Quality Improvement In the Manufacture of Liquid Crystal Displays Using Uniform Design

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Abstract

When factorial designs or orthogonal arrays are used in an experiment, the number of runs required may be larger than that can be accommodated in practice, even for moderate numbers of factors and levels of factors. In such a case, the choice of uniform designs is a feasible alternative. A uniform design is a design in which the design points distribute uniformly over the entire design space. Uniform designs can be constructed by minimizing a discrepancy over the design space. This paper reports a successful application of uniform design in the manufacture of liquid crystal displays, in which the information obtained from the experiment resulted in a significant improvement of the percentage yield of the process.

Key words. Design of experiments, uniform design, discrepancy.

1. Introduction.

Design of experiments is a useful tool which is now widely applied in product design and process design. When the relationship between the response and the potential contributing factors is not fully known, experiments may be carried out at different combinations of different levels of the factors, in order to identify the important factors and how they contribute to the response.

Over the last half century, statisticians have suggested a variety of design layouts that are suitable for different situations. Such design layouts include full factorial designs, fractional factorial designs, block designs, orthogonal arrays, Latin squares, supersaturated designs, and so on (Cochran and Cox (1957), John and Quenouille (1977), Box *et al* (1978), Montgomery (1991), Dey and Mukerjee (1999)). A relatively new type of design that provides experimenters with another choice is the *uniform design*, which has growing popularity and has been used successfully in various industries in recent years (Fang (1980), Fang and Wang (1994), Fang (2002), Fang *et al* (2000), Li (2002)). A uniform design has the advantage that it allows an experiment to be performed in a relatively small number of runs when the number of factors and the numbers of levels of the factors are large, and thus can complement factorial designs and orthogonal arrays when such designs cannot be realized in practice due to the large number of runs required. Uniform designs are characterized by the "uniformity" of distribution of design points over the entire design space, which can be achieved by minimizing a discrepancy. It is known that some commonly used designs such as balanced incomplete block designs have high uniformity (Liu and Chan (2003)), and uniformity is essentially equivalent to minimum aberration (Fang and Mukerjee (2000)).

This paper provides a case study to illustrate how uniform design was applied in an experiment to improve product quality in the manufacture of liquid crystal displays (LCDs), while other designs such as orthogonal arrays are not suitable because the number of runs had to be economized. In the Section 2, discrepancies and uniform designs are briefly introduced. In Section 3, the manufacturing process for LCDs is briefly described. Section 4 describes how an experiment was conducted using uniform design, and how the results obtained helped improve the yield of the manufacturing process. Section 5 is devoted to discussion and conclusion.

2. Discrepancy and uniform design

A uniform design is a design in which the distribution of design points minimizes a discrepancy over the entire design space. The uniform design has been used as a "space filling" technique in numerical computation, computer experiments and Quasi-Monte Carlo methods (Warnock (1972), Wang and Fang (1981), Niederreiter (1992)). Intuitively speaking, a uniform design is one whose design points distribute "very uniformly" over the entire design space. To illustrated what a uniform design is, consider the s-dimensional unit cube $C^s = \{(\mathbf{x} = (x_1, ..., x_s)' : 0 \leq x_i \leq 1(i = 1, ..., s)\}$ as the design space. Given any set $\mathcal{P} = \{\mathbf{x}_1, ..., \mathbf{x}_n\} \subset C^s$, its empirical distribution function is defined by

$$F_{\mathcal{P}}(\mathbf{x}) = n^{-1} \sum_{i=1}^{n} I(\mathbf{x}_i \leq \mathbf{x}), \tag{2.1}$$

where $I(\cdot)$ is the indicator function and the inequalities in (2.1) are with respect to componentwise order in the s-dimensional Euclidean space. Let $F(\mathbf{x})$ be the uniform distribution function on C^s. The L_p *discrepancy* of $\mathcal{P}$ is defined by

$$D_p(\mathcal{P}) = \left[\int_{C^s} |F_{\mathcal{P}}(\mathbf{x}) - F(\mathbf{x})|^p \, d\mathbf{x} \right]^{1/p}. \tag{2.2}$$

For each fixed n, a "good lattice point set" is a set $\mathcal{P}_0$ which minimizes $D_p(\mathcal{P})$ over all possible $\mathcal{P} = \{\mathbf{x}_1, ..., \mathbf{x}_n\} \subset C^s$, and a design with $\mathcal{P}_0$ as its design points is called a "uniform design". On any compact set other than C^s, uniform designs can be constructed using the same approach. Usually, $p = 2$ is chosen for computational convenience, as some computation formulas are available (Fang *et al* (2000)). Figure 1 shows examples of good lattice point sets constructed on a square and on a circle in the 2-dimensional space (Fang and Wang (1994)).

