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ORIGINAL ARTICLE

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An optimal yield mapping approach for the small and medium sized liquid crystal displays

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Abstract The ability to improve yield in the manufacturing process is an important competitiveness determinant for LCD factories. The 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. To increase the cell process yield, more conforming LCD panels must be produced from one glass substrate. The sorter is a robot used in LCD manufacturing systems to achieve higher yield for matching TFT and CF plates. This sorter contains several ports that can transfer CF glasses from CF cassettes to match TFT glasses. In this paper, the Hungarian method is applied to solve the yield-mapping problem with the sorter. This method provides an optimal solution to improve the cell process yield.

Keywords Hungarian method · Liquid crystal display (LCD) · Matching · TFT-LCD · Yield mapping

1 Introduction

Liquid crystal displays (LCDs) applications encompass a variety of consumer electronics including: personal digital assistants (PDA), cellular phones, digital cameras, computers, notebook computers, flat panel televisions, etc., because of its unsurpassed features in device size and radiation prevention compared with the conventional cathode radiation tube (CRT) device. LCDs can be divided into three major products: twisted nematic (TN), super twisted nematic (STN), and thin film transistor (TFT). The most widely used LCD for high information content displays is the TFT-LCD. In the 1980s, market demand forced a transition from twisted nematic displays to super twisted nematic displays. This higher-performance display is expected to grow rapidly and have a major market share in the display market. This led to today's amorphous silicon and low temperature poly silicon (LTPS) TFT-LCD. LTPS production technology is aimed at manufacturing small and medium sized LCD panels and 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.

The manufacturing process for LCD 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 with integrated circuit fabrication. The top substrate is the color filter plate. Color filter (CF) glasses are usually purchased from outside vendors. A LCD cell process consists of one TFT and color filter line each, usually in parallel production steps. Both the TFT plate and color filter plate are first coated with a thin layer of polyimide [1]. The polyimide layers are then rubbed in prearranged directions to align the liquid-crystal director. The color filter plate is then sprayed with spherical plastic spacers. An epoxy seal material is applied to the color filter plate, which is then aligned to the TFT plate. The two substrates are laminated together and the glass plate is scribed to the appropriate display panel. A liquid crystal material is injected into the gap between the glass plates to complete the assembly operation. The final step is module assembly, involves applying polarizers to both sides of the liquid-crystal cell and integrating the peripheral drive IC circuit onto the substrate for driving the display. A typical LTPS process is shown in Fig. 1. For a concise presentation, readers are referred to O'Mara [2] and Blake [3, 4] for a detailed discussion of the manufacturing process.

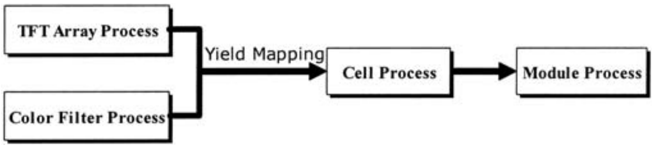

Fig. 1. LTPS TFT LCD process flow

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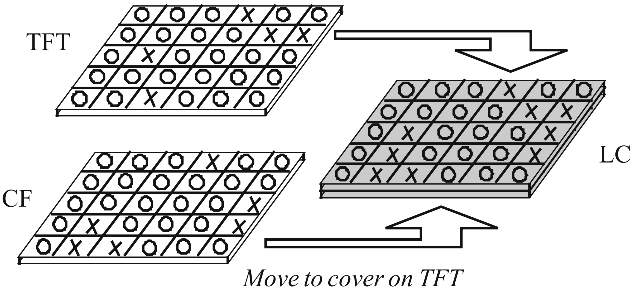
The yield loss occurs in three major manufacturing sectors: array, cell, and module assembly processes; however, the post-mapping yield loss from the cell process is one of the most critical steps. This paper aims to propose an efficient method to improve yield rate in the cell process.

