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Integer Programming Approach to the Convergence Adjustment on Color Display Tube

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Abstract. In this paper, we consider the adjustment of convergence on Color Display Tube (CDT). Convergence is a measure of how well the red, green and blue beams are physically aligned with each other to strike the same area on the screen. When misconvergence (convergence error) occurs, one way of compensating it is to attach several ferrite sheets on the inner part of Deflection Yoke (DY). We suggest an optimization model of misconvergence compensation process and report test results for 81 DY samples. As a result, more than 90% of the samples could be made to satisfy the required convergence criteria.

Keywords: color display tube, deflection yoke, convergence adjustment, integer programming

1. INTRODUCTION

We consider the adjustment of convergence arising in the manufacturing process of color monitors. The structure of Color Display Tube (CDT or Cathode Ray Tube (CRT)) is shown in Figure 1 (Chung *et al.*, 1995a, Chung *et al.*, 1995b). After three electron beams are emitted from R (red), G (green), B (blue) electron guns, they are deflected by Convergence and Purity Magnets (CPM) rings on the neck and the Deflection Yoke (DY) attached to the funnel glass cone. Electron beams which have passed through CPM rings are deflected by horizontal and vertical magnetic fields generated by two coils of DY. Then, the beams pass one of the shadow mask holes and collide with red, green and blue phosphors placed (painted) on the backside of the CDT's glass in a pattern of dots, and the excited phosphors emit light. The beams scan across the screen by the deflection mechanism, creating an image that you see. Refer to Chung *et al.* (1995a) and Chung *et al.* (1995b) for more detailed operation and adjustment of CDT.

To realize a vivid color on the screen, the three beams need to hit the same area on the screen. In other words, convergence of the beams is of great importance. Misconvergence (convergence error) causes sharply defined characters or objects to have colored fringes (Keller, 1997).

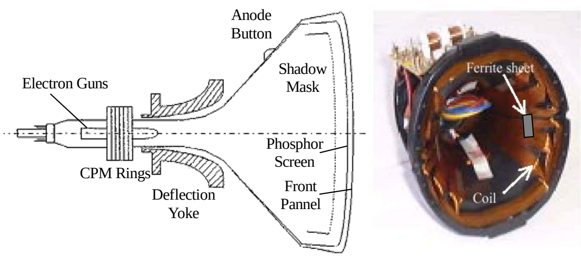

Figure 1. Color Display Tube (CDT) and Deflection Yoke (DY)

Convergence can be accomplished by design optimization of coil distributions of DY (Nishimura *et al.*, 1997, Joe *et al.*, 1996). But minor misconvergence generally inevitable when coils have been wound, can be diminished by attaching ferrite sheets to the inner part of DY. The misconvergence of the beams (colors) is usually characterized by distances between each pair of the three

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beams measured at some selected control points on the screen (see section 2.1). Ferrite sheet has the capability of changing local trajectories of the beams and can be used to improve convergence (compensate misconvergence) in the affected region of screen.

In the factory, most DYs in the production line require convergence adjustments. The workers inspect each DY in the line by placing it in the measuring system. If misconvergence occurs, they intuitively determine the locations where ferrite sheets should be attached to correct misconvergence. If the convergence after attaching sheets is not satisfactory, they repeat the process until good convergence performance is attained. Skilled workers generally succeed in correcting misconvergence within two or three trials, each requiring only a few seconds. However, it takes much more time for a novice (an unskilled worker) to correct misconvergence. Depending on workers, it generally takes six months or even up to one and a half years for them to become experts for this process. Therefore, this process is a bottleneck in increasing the productivity of the color monitors.

We developed a visualized guidance system to increase efficiency of the convergence adjustment process and improve convergence quality. Its main function is to read out misconvergence of the beams and indicate visually the locations where ferrite sheets should be attached to compensate misconvergence. It can assist the workers in attaching the sheets even if they are novices at this process. This paper deals with the main algorithm applied in the system.