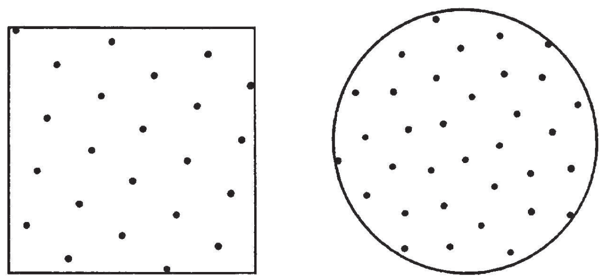


Figure 1. Two examples of good lattice point sets.

For any n, s, and any range of variation of each coordinate in $\mathbf{x}$, a uniform design of n points can always be constructed. This means that a suitable uniform design with a relatively small number of runs n can always be provided to the experimenter when the number of factors and the levels of the factors are large but a large number of runs is prohibited because of constraints on resources, in which case designs such as orthogonal arrays are not suitable. Table 1 shows an example of a uniform design $U_n(15^5)$ with $n = 15$ runs and $r = 5$ factors each of which has 15 levels; and a uniform design $U_{12}(4^2{\times}3)$ with $n = 12$ runs and two factors each of which has 4 levels, and one factor which has 3 levels (Fang (1994)). On the other hand, the minimum number of runs n of the $L_n(15^5)$ and $L_n(4^2{\times}3)$ orthogonal arrays are $15^2 = 225$ and $4^2{\times}3 = 48$, respectively.

Table 1. Two examples of uniform design.

Run number	Factor I	II	III	IV	V
1	1	4	7	11	13
2	2	8	14	7	11
3	3	12	6	3	9
4	4	1	13	14	7
5	5	5	5	10	5
6	6	9	12	6	3
7	7	13	4	2	1
8	8	2	11	13	14
9	9	6	3	9	12
10	10	10	10	5	10
11	11	14	2	1	8
12	12	3	9	12	6
13	13	7	1	8	4
14	14	11	8	4	2
15	15	15	15	15	15

A $U_n(15^5)$ uniform design.

Run number	Factor I	II	III
1	1	1	1
2	1	2	2
3	1	3	3
4	2	4	1
5	2	1	2
6	2	2	3
7	3	3	1
8	3	4	2
9	3	1	3
10	4	2	1
11	4	3	2
12	4	4	3

A $U_{12}(4^2 \times 3)$ uniform design.

To construct a uniform design with n points in a compact set $\mathcal{C}$ is to construct a good lattice point set $\mathcal{P} \subset \mathcal{C}$ of n points which has minimum discrepancy. Since minimization of $D_2(\mathcal{P})$ usually involves heavy computational load, heuristic optimization algorithms such as threshold accepting have to be employed (Winker and Fang (1997)). In recent years, many uniform designs have been constructed and are available, for example, from the web site www.math.hkbu.edu.hk/UniformDesign.

In order to improve properties of $D_p(\mathcal{P})$ such as symmetry property and projection uniformity over all sub dimensions, other discrepancies have been defined. They include the symmetric L_p discrepancy, centered L_p discrepancy, the modified L_p discrepancies, and so on. Readers are referred to Hickernell (1998a, 1998b) for details.

3. Manufacturer of liquid crystal display (LCD)

LCD is an electronic device that is now widely used in consumer and industrial products. In a liquid, molecules are completely free to move and rotate, while in a crystal, molecules are fixed in position and orientation. Liquid crystal (LC) is a liquid that has a partially crystalline structure. An LCD operates by manipulating the light that passes through the LC. When a voltage is applied to an LCD, molecules in the LC will align and rotate along the electric field, and when light passes through the LC, the emerging light will be polarized. This phenomenom allows LCD's with specific patterns of display be designed and manufactured. The manufacturing process of LCD's is complicated and has four main steps to be carried out in a sequence, namely, photolitho, batch formation, semi-finishing and finishing. Photolitho refers to formation of a litho conductive circuit of a specific pattern on the glass plate. In batch formation, two glass plates are glued together to form a batch. In the semi-finishing step, individual small cells are cut from a large batch and filled with LC to form functional LCDs (semi-finishing products). In finishing, the functional LCDs are bonded to other electronic components such as printed circuit boards to form complete LCDs. The flow of the first three steps are shown below. The finishing step, however, varies from product to product and cannot be represented by a single flow diagram.

