth plate from the jth sample CF cassette. Otherwise, $x_{ikjl} = 0$. This is the decision variable from the plates-matching LP formulation.

The plates-matching problem can then be formulated as

$$\text{Maximize} \qquad \phi_{ij} = \sum_{k=1}^{r(s-1)} \sum_{l=1}^{r(s-1)} f_{ikjl} x_{ikjl} \tag{1}$$

$$\text{Subject to} \quad \sum_{k=1}^{r(s-1)} x_{ikjl} = 1, , \qquad \text{for } l = 1, 2, \ldots, r(s-1) \tag{2}$$

$$\sum_{l=1}^{r(s-1)} x_{ikjl} = 1, , \qquad \text{for } k = 1, 2, \ldots, r(s-1) \tag{3}$$

$$\text{and} \qquad x_{ikjl} \in \{0, 1\}. \tag{4}$$

Equation (1) is the objective function for maximizing the yield when the ith sample TFT cassette and the jth sample CF cassette are chosen. Equation (2) assures that each CF plate has exactly one matching TFT plate. Equation (3) assures that each TFT plate has exactly one matching CF plate. Equation (4) is the {0, 1} constraint for the decision variables. Using (1) – (4), we can solve for various ports in the post-mapping yield problem.

The proposed LP approach will solve the plates-matching LP formulation $C_{s-1}^N \times C_{s-1}^N$ times for all of the possible cassettes-matching instances. Although this formulation is a combinatorial problem and for each sample matched cassettes there are $(r(s-1))!$ different matches. This is the typical assignment problem structure. Because their structure, some special algorithms have been developed that can solve the problem very efficiently. The most well-known is the Hungarian method, first proposed by Kuhn [3] in 1955. In the Hungarian method, a one-to-one match is required. This method covers all of the zeros in the reduced cost matrix by determining the minimum number of lines. As pointed out by Lotfi [4], finding the minimum number of lines to cover all of the zeros can become a tedious task. He developed a labeling algorithm for this task. Besides the Hungarian method, the Simplex method for linear programming was modified to solve the matching problem (Paparrizos [5], Hung [6]). A scaling algorithm for the assignment problem was introduced by Goldberg and Kennedy [7]. Other relevant research solutions can be found from Balinski [8], Ji *et al.* [9], and Arora *et al.* [10].

B. Proposed Reduction Algorithm for Solving the Cassettes-Matching Problem

Assume that there are N TFT and N CF cassettes in queue. The objective of the cassettes-matching problem is to find N TFT cassettes matching N CF cassettes such that the panel sum from the matching is maximized. In this subsection, we consider the situation when the sorter has four ports. The mapping process arbitrarily retrieves three cassettes each time from each queue line.

Given a set $S = \{1, 2, 3 \ldots, N\}$, let sample space S_1, S_2 and S_3 be the set of all combinations of C_1^N, C_2^N and C_3^N, respectively, and m is a positive integer. We define the following.

δ_{ij} 1 when the ith sample TFT cassette is matched with the jth sample CF cassette. Otherwise, $\delta_{ij} = 0$.

Let

$$\delta_{ij} = \begin{cases} x_{ij}, & \text{if each sample contains three cassettes} \\ y_{ij}, & \text{if each sample contains two cassettes} \\ z_{ij}, & \text{if each sample contains one cassette} \end{cases}$$

$$\phi_{ij} = \begin{cases} a_{ij}, & \text{if each sample contains three cassettes} \\ b_{ij}, & \text{if each sample contains two cassettes} \\ c_{ij}, & \text{if each sample contains one cassette.} \end{cases}$$

Then, the maximum matching problem can be stated as follows.

1) When $N = 3m$

$$\text{Maximize} \qquad Z = \sum_{i=1}^{C_3^N} \sum_{j=1}^{C_3^N} a_{ij} x_{ij} \tag{5}$$

$$\text{Subject to} \quad \sum_{j=1}^{C_3^N} x_{ij} = 1, \qquad \text{for } i \in A \tag{6}$$

$$\sum_{i=1}^{C_3^N} x_{ij} = 1, \qquad \text{for } j \in A \tag{7}$$

$$\text{and} \qquad x_{ij} \in \{0, 1\}, \qquad \text{for all } i \text{ and } j \tag{8}$$

where

$$A = \left\{ A_1, A_2, \ldots, A_m \mid A_1, A_2, \ldots, A_m \in S_3, \right.$$
$$\left. A_i \cap A_j = \phi \ \forall i \neq j, \ \bigcup_i^m A_i = S \right\}.$$