There have been a few studies about convergence adjustment on CDT. Chung *et al.* (1995a), Chung *et al.* (1995b) and Song *et al.* (1999) considered (neuro-) fuzzy models to express the relationship between input (location of ferrite sheets) and output (change in misconvergence). However, they did not report detailed experimental results. Verikas *et al.* (2000) used a neural network approach and presented successful results in convergence adjustment, but the test environment is different from ours and criteria for successful adjustment (acceptable range of distances between the beams) are not reported in their work.

In this paper, we develop an integer programming model on the misconvergence compensation process. In order to use the integer programming model, we take the assumption that the misconvergence has a linearity property (Song *et al.,* 1999; Verikas, 2000); definition and validation of the property are given in the next section. By solving the model, we can get the minimum number of sheets needed to compensate misconvergence in a single step, whereas iterative approaches were used in the previous research.

To find an optimal solution to the integer programming model, we apply linear programming (LP)-based branch-and-bound algorithm (Nemhauser and Wolsey 1988). The experimental results of this research show that the integer programming approach can be a preferable option in compensating misconvergence.

The remainder of this paper is organized as follows. We describe how to identify the misconvergence and test if the linearity property holds in section 2. We present an integer programming model in section 3. In section 4, we test the model through real experiments. Finally, the last section presents concluding remarks.

2. MISCONVERGENCE AND LINEARITY PROPERTY

2.1 Identifying Misconvergence

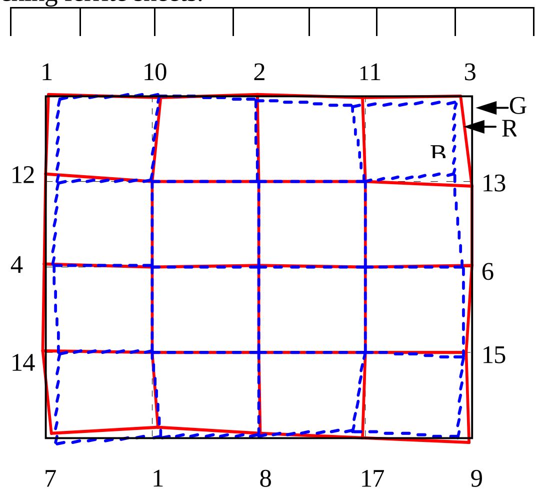
In the process of identifying misconvergence, white cross-hatch pattern (called raster) is displayed on the screen and sensing devices such as CCD cameras are used to evaluate the horizontal and vertical distances between the red, green and blue lines comprising a white line. Typical test pattern has five horizontal lines and five vertical lines, offering 25 cross points. In mass-production line, however, distances at 17 points are considered to be enough to describe whole misconvergence characteristics of a CDT. An example of raster and such 17 points are shown in Figure 2.

Misconvergence is usually characterized by six parameters for each point which represent the vertical and horizontal relative positions (in μm) of every beam pair: RGx, RGy, BGx, BGy, RBx and RBy. For example, RGx (or RGy) is the relative position of the red beam with respect to the green beam in horizontal (or vertical) axis. If this value is positive, the red beam is positioned at the right of (or above) the green beam. Other values are defined similarly. By measuring RGx, RGy, BGx and BGy, we can also obtain RBx and RBy from the relationship: $\mathrm{RBx} = \mathrm{RGx} - \mathrm{BGx}$ and $\mathrm{RBy} = \mathrm{RGy} - \mathrm{BGy}$. In short, the misconvergence can be characterized by a vector of 102 (=17×6) components, where every six values correspond to each control point (see Figure 2).

Since green beam is usually positioned between red and blue beams, sometimes only RBx and RBy are considered in the adjustment process (Chung *et al.,* 1995a; Chung *et al.,* 1995b; Song *et al.,* 1999; Verikas 2000). However, since that is not always the case actually, we consider all six parameters at each point throughout this study.

We determine that a DY satisfies convergence criteria if each parameter value lies within a restricted range. The required ranges differ depending on the measuring points. Points 2, 4, 5, 6 and 8 of axial region in Figure 2 are categorized as A zone, the rest of points are categorized as B zone. Data in A (or B) zone should have their absolute values not more than T_A (or T_B), where $T_A < T_B$.