<u>Photolitho</u>: (glass with conducting film) → coated with photoresisting material → UV exposure → developing → etching → stripping → (glass with circuit)

<u>Batch formation</u>: (glass with circuit) → layer printing → PI printing → rubbing → printing → mounting → (batch)

<u>Semi-finishing</u>: (batch) → scribing → breaking → carrier loading → filling → closing → rough cleaning → final curing → functional quality check → (semi-finished

product)

In each part of this complicated manufacturing process, design of experiment can help improve quality and efficiency. This paper is concerned with a project specifically focused at improvement of the yield in the "filling" process in the semi-finishing step in an Asian plant of a multinational manufacturer. In order to produce LCD's that are suitable for a low voltage operating environment, the plant recently introduced glass fibre filling rod as a conductor for the filling of glass cells. Since then, incomplete filling became a great problem in production as it caused a reject percentage significantly higher then the target of 1%. The objective of this project was to find out an optimal way of preparing the glass fibre rod and filling the cell in order to bring the reject percentage down to an acceptable level. A sketch of the setup for the filling the cell with LC is shown in Figure 2. The detailed procedure of filling is too technical to be further discussed here. In this process, the values of the following five factors can be adjusted:

1. Vacuum time, V (inn minute): The duration of time for which the filling chamber is kept vacuum.
2. Flooding time, F (in minute): The duration of time for which the cell (container of LC in the LCD) is in contact with the filling rod.
3. Thickness of the filling rod, T: The number of pieces of glass fiber clamped together to form the filling rod.
4. Level of liquid crystal, L (in mm): The height of the LC level in the container in which the filling rod is to be immersed in.
5. Soaking time before filling, S (in hour): The duration of time for which the filling rod is to be immersed in the preparation tray containing LC.

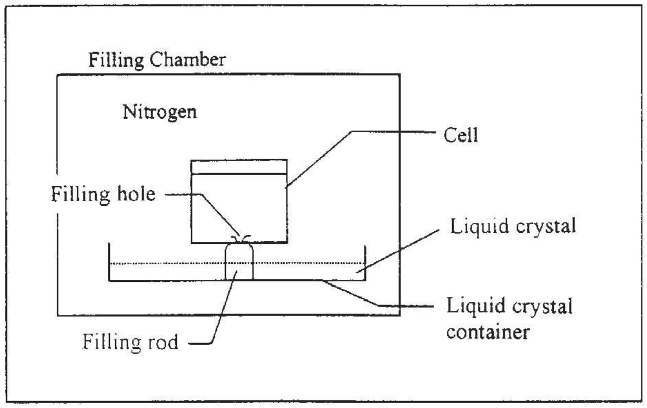
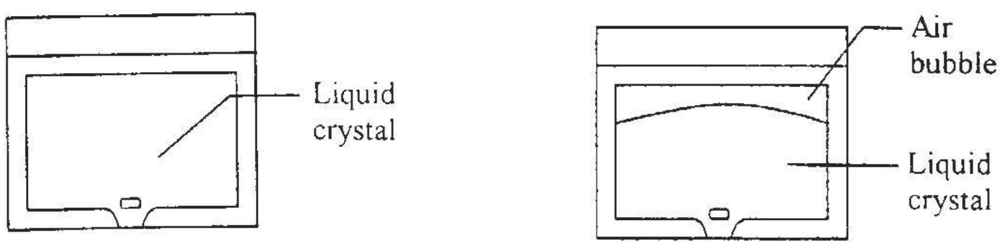


Figure 2. Setup for liquid crystal filling.



(a) Completely filled cell

(b) Incompletely filled cell

Figure 3. Complete filling and incomplete filling.

A cell produced will be rejected when filling is incomplete, which means formation of an air bubble inside the cell; otherwise, it will be accepted. Figure 3 shows the drawings of a completely filled and an incompletely filled cell. The response function of the process is the yield, which is the percentage of accepted LCD's. Before this yield improvement project, the five factors are set at the following levels by experience: $V = 20$, $F = 13$, $T = 5$, $L = 2$, $S = 1.5$. For such a setting, the yield was far from being satisfactory, as reject percentage was as high as 20% in the beginning of the process, and stabilized to only about 4% after a long period of time.

It was decided that an experiment should be conducted to find out the relationship between the five factors, V, F, T, L, S, and the yield. The details are described in the next section.

4. The experiment.

In actual production, because of various physical constraints, the equipment used and the production speed required, there are lower and upper limits for the values of the factors V, F, T, L, S. Experience suggested that under such constraints, good yield would likely be obtained when the values of these factors are in the following ranges:

$$16 \le V \le 24, \quad 9 \le F \le 17, \quad 4 \le T \le 8, \quad 2 \le L \le 23, \quad 1 \le S \le 3, \tag{4.1}$$

although the production team did not exclude the possibility that an optimal setting will be outside these ranges. Since it was not known whether good yield would be obtained when values of these factor were at their lower ends, higher ends or in the middle of their ranges, it was obvious to the production team that two-level designs were not satisfactory. From a practical consideration based on the available settings in equipment used and previous experiences about the effect of variations of the factors on the yield, the following settings for the factors were suggested for the experiment:

Factor I, V: 16, 18, 20, 22, 24 (Levels 1, 2, 3, 4, 5);

Factor II, F: 9, 11, 13, 15, 17 (Levels 1, 2, 3, 4, 5);

Factor III, T: 4, 5, 6, 7, 8 (Levels 1, 2, 3, 4, 5);

Factor IV, L: 2 (just immersed), 11 (half-immersed), 23 (fully-immersed) (Levels 1, 2, 3);

Factor V, S: 1, 1,5, 2, 2.5, 3 (Levels 1, 2, 3, 4, 5).