2 Yield mapping

A given substrate (plate or glass) could contain different numbers of cells (panels) depending on its embedded cell size, e.g., one piece of the PDA display. The size of a cell varies from the small size used in a camera viewfinder to the large diagonal panel used in a television display. 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 positions of cells in both plates. A matched LCD cell is "good" only when both the CF and TFT cells are "good". When one of the cells from either the TFT or CF plate is bad, the matched LCD cell is bad and results in a post-mapping yield loss. The cell mapping information is shown in Fig. 2.

The sorter is a robot used in LCD manufacturing systems to achieve higher yield for matching TFT and CF plates. This sorter usually contains r ports that can handle the $r-1$ CF cassettes and $r-1$ TFT cassettes matching problem. Assume that there are N TFT and N CF cassettes in queue. Each cassette contains typically 20 glasses (plates). The mapping process first places three CF cassettes and one empty cassette onto a sorter to matching indicated TFT cassettes for a sorter with four ports. Assume that sixty plates from the TFT cassettes and CF cassettes are numbered $T_1, T_2, \ldots, T_{60}$ and $C_1, C_2, \ldots, C_{60}$, respectively. The matching process chooses one TFT plate (T_i) and one CF plate (C_j) to form a matched LCD plate. This step is called "plates-matching" as illustrated in Fig. 3.



where panel = ○ if cell is conforming by inspection
= × if cell is nonconforming by inspection

Fig. 2. The cell mapping

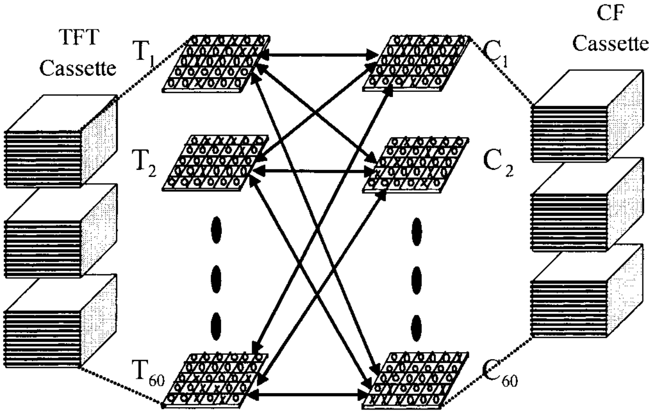


Fig. 3. Plates matching (A plate has 30 panels)

In practice, the large-sized displays usually scribe glass in advance and then into cell process. For the small and medium size LCD panels, scribing glass in advance and then during the cell process produces lower economy of scale. For example, per plate contains 50 panels scribing glass in advance that must perform the cell process 50 times. An efficient method is desired to improve yield rate for the small and medium size LCD panels.

3 Proposed approaches

This research proposes a linear programming (LP) formulation to maximize the yield rate through an optimal matching process to obtain a greater number of acceptable LCD panels to improve the cell process yield. The results were benchmarked against two heuristics used in practice. The two heuristics will be discussed first followed by the proposed LP approach.

A. Random mapping

The simplest method is to match TFT and CF using a random approach. This approach randomly chooses a pair of plates into the cell process and does not need to use the sorter. The advantages of random matching are that it is quick and easy to perform. A possible disadvantage is that not considering glass yield information might lead to LCD scrap and yield losses.

B. Greedy algorithm

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. We discuss the greedy algorithm for plates-matching for a sorter with four ports as follows:

Step 1: Sort the sixty 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 to choose the "best" matching CF plate from those 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 those remaining 59 plates. This matching procedure continues until the last TFT plate is matched with the last CF plate.

C. Linear programming formulation

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. 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 of 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, the plates-matching can be formulated as a linear programming problem. Notation is defined before the LP formulation as follows:

$n =$ The cell quantities of plate (substrate).

$r =$ The number of ports of the sorter.

$f_{ij} =$ The mapping function represents the matching yield for the ith plate from TFT cassettes and the jth plate from CF cassettes. Let two ordered n-tuples $\mathrm{p} = (p_1, p_2, \dots, p_n)$ and $\mathrm{q} = (q_1, q_2, \dots, q_n)$ represent panels of TFT plate and corresponding CF plate. Where $p_1, p_2, \dots, p_n,\ q_1, q_2, \dots, q_n = 0$ (bad panel) or 1 (good panel). Then $f_{ij} = \mathrm{p} \cdot \mathrm{q} = p_1 q_1 + p_2 q_2 + \ldots + p_n q_n$.