2) When $N = 3m + 2$

$$\text{Maximize} \qquad Z = \sum_{i=1}^{C_3^N} \sum_{j=1}^{C_3^N} a_{ij} x_{ij} + \sum_{i=1}^{C_2^N} \sum_{j=1}^{C_2^N} b_{ij} y_{ij} \tag{9}$$

$$\text{Subject to} \quad \sum_{j=1}^{C_3^N} x_{ij} = 1, \qquad \text{for } i \in D \tag{10}$$

$$\sum_{i=1}^{C_3^N} x_{ij} = 1, \qquad \text{for } j \in D \tag{11}$$

$$\sum_{j=1}^{C_2^N} y_{ij} = 1, \qquad \text{for } i \in E \tag{12}$$

$$\sum_{i=1}^{C_2^N} y_{ij} = 1, \qquad \text{for } j \in E \tag{13}$$

$$\text{and} \qquad x_{ij}, y_{ij} \in \{0, 1\}, \qquad \text{for all } i \text{ and } j \tag{14}$$

where $D = \{B_1, B_2, \ldots, B_m\} \subset B$, $E = \{B_{m+1}\} \subset B$

$$B = \left\{ B_1, B_2, \ldots, B_m, B_{m+1} \mid B_1, B_2, \ldots, B_m \in S_3, \right.$$
$$\left. B_{m+1} \in S_2, \text{ and } B_i \cap B_j = \phi \ \forall i \neq j, \ \bigcup_i^{m+1} B_i = S \right\}.$$

3) When $N = 3m + 1$

$$\text{Maximize} \qquad Z = \sum_{i=1}^{C_3^N} \sum_{j=1}^{C_3^N} a_{ij} x_{ij} + \sum_{i=1}^{C_1^N} \sum_{j=1}^{C_1^N} c_{ij} z_{ij} \tag{15}$$

$$\text{Subject to} \quad \sum_{j=1}^{C_3^N} x_{ij} = 1, \qquad \text{for } i \in F \tag{16}$$

$$\sum_{i=1}^{C_3^N} x_{ij} = 1, \qquad \text{for } j \in F \tag{17}$$

$$\sum_{j=1}^{C_1^N} z_{ij} = 1, \qquad \text{for } i \in G \tag{18}$$

$$\sum_{i=1}^{C_1^N} z_{ij} = 1, \qquad \text{for } j \in G \tag{19}$$

and $$x_{ij}, z_{ij} \in \{0,1\}, \qquad \text{for all } i \text{ and } j. \tag{20}$$

where $F = \{C_1, C_2, \ldots, C_m\} \subset C, G = \{C_{m+1}\} \subset C$

$$C = \Big\{ C_1, C_2, \ldots, C_m, C_{m+1} \mid C_1, C_2, \ldots, C_m \in S_3, \; C_{m+1} \in S_1, \text{ and } C_i \cap C_j = \phi \; \forall i \neq j, \bigcup_{i}^{m+1} C_i = S \Big\}.$$

Although these formulations have an assignment problem structure, the Hungarian method cannot be applied to obtain the optimal solution because the elements in the sample space S_2 and S_3 are not pairwise mutually exclusive events and they cannot satisfy a one-to-one match. However, if N is small, we can use the total enumeration method to find an optimal solution by computing all of the possible assignments. When N is large, the total enumeration method is not practical for solving the matching problem because of the very high computation time requirements. In this study, we present a reduction algorithm based on the Hungarian method for solving the large-sized TFT and CF cassettes-matching problem.

The proposed approach uses the ϕ_{ij} from the plate-matching solution results as the input to model the optimal cassette-matching problem, as shown in (21) – (24).

Maximize $$Z = \sum_{i=1}^{N} \sum_{j=1}^{N} c_{ij} z_{ij} \tag{21}$$

Subject to $$\sum_{i=1}^{N} z_{ij} = 1, \qquad \text{for } j = 1, 2, \ldots, N \tag{22}$$

$$\sum_{j=1}^{N} z_{ij} = 1, \qquad \text{for } i = 1, 2, \ldots, N \tag{23}$$

and $$z_{ij} \in \{0,1\}. \tag{24}$$

Equation (21) is the objective function that maximizes the yield through cassette matching. Equation (22) assures that each CF cassette is matched to exactly one TFT cassette. Equation (23) assures that each TFT cassette has exactly one matching CF cassette. Equation (24) is the {0, 1} constraint for the decision variables. The cassette-matching formulation also has the special assignment problem structure and can be solved efficiently using the Hungarian method.

Using (21) – (24), each TFT cassette has exactly one matching CF cassette. This is the optimal solution for cassette matching. The proposed reduction algorithm based on the optimal solution for the cassette matching produces an excellent solution and reduces the computational complexity for cassettes matching. The procedure for the proposed reduction algorithm is listed as follows.

Step 1) Using (1) – (4), find ϕ_{ij} for plate matching.

Step 2) Using (21) – (24), find Z for cassette matching.