Because of the limitation in resources, altogether not more than 40 different settings of factors, that is, 40 runs, were available for this experiment, but the materials available allowed a large number of repeated trials in each run. Since it is unknown whether the optimal setting would lie outside the ranges specified in (4.1), the production team did not want to risk performing 40 runs in one round, but decided to run several rounds of experiments sequentially, making a total of not more than 40 runs. It was decided to perform 15 runs in the first round, and use the remaining 25 runs for subsequent rounds. There were 4 factors each having 5 levels, and one factor having 3 levels. Commonly known designs such as factorial designs or orthogonal arrays were not suitable for this experiment – since a $5^4 \times 3$ full factorial design requires $5^4 \times 3 = 1875$ runs, while a $5^4 \times 3$ orthogonal requires a multiple of $5^2 \times 3 = 75$ runs. With the given numbers of factor, levels and runs, a $U_{15}(5^4 \times 3)$ uniform design was adopted for the first round of experiment.

<u>The 1st round of the experiment.</u>

A $U_{15}(5^4 \times 3)$ uniform design can be formed by minimizing $D_p(\mathcal{P})$. More conveniently, a design which is close to a $U_{15}(5^4 \times 3)$ uniform design can be formed by combining adjacent three levels of the first four columns in Table 1 to form four 5-level columns, and combining adjacent five levels of the fifth columns to form a

3-level column. This is shown as follows:

Factors I, II, III, V: 1,2,3 $\rightarrow \underline{1}$; 4,5,6 $\rightarrow \underline{2}$; 7,8,9 $\rightarrow \underline{3}$; 10,11,12 $\rightarrow \underline{4}$; 13,14,15 $\rightarrow \underline{5}$.

Factor IV: 1,2,3,4,5 $\rightarrow \underline{1}$; 6,7,8,9,10 $\rightarrow \underline{2}$; 11,12,13,14,15 $\rightarrow \underline{3}$.

Table 2. A $U_{15}(5^4 \times 3)$ uniform design generated

from the $U_{15}(15^5)$ uniform design in Table 1.

Run	Factor				
number	I (V)	II (F)	III (T)	IV (L)	V (S)
1	1 (16)	2 (11)	3 (6)	3 (23)	5 (3)
2	1 (16)	3 (13)	5 (8)	2 (11)	4 (2.5)
3	1 (16)	4 (15)	2 (5)	1 (2)	3 (2)
4	2 (18)	1 (9)	5 (8)	3 (23)	3 (2)
5	2 (19)	2 (11)	2 (5)	2 (11)	2 (1.5)
6	2 (18)	3 (13)	4 (7)	2 (11)	1 (1)
7	3 (20)	5 (17)	2 (5)	1 (2)	1 (1)
8	3 (20)	1 (9)	4 (7)	3 (23)	5 (3)
9	3 (20)	2 (11)	1 (4)	2 (11)	4 (2.5)
10	4 (22)	4 (15)	4 (7)	1 (2)	4 (2.5)
11	4 (22)	5 (17)	1 (4)	1 (2)	3 (2)
12	4 (22)	1 (9)	3 (6)	3 (23)	2 (1.5)
13	5 (24)	3 (13)	1 (4)	2 (11)	2 (1.5)
14	5 (24)	4 (15)	3 (6)	1 (2)	1 (1)
15	5 (24)	5 (17)	5 (8)	3 (23)	5 (3)

The design formed is shown in Table 2, and was adopted as the layout for the first round of the experiment. The numbers in brackets in Table 2 are the actual values of the factors.

Because of the equipment used, 5 trays each containing 66 experimental units were available for each run. The numbers of accepted LCD's ("good cells") obtained from each tray in the 15 runs in the first round of the experiment are shown in Table 3, which shows that Run 1 produced perfect result, and Runs 8 and 12 produced reasonably good result.