$x_{ij} = 1$ When the ith plate from TFT cassettes is matched with the jth plate from CF cassettes. Otherwise, $x_{ij} = 0$. This is the decision variable from the plates-matching LP formulation.

The plates-matching problem can then be formulated as Eqs. 1– 4.

$$\text{Maximize} \quad Z = \sum_{i=1}^{20(r-1)} \sum_{j=1}^{20(r-1)} f_{ij} x_{ij} \tag{1}$$

$$\text{Subject to} \quad \sum_{i=1}^{20(r-1)} x_{ij} = 1 \quad \text{for} \quad j = 1, 2, \cdots, 20(r-1) \tag{2}$$

$$\sum_{j=1}^{20(r-1)} x_{ij} = 1 \quad \text{for} \quad i = 1, 2, \cdots, 20(r-1) \tag{3}$$

and

$$x_{ij} \in \{0, 1\} \tag{4}$$

Equation 1 is the objective function for maximizing the yield when the TFT cassettes and the CF cassettes 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 Eqs. 1– 4, we can solve various ports in the post-mapping yield problem.

Although the proposed LP approach formulation is a combinatorial Problem, it has the typical assignment problem structure that can be solved efficiently using a special algorithm, the Hungarian method. In the Hungarian method a one-to-one match is required. The first Hungarian method for the assignment problem was proposed by Kuhn [5] in 1955. Another approach to solving the assignment problem is referred to Hung and Rom [6]. Readers are referred to Taha [7] and Winston [8] for a detailed discussion of the assignment problem and Hungarian method. In the literature, the Hungarian method has been applied to solve matching problems. For example, Hsieh et al. [9] apply the Hungarian method to solve a bipartite weighted matching problem for online Chinese character recognition and propose a greedy algorithm based on the Hungarian method by restricting the above matching which satisfies the constraints of geometric relation.

4 Results and discussion

A. The Problem

To illustrate the effectiveness of the proposed optimal solution approach, 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. Four different cell sizes use the same plate. The larger the cell size, the fewer the number of cells used for a single plate. The corresponding number of cells for a given cell size is shown in Table 1.

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 has many choices. The higher the CF yield rate, the higher the cost. Based on the company's historical data, four scenarios were investigated in this study. In practice, the data can only be obtained through extra procedures with special equipment. Without losing its reality, random numbers were used to simulate the defective cells on a plate for a given plate yield rate. A random number generator output a value of 0 or 1 is 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 [10].

B. Numerical results and discussion

LCD plates have some defect types. The sources of defect types are from different stages of the manufacturing process. Materials, equipment, operations, etc., can cause the problems. We compare the performance of different algorithms for the following four defects types of LCD plates:

1) The defective panels scatter randomly on the TFT plate as illustrated in Fig. 4a.
2) There are 80% defective panels gathered at the second quadrant of the TFT plate as illustrated in Fig. 4b.

Table 1. Cell size versus number of cells

Number of panels (n)	30	50	70	100
Size (in)	6.7	5.2	3.9	3

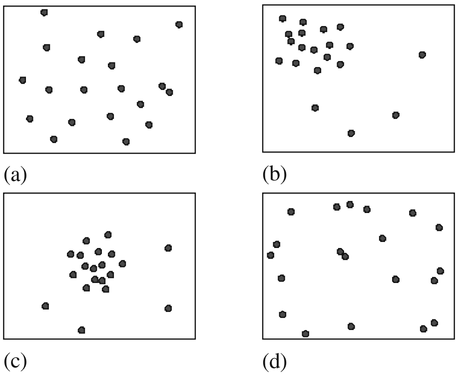

(a) (b) (c) (d)

Fig. 4. Defect types

3) There are 80% defective panels gathered at the center of the TFT plate as illustrated in Fig. 4c.
4) There are 80% defective panels gathered at the edge of the TFT plate as illustrated in Fig. 4d.