Step 3) Let TFT_i represent the ith TFT cassette and CF_j represent the jth CF cassette. By step 2, each TFT cassette has exactly one matching CF cassette. This can be denoted by $(\mathrm{TFT}_i) \leftrightarrow (\mathrm{CF}_j)$ $i, j = 1, 2, \ldots, N$.

Adjusting CF cassette in order such that $j = i$. We have

$$(\mathrm{TFT}_i) \leftrightarrow (\mathrm{CF}_i) \; i = 1, 2, \ldots, N.$$

TABLE I
COMPARISON OF OPTIMAL AND PROPOSED REDUCTION ALGORITHM SOLUTIONS WHEN $N = 4, 5, 6$, AND $n = 30$

Conditions \ Method		Proposed Reduction algorithm	Optimal solution (Total enumeration)	Difference (Panel)
TFT yield 90% CF yield 85% $s=4, n=30$	$N=4$	1946	1946	0
	$N=5$	2444	2444	0
	$N=6$	2932	2932	0
TFT yield 90% CF yield 90% $s=4, n=30$	$N=4$	2044	2044	0
	$N=5$	2556	2556	0
	$N=6$	3070	3070	0
TFT yield 90% CF yield 95% $s=4, n=30$	$N=4$	2123	2123	0
	$N=5$	2654	2655	1 panel
	$N=6$	3191	3192	1 panel

TABLE II
COMPARISON OF TOTAL ENUMERATION AND PROPOSED REDUCTION ALGORITHM FOR COMPUTATIONAL COMPLEXITY ($s = 4$)

Cassettes \ Solution		Proposed Reduction algorithm	Total enumeration method
$N=3m$	LP operation	$C_3^N + (N \times N) + 1$	$C_3^N \times C_3^N$
	The number of ways	$\frac{C_3^N \times C_3^{N-3} \times C_3^{N-6} \times \ldots \times C_3^3}{m!}$	$\frac{(C_3^N \times C_3^{N-3} \times C_3^{N-6} \times \ldots \times C_3^3)^2}{m!}$
$N=3m+2$	LP operation	$C_3^N + C_2^N + (N \times N) + 1$	$C_3^N \times C_3^N + C_2^N \times C_2^N$
	The number of ways	$\frac{C_2^N \times C_3^{N-2} \times C_3^{N-5} \times \ldots \times C_3^3}{m!}$	$\frac{(C_2^N \times C_3^{N-2} \times C_3^{N-5} \times \ldots \times C_3^3)^2}{m!}$
$N=3m+1$	LP operation	$C_3^N + (N \times N) + 1$	$C_3^N \times C_3^N + C_1^N \times C_1^N$
	The number of ways	$\frac{C_1^N \times C_3^{N-1} \times C_3^{N-4} \times \ldots \times C_3^3}{m!}$	$\frac{(C_1^N \times C_3^{N-1} \times C_3^{N-4} \times \ldots \times C_3^3)^2}{m!}$
$N=10$	LP operation	221	14500
	The number of ways	2800	47040000

Step 4) The assignment of the ith sample TFT cassette to the jth sample CF cassette must satisfy the following conditions:

$$(\mathrm{TFT}_i, \mathrm{TFT}_j, \mathrm{TFT}_k) \leftrightarrow (\mathrm{CF}_i, \mathrm{CF}_j, \mathrm{CF}_k)$$
$$i, j, k = 1, 2, \ldots, N, \; i \neq j \neq k$$
$$(\mathrm{TFT}_i, \mathrm{TFT}_j) \leftrightarrow (\mathrm{CF}_i, \mathrm{CF}_j) \; i \neq j$$
$$\text{when } N = 3m + 2$$
$$(\mathrm{TFT}_i) \leftrightarrow (\mathrm{CF}_i)$$
$$\text{when } N = 3m + 1.$$

Step 5) Using (1) – (4), calculate all assignments in Step 4).

Step 6) Find maximum yield for N TFT cassettes matching N CF cassettes.

The proposed algorithm can be used to find an excellent solution with much less computational effort. Using Step 2), an optimal solution for one-to-one cassette matching can be obtained. When the sorter is used, selecting the corresponding cassettes as a sample group will produce better solutions. In Step 4), the number of plates-matching sets will be reduced from $C_3^N \times C_3^N$ to C_3^N. Table I compares the optimal solution and proposed reduction algorithm for computational results when $N = 4, 5, 6$, and $n = 30$, where n represents the plate cell (panel) quantities. Under these test conditions, we can see that the solutions obtained using the proposed reduction algorithm were optimal or near optimal. When N is large, finding an optimal solution becomes complex and difficult. Table II compares the total enumeration method and proposed reduction algorithm in computational complexity for a sorter with four ports.