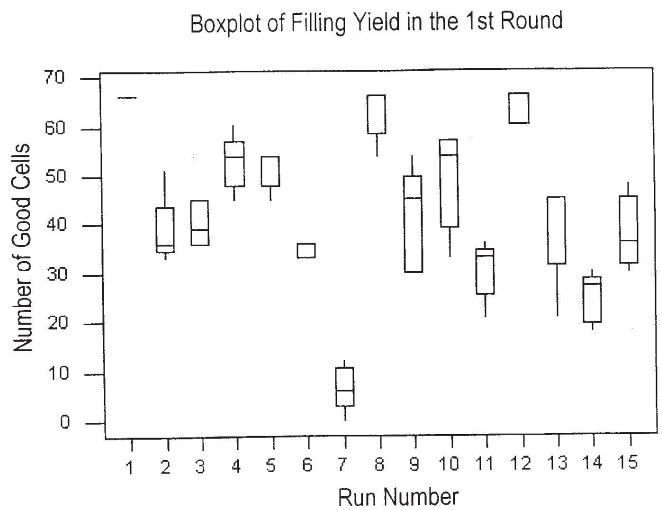


Figure 4. Boxplot of filling yield in the 1st round of experiment

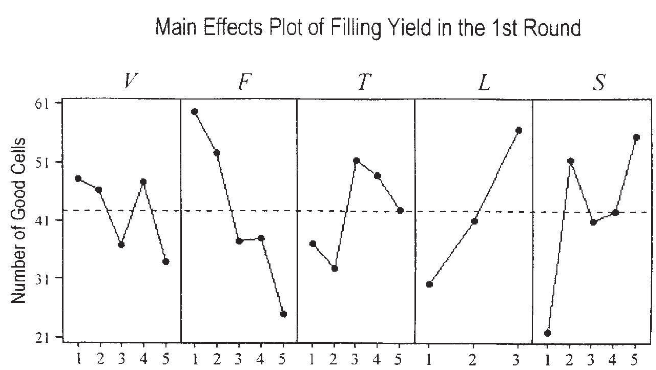


Figure 5. Main effects plot of filling yield in the 1st round of experiment.

Table 3. Results of the 1st round.

Run number	Tray 1	2	3	4	5	Mean	S.D.
1	66	66	66	66	66	66	0
2	33	36	36	36	51	38.4	7.16
3	36	36	45	39	45	40.2	4.55
4	45	54	51	60	54	52.8	5.45
5	45	54	54	51	54	51.6	3.91
6	33	36	33	36	36	34.8	1.64
7	0	6	6	12	9	6.6	4.45
8	54	66	63	66	66	63.0	5.20
9	30	30	54	45	45	40.8	10.52
10	33	45	57	54	57	49.2	10.31
11	21	30	33	36	33	30.6	5.77
12	60	60	66	66	66	63.6	3.29
13	21	45	45	42	45	39.6	10.48
14	18	21	27	27	30	24.6	4.93
15	30	36	33	42	48	37.8	6.50

Figures 4 and 5 show the boxplot and the main effect plot, respectively, of the outcome of the first round. In the good runs, Runs 1, 8 and 12, L was at the highest value 23, which agreed with Figure 5 which shows that the yield increased as L increased. Although Figure 5 shows that the lowest value of F gave the highest yield, the value of F in the best run, Run 1, was set at 11 which was not the lowest value. This indicated existence of interactions among factors.

In the best run, Run 1, V was set at the smallest value 16. In production, the vacuum time V and the flooding time F significantly affect the production rate, since the smaller V and F, the shorter the cycle time and the higher the production rate. It was decided that a 2nd round of experiments should be performed to further investigate whether V and F could be reduced to beyond their lower boundaries (16 and 9, respectively) of their ranges in (4.1) and yet still produced the same high yield.

<u>The 2nd round of experiment.</u>

Basically, the levels of the best run, Run 1, was used as the centre in setting up the design for this round of experiment. However, since factor F showed a decreasing main effect in Figure 5, the level for this factor was set on the low side, hoping to obtain a good design that has a small value of F. Also, since factor S did not show a strictly increasing or decreasing effect over the entire range $1 \leq S \leq 3$ in Figure 5, this whole range was in this design in order to better investigate the effect of S.

Since factor L shows an increasing main effect on Figure 5, which agrees with the engineering intuition that a higher level of LC would produce better filling effect, L was fixed at 23 (which was its value in Run 1) so that this round of experiment can be performed with a smaller number of runs. Three levels were chosen for each of V, F, T, and S, as shown below:

Factor I, V: 12, 16, 20 (Levels 1, 2, 3);

Factor II, F: 7, 9, 11 (Levels 1, 2, 3);

Factor III, T: 5, 6, 7 (Levels 1, 2, 3);

Factor IV, L: 23 (fixed);

Factor V, S: 1, 2, 3 (Levels 1, 2, 3).