The total average yield rates for four defect types of TFT and CF plates were set at 90% and 85%, respectively. The numerical results for random mapping, greedy algorithm and Hungarian method mapping using a sorter with four ports are summarized in Tables 2, 3, 4 and 5. The greedy algorithm is implemented on a program. The LP formulation is solved by a commercial mathematical programming solver, LINGO. Both the greedy algorithm and LP formulation computation time is about 1 s.

As we can see, the Hungarian method consistently generated a superior solution compared to the other algorithms for the four defect types with TFT average yield 90% and CF average yield 85%. In Table 2, the Hungarian method for the average improvement yield from random mapping and the greedy algorithm were 3.5164% and 1.2813%, 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 is about US$876. The expected monthly profit increases from random mapping and the greedy algorithm were about US$924 000 and US$337 000, respectively. Similarly, in Tables 3, 4, and 5, the expected monthly profit increase from random mapping and greedy algorithm were about US$800 000 and US$356 000, US$812 000 and US$362 000, and US$876 000 and US$392 000, respectively.

Table 2. Mapping results in 95% confidence interval for defective panels scatter randomly on the plate with TFT average yield 90% and CF average yield 85%

Method Panels	Random mapping	Greedy algorithm	Hungarian method	Improvement yield
30	76.4867 ± 0.0161	79.7000 ± 0.2393	81.2889 ± 0.1040	4.8022%, 1.5889%
50	76.4880 ± 0.0214	78.8267 ± 0.1010	80.1200 ± 0.0796	3.6320%, 1.2933%
70	76.4916 ± 0.0061	78.3524 ± 0.1169	79.5905 ± 0.0400	3.0989%, 1.2381%
100	76.5094 ± 0.0163	78.0367 ± 0.0909	79.0417 ± 0.0585	2.5323%, 1.0050%
Average	76.4939%	78.7290%	80.0103%	3.5164%, 1.2813%

Table 3. Mapping results in 95% confidence interval for 80% defective panels gathered at the second quadrant of the plate with TFT average yield 90% and CF average yield 85%

Method Panels	Random mapping	Greedy algorithm	Hungarian method	Improvement yield
30	76.5082 ± 0.0870	78.8389 ± 0.1701	80.5611 ± 0.2373	4.0529%, 1.7222%
50	76.5190 ± 0.0273	78.2667 ± 0.1211	79.7333 ± 0.0665	3.2143%, 1.4666%
70	76.4912 ± 0.0321	78.0119 ± 0.1224	79.2048 ± 0.0618	2.7136%, 1.1929%
100	76.4895 ± 0.0495	77.6517 ± 0.0802	78.6917 ± 0.0832	2.2022%, 1.0400%
Average	76.5020%	78.1923%	79.5477%	3.0458%, 1.3554%

Table 4. Mapping results in 95% confidence interval for 80% defective panels gathered at the center of the plate with TFT average yield 90% and CF average yield 85%

Method Panels	Random mapping	Greedy algorithm	Hungarian method	Improvement yield
30	76.5193 ± 0.0801	78.8222 ± 0.2270	80.5333 ± 0.2079	4.0140%, 1.7111%
50	76.4841 ± 0.0412	78.2367 ± 0.1033	79.7333 ± 0.0954	3.2492%, 1.4966%
70	76.5391 ± 0.0199	78.0833 ± 0.1293	79.3571 ± 0.0440	2.8180%, 1.2738%
100	76.5186 ± 0.0249	77.7733 ± 0.0554	78.7967 ± 0.0533	2.2781%, 1.0234%
Average	76.5153%	78.2289%	79.6051%	3.0898%, 1.3762%

Table 5. Mapping results in 95% confidence interval for 80% defective panels gathered at the edge of the plate with TFT average yield 90% and CF average yield 85%