TABLE III
CELL SIZE VERSUS NUMBER OF CELLS

glass substrate size: 620mm x 750mm					
Number of Panels (n)	6	30	50	70	100
Size (inch)	14.1	6.7	5.2	3.9	3

TABLE IV
MAPPING RESULTS IN 95% CONFIDENCE INTERVAL FOR TFT AVERAGE YIELD 90% AND CF AVERAGE YIELD 85%

Method / Panels	2 ports/sorter	3 ports/sorter	4 ports/sorter	5 ports/sorter
6	82.9167 ± 0.4215	83.7917 ± 0.3568	83.8889 ± 0.3628	84.0625 ± 0.4457
30	80.2333 ± 0.2463	80.9333 ± 0.1219	81.2889 ± 0.1040	81.5292 ± 0.0675
50	79.3200 ± 0.1610	79.8400 ± 0.0731	80.1200 ± 0.0796	80.3875 ± 0.0567
70	78.8357 ± 0.1406	79.2893 ± 0.1113	79.5905 ± 0.0400	79.7482 ± 0.0440
100	78.3900 ± 0.0920	78.7950 ± 0.0375	79.0417 ± 0.0585	79.1700 ± 0.0702
Average	79.9391 %	80.5299 %	80.7860 %	80.9795 %

TABLE V
MAPPING RESULTS IN 95% CONFIDENCE INTERVAL FOR TFT AVERAGE YIELD 90% AND CF AVERAGE YIELD 90%

Method / Panels	2 ports/sorter	3 ports/sorter	4 ports/sorter	5 ports/sorter
6	86.2500 ± 0.7567	86.7500 ± 0.6560	87.0833 ± 0.6016	87.8333 ± 0.4342
30	84.0833 ± 0.1013	84.8750 ± 0.1645	85.1278 ± 0.2070	85.4208 ± 0.1758
50	83.4800 ± 0.1501	84.0000 ± 0.1306	84.2167 ± 0.0828	84.4325 ± 0.0631
70	83.0143 ± 0.1315	83.4357 ± 0.0668	83.6619 ± 0.0722	83.8250 ± 0.0583
100	82.6600 ± 0.0980	83.0025 ± 0.0677	83.2100 ± 0.0491	83.3500 ± 0.0223
Average	83.8975 %	84.4126 %	84.6599 %	84.9723 %

IV. ILLUSTRATIONS

A. Problem

To illustrate the effectiveness of the proposed approaches, a case study was adapted from a LTPS TFT-LCD manufacturing firm in Hsinchu, Taiwan. In this case study, the plate size was 620 mm × 750 mm. Five different cell sizes use the same plate. The corresponding number of cells for a given cell size is shown in Table III.

The TFT average yield rate is about 90% for LCD factories. Color filter (CF) glasses are usually purchased from outside vendors. Therefore, the CF yield rate varies. The higher the CF yield rate, the higher the purchasing cost. Based on the company's historical data, three scenarios were investigated in this study. That is, the total average yield rates for TFT and CF plates were set at 90% and 85%, 90% and 90%, 90% and 95%, respectively.

In practice, the data can only be obtained through extra procedures with special equipment. Without losing this reality, random numbers were used to simulate the defective cells for a given yield rate. A random number generator output a value of 0 or 1 determined using the Bernoulli distribution. If the output value is 1, the cell is good. If the output value is 0, the cell is defective. Ten replications were performed to construct a 95% confidence interval on the mean for each experimental scenario.

B. Implementation Results of Plates Matching

Using proposed LP formulation, the implementation results (optimal solutions) for various ports on the sorter are summarized in Tables IV–VI, and Figs. 7–9. In Table IV, the average yield ratio increases as the number of ports increases. The average improvement yield was 0.5908%, 0.2561% and 0.1935% each time the sorter added one port. Similarly, in Tables V and VI, the expected yield increase was 0.5151%, 0.2473% and 0.3124%, 0.4639%, 0.2080% and 0.1476%, respectively.

TABLE VI
MAPPING RESULTS IN 95% CONFIDENCE INTERVAL FOR TFT AVERAGE YIELD 90% AND CF AVERAGE YIELD 95%

Method / Panels	2 ports/sorter	3 ports/sorter	4 ports/sorter	5 ports/sorter
6	88.5833 ± 0.6315	89.2500 ± 0.4168	89.5000 ± 0.2616	89.6250 ± 0.1962
30	87.6333 ± 0.1760	88.2833 ± 0.1691	88.4833 ± 0.1634	88.6833 ± 0.1135
50	87.3200 ± 0.1253	87.6400 ± 0.0889	87.8633 ± 0.0307	88.0225 ± 0.0381
70	87.0357 ± 0.0909	87.3786 ± 0.0514	87.5952 ± 0.0501	87.7268 ± 0.0471
100	86.7100 ± 0.0980	87.0500 ± 0.0572	87.2000 ± 0.0329	87.3225 ± 0.0230
Average	87.4565 %	87.9204 %	88.1284 %	88.2760 %