For such a selection of levels, a 3^4 orthogonal array (which requires $3 \times 3 = 9$ runs) was used. The setup is shown in the first 6 columns of Table 4. The results are shown in columns 7 to 13 of Table 4. The boxplot and the main effect plot are shown in Figure 6 and 7, respectively.

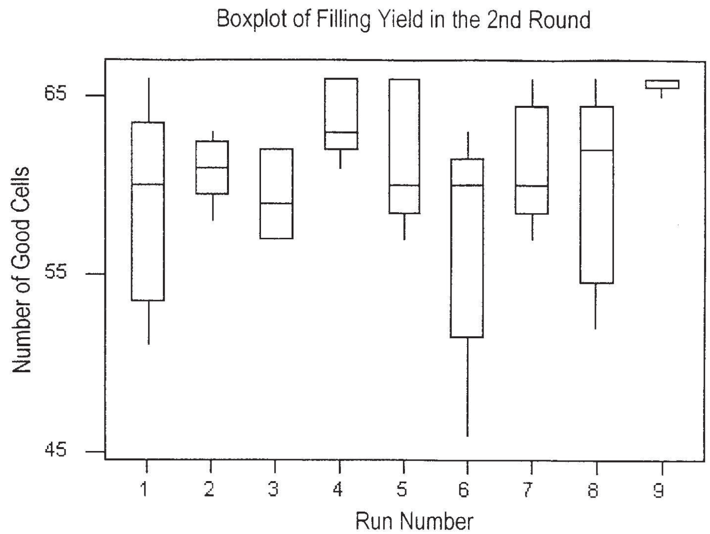


Figure 6. Boxplot of filling yield in the 2nd round of experiment

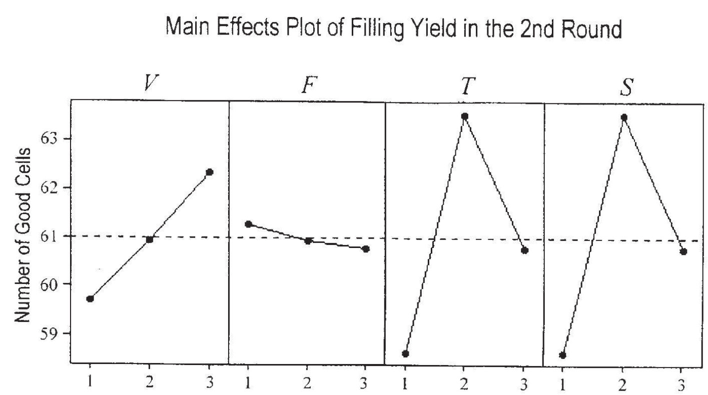


Figure 7. Main effects plot of filling yield in the 2nd round of experiment.

Table 4 shows that the only run with good yield (mean 65.9) was Run 24, which unfortunately had the largest value $V = 20$ for vacuum time, although F was in the middle range.

Both Figure 5 and Figure 7 shows that the main effect of T gave the best yield at $T = 6$, which agreed with the fact that $T = 6$ or 7 in the best three runs in the 1st round (Runs 1, 8, 12) and the best run in the 2nd round (Run 24). Therefore, $T = 6$ was fixed in the next round of experiment in order to reduced the number of runs.

Table 4. Results of the 2nd round.

Run number	V	F	T	L	S	Tray 1	2	3	4	5	Mean	S.D.
16	12	7	5	23	1	51	61	60	56	66	58.8	5.63
17	12	9	6	23	2	56	62	61	63	61	61.0	1.87
18	12	11	7	23	3	57	59	57	62	62	59.4	2.51
19	16	7	6	23	2	61	63	63	66	66	63.8	2.17
20	16	9	7	23	3	57	60	60	66	66	61.8	4.02
21	16	11	5	23	1	46	60	57	63	60	57.2	6.61
22	20	7	7	23	3	57	60	63	60	66	61.2	3.42
23	20	9	5	23	1	66	66	62	57	63	60.0	5.52
24	20	11	6	23	2	65	65	66	56	66	65.9	0.45

<u>The 3rd round of experiment.</u>

In this round of experiment, emphasis was focused on investigating the effects by varying V and F. The factors T and S were fixed at 6 and 2, respectively. The levels of factors were set as follows: Factor I, V: 12, 14, 16, 18, 20, 22 (Levels 1, 2, 3, 4, 5);

Factor II, F: 7, 9, 11 (Levels 1, 2, 3);

Factor III, T: 6 (fixed);

Factor IV, L: 23 (fixed);

Factor V, S: 2 (fixed).