Method Panels	Random mapping	Greedy algorithm	Hungarian method	Improvement yield
30	76.4869 ± 0.0262	79.0611 ± 0.2048	81.1111 ± 0.1060	4.6242%, 2.0500%
50	76.5294 ± 0.0293	78.5033 ± 0.1392	80.0000 ± 0.0803	3.4706%, 1.4967%
70	76.4811 ± 0.0293	78.0786 ± 0.0779	79.4095 ± 0.0845	2.9284%, 1.3309%
100	76.4896 ± 0.0146	77.7200 ± 0.0878	78.8050 ± 0.0500	2.3154%, 1.0850%
Average	76.4968%	78.3408%	79.8314%	3.3347%, 1.4907%

Table 6. Mapping results in 95% confidence interval for defective panels scatter randomly

Method Conditions		Random mapping	Hungarian method	Difference
TFT yield	$n = 30$	85.5009 ± 0.0194	88.4833 ± 0.1634	2.9824%
90%	$n = 50$	85.5039 ± 0.0091	87.8633 ± 0.0307	2.3594%
CF yield	$n = 70$	85.5095 ± 0.0097	87.5952 ± 0.0501	2.0857%
95%	$n = 100$	85.5007 ± 0.0091	87.2000 ± 0.0329	1.6993%
TFT yield	$n = 30$	86.3970 ± 0.0130	88.9389 ± 0.0687	2.5419%
90%	$n = 50$	86.4057 ± 0.0085	88.5700 ± 0.0650	2.1643%
CF yield	$n = 70$	86.3989 ± 0.0087	88.2333 ± 0.0513	1.8344%
96%	$n = 100$	86.3974 ± 0.0073	87.9550 ± 0.0342	1.5576%
TFT yield	$n = 30$	87.2971 ± 0.0131	89.4056 ± 0.0623	2.1085%
90%	$n = 50$	87.3016 ± 0.0064	89.1567 ± 0.0374	1.8551%
CF yield	$n = 70$	87.2980 ± 0.0093	88.8810 ± 0.0681	1.5830%
97%	$n = 100$	87.2985 ± 0.0074	88.6583 ± 0.0370	1.3598%
TFT yield	$n = 30$	88.2010 ± 0.0115	89.7444 ± 0.0598	1.5434%
90%	$n = 50$	88.2019 ± 0.0064	89.5833 ± 0.0377	1.3814%
CF yield	$n = 70$	88.2006 ± 0.0071	89.4262 ± 0.0498	1.2256%
98%	$n = 100$	88.1981 ± 0.0059	89.3000 ± 0.0446	1.1019%
TFT yield	$n = 30$	89.0996 ± 0.0079	89.9167 ± 0.0429	0.8171%
90%	$n = 50$	89.0981 ± 0.0063	89.8933 ± 0.0293	0.7952%
CF yield	$n = 70$	89.1007 ± 0.0033	89.8524 ± 0.0287	0.7517%
99%	$n = 100$	89.0998 ± 0.0039	89.8000 ± 0.0210	0.7002%

In Tables 2, 3, 4 and 5, the average yield ratio from random mapping, without respect to the panel quantities per substrate. This is unlike the others algorithm where average yield ratio increased as the panel quantities decreased. This implies that if the displays size is very small or if CF is purchased by a very high yield rate, random mapping is feasible.

Table 6 represents the numerical results for defective panels scatter randomly on the plate with TFT total average yield rates 90% and CF total average yield rates 95% to 99%. According to LCD firm estimation, the difference between random mapping and using sorter mapping does not exceed yield 1%. Therefore, LCD firms should purchase CF with yield rates no less than 99% for using random mapping with TFT yield 90%.

5 Conclusions

Yield control is an important factor for a TFT LCD manufacturing firm to gain a competitive edge. The post-mapping yield control problem has a significant impact on TFT LCD manufacturing. For the small to medium sized displays, scribing glass in advance and then during the cell process produces a lower economy of scale. A judicious matching policy is very cost effective because it does not require a significant investment to produce yield improvement. This research proposed a linear programming formulation to maximize the yield rate through an optimal matching process to obtain a greater number of acceptable LCD panels to improve the cell process yield. The results were compared with two heuristics seen in practice and showed superior solution quality. Implementation results revealed that the proposed approach is effective in solving a practical problem.

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