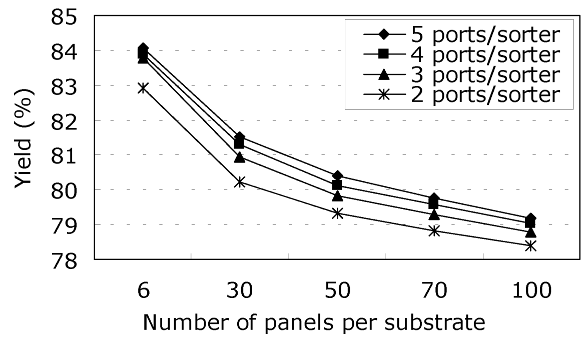

Fig. 7. Comparison of the effect with different numbers of ports on the sorter for various panels with TFT and CF plates average yield rates are 90% and 85%, respectively.

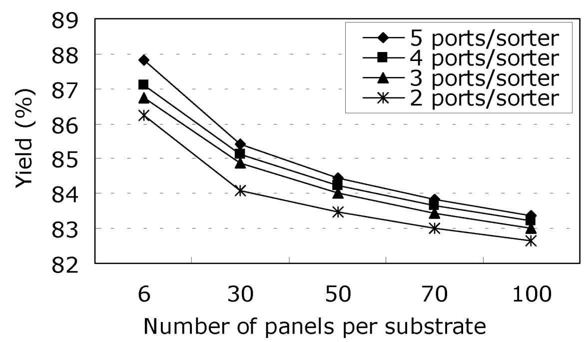

Fig. 8. Comparison of the effect with different numbers of ports on the sorter for various panels with TFT and CF plates average yield rates are 90% and 90%, respectively.

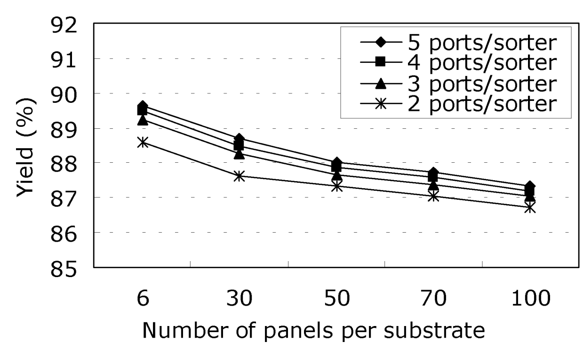

Fig. 9. Comparison of the effect with different numbers of ports on the sorter for various panels with TFT and CF plates average yield rates are 90% and 95%, respectively.

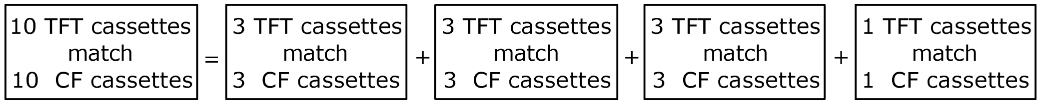

Fig. 10. TFT and CF match for a case involving $N = 10$ when the sorter has 4 ports.

TABLE VII
MAPPING RESULTS IN 95% CONFIDENCE INTERVAL FOR TFT AVERAGE YIELD 90% AND CF AVERAGE YIELD 85% ($N = 10, s = 4$)

Panels \ Method	Random Mapping	Sort Approach	Proposed Reduction Algorithm	Improvement
6	76.4928 ± 0.0148	83.6083 ± 0.1378	84.4583 ± 0.1596	7.9655%, 0.8500%
30	76.4926 ± 0.0070	81.1500 ± 0.0592	81.4267 ± 0.0352	4.9341%, 0.2767%
50	76.4951 ± 0.0065	80.0630 ± 0.0392	80.3280 ± 0.0314	3.8329%, 0.2650%
70	76.4992 ± 0.0036	79.5129 ± 0.0371	79.7050 ± 0.0312	3.2058%, 0.1921%
100	76.4989 ± 0.0037	78.9850 ± 0.0237	79.2150 ± 0.0514	2.7161%, 0.2300%
Average	76.4957 %	80.6638 %	81.0266 %	4.5309%, 0.3628%

TABLE VIII
MAPPING RESULTS IN 95% CONFIDENCE INTERVAL FOR TFT AVERAGE YIELD 90% AND CF AVERAGE YIELD 90% ($N = 10, s = 4$)