The setup and the observed results are shown in Table 5. The 25th – 32nd runs form a 3×3 full factorial designs on V and F apart from the missing run $(V, F) = (20, 11)$ which was already performed as Run 24 in the 2rd round of experiment. Runs 33 – 36 were set in an *ad hoc* manner. Runs 33 and 34 were set for small V, while Run 35 was set for large V in order to investigate the effect of large V on the outcome. Run 36 was intended for investigating whether the total cycle time for the 1st run (the best run obtained) can be reduced by reducing F and S. The boxplot and the main effect plot are shown in Figures 8 and 9, respectively. Runs 28, 29, 30 and 35 gave good results, while Run 30 was the best in this round. The results of this round did not provide any clue for reduction of cycle time.

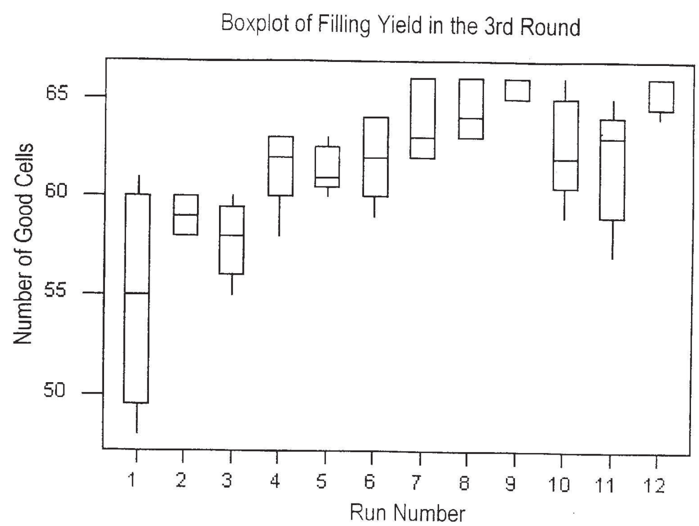


Figure 8. Boxplot of filling yield in the 3rd round of experiment

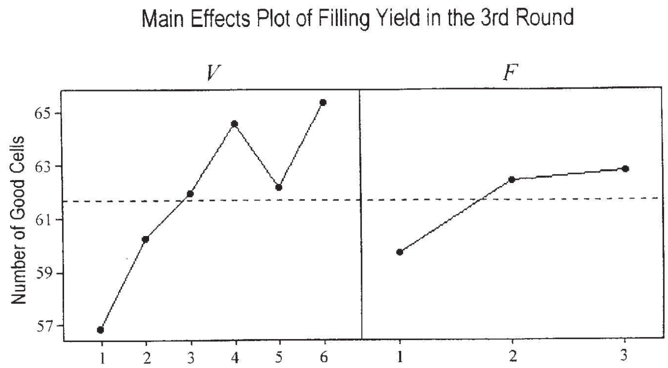


Figure 9. Main effects plot of filling yield in the 3rd round of experiment.

Table 5. Results of the 3rd round.

Run number	V	F	T	L	S	Tray 1	2	3	4	5	Mean	S.D.
25	14	7	6	23	2	55	57	60	58	59	57.8	1.92
26	14	9	6	23	2	58	62	62	63	63	61.6	2.07
27	14	11	6	23	2	60	61	61	62	63	61.4	1.14
28	18	7	6	23	2	62	62	66	63	66	63.8	2.05
29	18	9	6	23	2	64	63	63	66	66	64.4	1.52
30	18	11	6	23	2	65	66	66	66	65	65.6	0.55
31	20	7	6	23	2	59	62	62	64	66	62.6	2.61
32	20	9	6	23	2	57	61	63	63	66	61.8	3.03
33	12	7	6	23	2	48	51	55	59	61	54.9	5.40
34	12	11	6	23	2	58	58	60	59	60	59.0	1.00
35	22	11	6	23	2	65	66	64	66	66	65.4	0.89
36	16	9	6	23	2	59	61	62	64	64	62.0	2.12

<u>The 4th round of experiment.</u>

In this round, only one run set at $(V, F, T, L, S) = (12, 11, 6, 23, 4)$ was performed. The purpose was to investigate whether the vacuum time $V = 16$ in the best run,

Run 1, can be reduced to 12 at the expense of increasing the soaking time S. The result is negative, as shown in Table 6. Due to scarcity of material, only four trays were used in this round. Since the yield was not high, the result did not provide any clue for achieving high yield under reduction of cycle time.

Table 6. Results of the 4th round.

Run						Tray					
number	V	F	T	L	S	1	2	3	4	Mean	S.D.
37	12	11	6	23	4	56	59	58	58	57.3	1.50

<u>The 5th round of experiment.</u>

In this final round, based on the setting of the best run obtained so far (Run 1), two runs were performed with a low value of V combined with a medium value of F, and a medium value of V combined with a low value of F in order to investigate whether good yield could be obtained when either the flooding time or vacuum time is reduced. Due to scarcity of material, only four trays were used in this experiment. The results are shown in Table 7. The results again gave no clue to obtaining high yield under reduction of cycle time.