Panels \ Method	Random Mapping	Sort Approach	Proposed Reduction Algorithm	Improvement
6	81.0035 ± 0.0092	87.3250 ± 0.2291	88.2500 ± 0.1013	7.2465%, 0.9250%
30	80.9986 ± 0.0067	85.0350 ± 0.0905	85.3583 ± 0.0309	4.3597%, 0.3233%
50	80.9998 ± 0.0048	84.1190 ± 0.0450	84.3660 ± 0.0246	3.3662%, 0.2470%
70	81.0024 ± 0.0040	83.6107 ± 0.0234	83.8121 ± 0.0240	2.8097%, 0.2014%
100	81.0000± 0.0022	83.1655 ± 0.0352	83.3085 ± 0.0151	2.3085%, 0.1430%
Average	81.0009 %	84.6510 %	85.0190 %	4.0181%, 0.3679%

TABLE IX
MAPPING RESULTS IN 95% CONFIDENCE INTERVAL FOR TFT AVERAGE YIELD 90% AND CF AVERAGE YIELD 95% ($N = 10, s = 4$)

Panels \ Method	Random Mapping	Sort Approach	Proposed Reduction Algorithm	Improvement
6	85.5038 ± 0.0063	89.3500 ± 0.1005	89.8750 ± 0.0644	4.3712%, 0.5250%
30	85.4991 ± 0.0059	88.3933± 0.1062	88.6467 ± 0.0798	3.1476%, 0.2534%
50	85.4991 ± 0.0037	87.8340 ± 0.0289	88.0450 ± 0.0308	2.5459%, 0.2110%
70	85.5005 ± 0.0028	87.5129 ± 0.0296	87.6621 ± 0.0152	2.1616%, 0.1492%
100	85.5019 ± 0.0017	87.1610 ± 0.0217	87.2815 ± 0.0163	1.7796%, 0.1205%
Average	85.5009 %	88.0502 %	88.3021 %	2.8012%, 0.2518%

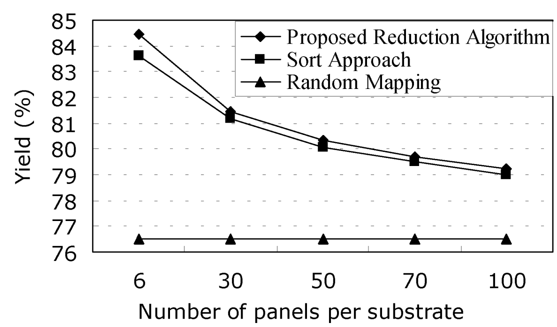

Fig. 11. Comparison effect with three different algorithms for various panels using 10 TFT and CF cassettes with average yield rates of 90% and 85%, respectively.

Figs. 7–9 show that the improvement decreases with the increase in the number of panels. Given the same defect rate, the number of defective patterns increased with the number of panels in a plate. Assume that the average defect rate is 20% for a plate. When the number of panels is 5, there is 1 defective panel that results in 5 defect patterns. This one defect has five possible panel locations. When the number of panels is 10, the number of defective patterns is $C_2^{10} = 45$. The greater the number of patterns, the smaller the mapping yield. This explains why the improvement decreases with the increase in the number of panels.

C. Implementation Results of the Cassettes-Matching

Fig. 10 shows that 10 TFT cassettes and 10 CF cassettes in queue can be divided into four classes for yield mapping on a sorter with four ports. The optimal matching yield for the four classes is not practical to solve because of the very high computation time requirements.

In practice, the random mapping approach is frequently employed by engineers when n is large. This approach randomly chooses a pair of cassettes and a pair of plates for the cell process. This approach does not need to use the sorter. It is straightforward in implementation but the solution quality cannot be guaranteed. Another method is to use sorting techniques to improve the post-mapping yield. This approach uses the LP formulation according to the magnitude of the yield rate. However, it cannot assure the optimal solution. The sort approach procedures are listed as follows:

Step 1) Sort the N TFT cassettes in queue in descending order by yield rate.

Step 2) Sort the N CF cassettes in queue in descending order by yield rate.

Step 3) Using **(1) – (4)** calculate all assignments

$$(\mathrm{TFT}_1, \mathrm{TFT}_2, \mathrm{TFT}_3) \leftrightarrow (\mathrm{CF}_1, \mathrm{CF}_2, \mathrm{CF}_3)$$
$$(\mathrm{TFT}_4, \mathrm{TFT}_5, \mathrm{TFT}_6) \leftrightarrow (\mathrm{CF}_4, \mathrm{CF}_5, \mathrm{CF}_6)$$
$$(\mathrm{TFT}_7, \mathrm{TFT}_8, \mathrm{TFT}_9) \leftrightarrow (\mathrm{CF}_7, \mathrm{CF}_8, \mathrm{CF}_9)$$
$$(\mathrm{TFT}_{10}) \leftrightarrow (\mathrm{CF}_{10}).$$

Our proposed reduction algorithm can be used to find an optimal or near-optimal solution. To illustrate the effectiveness of the proposed reduction algorithm, the situation of $N = 10$ and $s = 4$ is considered in this subsection. To obtain solutions, we used the commercial software MATLAB and EXCEL. The numerical results for random mapping, sort approach and proposed reduction algorithm mapping are summarized in Tables VII–IX, and Figs. 11–13. The average CPU time on a Pentium 4 workstation for the proposed reduction algorithm was about 3 min. The sort approach required about 0.5 min.