Table 7. Results of the 5th round.

Run						Tray					
number	V	F	T	L	S	1	2	3	4	Mean	S.D.
38	14	11	6	23	3	66	62	62	64	62.0	1.63
39	16	9	6	23	3	59	61	63	62	61.3	1.71

Findings of the five rounds of experiment showed that Run 1 (1st round), Run 24 (2nd round) and Run 30 (3rd round) were the best among all. These runs have the same value of F, the same value of T, and the same value of L, as shown in Table 8. Comparing these three runs, Run 1 has the largest mean, and smallest standard deviation, and most importantly from production point of view, the smallest value of

V which gives the shortest cycle time. Therefore the settings of Run 1 was adopted in future production. The filling yield (100% minus the reject percentage in %) of 20 production cycles using Run 1 are shown in Figure 10, which indicates that the target of $\leq$ 1% reject percentage was achieved, and therefore the problem of high reject percentage in production was solved.

Table 8. The best three runs.

Run number	V	F	T	L	S	Mean	S.D.
1	16	11	6	23	3	66	0
24	20	11	6	23	2	65.9	0.45
30	18	11	6	23	2	65.6	0.55

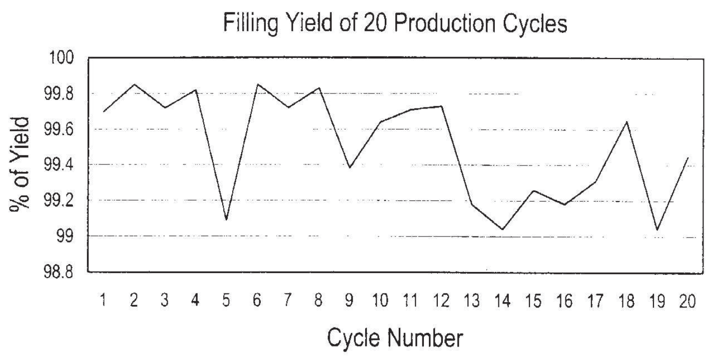


Figure 10. Filling yield of 20 production cycles using the setting of Run 1.

5. Discussion and conclusion.

Design of experiments is a useful tool for exploring the dependence relationship of the response on various possible contributing factors. When traditional designs such as factorial designs or orthogonal arrays are used, the total number of runs required is sometimes larger that can be accommodated in an experiment, even for a moderate number of factors and a moderate number of levels of the factors. In such a situation, uniform designs is a possible alternative. The uniform design is a type of design which has its experimental points scattering uniformly over the entire design space, and thus is ideal for exploratory prediction of the response when the form of the response surface is unknown. Using a uniform design, the experiment can be completed in a much smaller number of runs, even when the number of factors and the levels of factors are both large. Uniform designs can also be used when the number of runs available is large. A uniform design is constructed by minimizing a discrepancy. Different discrepancies have been defined and studied in detail, some convenient computational formulas are available, and tables for uniform designs are available on the web site www.math.hkbu.edu.hk/UniformDesign.

In this article, an example is presented to illustrate how a uniform design was used in an experiment to improve product quality in the manufacture of liquid crystal displays. The first round of experiment was performed using a uniform design, in which a combination of levels of factors that produces very good result was obtained in 15 runs. In order to further improve the result by reducing the cycle time of production, subsequent runs were performed using factorial designs. After a total of 39 runs, the best combination of levels of factors found was still the one obtained in the first round using uniform design, and this setting was adopted by the production term for mass production. Subsequent production data show that with this setting, the reject percentage stays below the target of 1%, and the high reject percentage problem in production was solved. However, based on the findings so far, it still unknown whether the reject percentage can be further reduced by adjusting the present setting of the factors, and whether good results can still be obtained at a higher production rate by decreasing the "vacuum time" and the "flooding time". Nevertheless, in the industry, there is always a trade-off between the amount of resources invested and the expected results. Although the high reject percentage problem is now solved, the production team still looks forward to further studying the process and continuously improving production quality and efficiency, should resources be available in the future for additional experiments.

Application of design of experiment has been popular in industries, since it was strongly advocated by G. Taguchi in the 1970's. In many cases, factorial designs and orthogonal arrays are used. This article reports an application of uniform design, as an alternative to factorial design and orthogonal array. Although many new theoretical results involving uniform design are obtained only recently and uniform design is still not as widely used as some other designs, the successful example in this article and many other successful examples obtained elsewhereee indicate that uniform design is as powerful as traditional designs (such as orthogonal arrays) but is more flexible in terms of the number of runs, and more wide-spread use of it will certain benefit industries.

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