In Table VII, the proposed reduction algorithm for the average improvement yield from random mapping and using sort approach mapping were 4.5309% and 0.3628%, respectively. Considering the costly TFT and CF plates, the expected improvement represents a significant profit increase. In the case study example, the monthly throughput was 30 000 LCD plates. The average cost per LCD plate

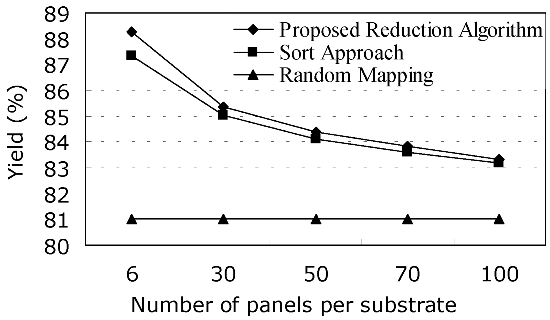

Fig. 12. Comparison effect with three different algorithms for various panels using 10 TFT and CF cassettes with average yield rates of 90% and 90%, respectively.

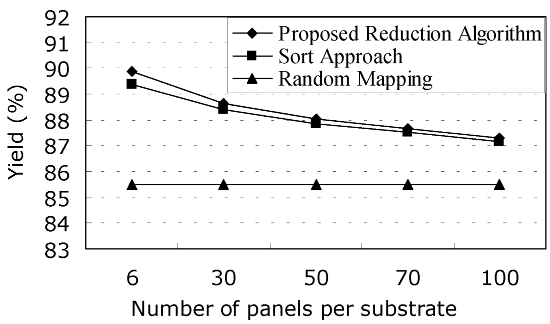

Fig. 13. Comparison effect with three different algorithms for various panels using 10 TFT and CF cassettes with average yield rates of 90% and 95%, respectively.

is about US$876. The expected monthly profit increases from random mapping and using sort approach mapping were about US$1200000 and US$95000, respectively. Similarly, in Tables VIII and IX, the expected monthly profit increases from random mapping and using sort approach mapping were about US$1100000 and US$97000, US$740000 and US$66000, respectively.

V. Discussion and Comparison

A. Discussion

In Figs. 11–13, the straight line at the bottom represents the average yield ratio from random matching, without respect to the panel quantity per substrate. This is unlike other algorithms in which the average yield ratio increased as the panel quantities decreased.

Because LTPS TFT-LCD focuses on manufacturing small and medium size LCD panels, scribing glass in advance and then into cell process produces lower economy of scale. If a random mapping approach is used, a great quantity of LCD display scrap is produced. Labor, material, and overhead costs are lost on scrapped displays. The LP formulation and the proposed reduction algorithm can provide a better choice. However, if the displays size is very small or CF yield rate is very high, random mapping is feasible because the mapping average yield ratio decreases gradually as the panel quantity increases and the distances between the top curve and the bottom straight line for Figs. 11–13 become smaller. For the large-sized displays, if TFT and CF glasses have higher yield, this proposed reduction algorithm could replace prior glass scribing. The mapping approach is more suitable for mass production than prior glass scribing.

B. Comparison

In the literature, several heuristics have been developed for combinatorial optimization problems, such as: construction methods [11], limited enumeration methods [12], improvement methods [13], sampling and clustering [14], simulated annealing methods [15], genetic algorithms [16], [17] and greedy randomized adaptive search procedure (GRASP) [18]. Among these, genetic algorithms (GAs) are a popular method for avoiding local optimal in improving the search. The GA attempts to parallel the biological evolution process to find better solutions. The genetic algorithm concept was introduced by Holland [16] in 1975. Recently, Ahuja *et al.* [17] applied a hybrid algorithm called a greedy genetic algorithm to produce very good results on large scale quadratic assignment problems (QAPs) from QAPLIB (a well-known library of QAP instances).

TABLE X
Comparison of Greedy Algorithm and Hungarian Method for Plates Matching

Conditions \ Method		Greedy Algorithm	Hungarian Method (Optimal Solution)	Difference (%)
TFT yield 90% CF yield 85% $N = 3$ 10 replications	$n = 6$	82.6111 %	83.8889 %	1.2778 %
	$n = 30$	79.7000 %	81.2889 %	1.5889 %
	$n = 50$	78.8267 %	80.1200 %	1.2933 %
	$n = 70$	78.3524 %	79.5905 %	1.2381 %
	$n = 100$	78.0367 %	79.0417 %	1.0050 %
CPU time		About 1 second	About 1 second	

A greedy algorithm makes a locally optimal choice and hopes with a globally optimal solution. Hence, the algorithm does not always yield the optimal solution. However, the greedy algorithm is quite powerful for a large-sized combinatorial problem. We discuss the greedy algorithm for plates and cassettes matching for a sorter with four ports as follows.

1) Greedy Algorithm for Plates Matching:

Step 1) Sort the 60 TFT plates in descending order by yield rate.

Step 2) Based on the sequence from Step 1), perform the "best" plates matching sequentially. "Best" indicates the highest yield. For example, the first TFT plate has the highest priority for choosing the "best" matching CF plate from 60 CF plates. When a TFT plate and a CF plate are chosen, their post-mapping yield is a direct compound, as shown in Fig. 2. The second TFT plate then chooses its "best" matching CF plate from the remaining 59 plates. This matching procedure continues until the last TFT plate is matched with the last CF plate.

Table X compares the greedy algorithm and Hungarian method for the plates-matching problems. Ten replications were performed to compare the mean for various panels using three TFT and CF cassettes with average yield rates of 90% and 85%, respectively. Under these test conditions, the differences in yield between the optimal solution and the solution obtained using the greedy algorithm has an average of 1.28%.

2) Greedy Algorithm Based on Hungarian Method for Cassettes Matching:

Step 1) Sort the N TFT cassettes in queue in descending order by yield rate.

Step 2) The first three TFT cassettes in queue (after sorting) have the highest priority to choose the best matching CF cassettes from those N CF cassettes in queue. The cassettes-matching yield is calculated using (1) – (4). The second three TFT cassettes in queue then chooses its best matching CF cassettes from the remaining $N - 3$ CF cassettes. This procedure continues until the last TFT cassette(s) in the queue is matched with the last CF cassette(s) in queue.

For comparison purposes, we randomly created an initial population of size 50 and used (1) – (4) in the GA process. The genetic operation settings were length of string $=$ 20 bits, crossover rate $=$ 0.8 with

TABLE XI
COMPARISON OF COMPUTATION RESULTS FOR GREEDY, GENETIC, AND PROPOSED REDUCTION ALGORITHMS WHEN $N = 10$

Conditions \ Method	Greedy Algorithm	GA	Proposed Reduction Algorithm
TFT yield 90% CF yield 85% $s=4, n=30$	81.37 %	81.45 %	81.53 %
	81.17 %	81.32 %	81.40 %
	81.10 %	81.34 %	81.40 %
TFT yield 90% CF yield 90% $s=4, n=30$	85.22 %	85.30 %	85.42 %
	84.90 %	85.24 %	85.32 %
	84.97 %	85.24 %	85.30 %
TFT yield 90% CF yield 95% $s=4, n=30$	88.52 %	88.61 %	88.75 %
	88.37 %	88.63 %	88.70 %
	88.37 %	88.54 %	88.58 %
CPU time	About 3 minutes	About 30 minutes	About 3 minutes

partial matched crossover (PMX) operator, mutation rate $= 0.1$ and 20 iterations. Nine samples were performed to compare the greedy algorithm, GA, and proposed reduction algorithms results for the case of $N = 10$. The results are shown in Table XI. As we can see, the proposed reduction algorithm consistently generated superior solutions than the other algorithms for the case using 10 TFT and CF cassettes with average yield rates of 90% and 85%, 90% and 90%, 90% and 95%, respectively. For n =6, 50, 70, or 100, the results are still consistent with $n = 30$.

VI. CONCLUSION

The post-mapping yield control problem has a significant impact on LTPS TFT LCD manufacturing. A judicious matching policy is very cost effective because it does not require a significant investment to produce yield improvement. Because the number of ports on the sorter is an important determinant in the post-mapping yield, this study proposed a linear programming formulation to compare various ports in the post-mapping yield control problem. This approach provided an optimal solution and offers LTPS TFT-LCD manufacturers important yield information. In addition, this study proposed a reduction algorithm to reduce the number of methods for choosing different objects to match when the total number of matched cassettes is large. This avoids computer over load and provides an excellent solution.

For LCD factories, the ability to improve yield in the manufacturing process is a very important competitiveness determinant. The proposed reduction algorithm produces very good results on the large scale cassettes-matching problem. This avoids a great quantity of LCD display scrap, reduces production costs and improves the production yield. Implementation results revealed that proposed approaches are effective in solving a practical problem.

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