We make one more comment about pre-processing. Three beams have different origins and directional vectors, and experience different magnetic fields, thus the sizes of cross-hatch patterns of three beams can be different from each other. If the difference of their sizes is significant, we cannot compensate misconvergence by attaching ferrite sheets and we need to attach a ferrite magnet bar to the rear part of DY. This study assumes that the pre-processing had been done and the misconvergence is minor so that it can be corrected by attaching ferrite sheets.



Point	RGx	RGy	BGx	BGy	RBx	RBy
1	54	13	215	-43	-161	56
2	-15	18	-23	-66	8	84
3	-144	-18	-217	-112	73	94
4	-14	32	134	8	-148	24
5	4	4	0	0	4	4
6	18	15	-105	-33	123	48
7	92	59	165	-93	-73	152
8	29	45	16	2	13	43
9	-38	-68	-160	0	122	-68
10	126	-25	118	-3	8	-22
11	-38	-23	-164	-148	126	125
12	1	84	185	-21	-184	105
13	2	-68	-234	73	236	-141
14	-23	16	209	-39	-232	55
15	-60	-2	-112	-80	52	78
16	80	123	148	-19	-68	142
17	20	-6	-158	76	138	-82

Figure 2. Raster and misconvergence representation at 17 points

2.2 Linearity of Misconvergence

Linearity property is stated as follows: change in misconvergence due to a ferrite sheet is independent of the current attachment of sheets. In other words, the vector of misconvergence change due to several sheets can be expressed as the sum of the vectors due to each sheet. Song *et al.* (1999) also defined the linearity and said that linearity held at the outer part of the surface of DY. But they did not present detailed test results. Verikas *et al.* (2000) used the linearity assumption without any tests. We may need sophisticated magnetic field models to verify this linearity assumption, which seems to be very difficult to obtain. Instead, we tried to verify it by experiments, which showed that we might assume the linearity property for practical purposes.

In our study, we tested linearity considering two sheets at a time. Theoretically, linearity for three or more sheets holds if linearity for two sheets holds. In the factory, rectangular sheets are used for compensation of misconvergence. Misconvergence change due to a rectangular sheet varies depending on its orientation as well as the location. Later, we test compensation of misconvergence with circular sheets in order not to consider the effect due to the orientation. But, in the test of linearity, we use both rectangular and circular sheets.

The location of a sheet to be attached to the inner part of DY can be expressed as polar coordinate (r, θ), where r represents the depth (radius from the center) and θ is the angle from positive x-axis (see Figure 3). Values of r vary from 1 to 7 as shown in the figure.

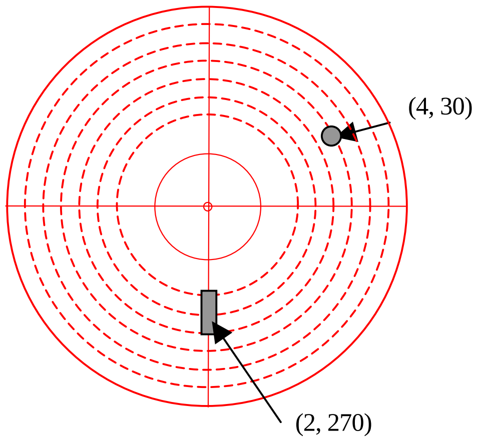


Figure 3. Coordinate to express location of sheets

We chose a set of four location pairs for rectangular sheets,

$$S(\theta,\phi):\ \{(2,\theta),(2,\phi)\},\{(2,\theta),(5,\phi)\},$$
$$\{(5,\theta),(2,\phi)\},\{(5,\theta),(5,\phi)\},$$

where θ, ϕ denote the angles of the two sheets in polar coordinate, respectively. We fix the orientation of the rectangular sheets so that they are aligned to point to the center of the DY as shown in Figure 3. We chose a set of two location pairs for circular sheets,

$$s(\theta,\phi):\ \{(2,\theta),(2,\phi)\},\{(4,\theta),(4,\phi)\}.$$

We considered 278 angle pairs in all for the test of linearity with the difference of them varying from 0 to 180.

To test linearity, we obtain the vector $x = y_1 + y_2 - z$, where y_1 and y_2 are vectors of misconvergence change due to each sheet and z is the vector in case that two sheets are attached together. We consider four parameters, RGx, RGy, BGx and BGy at the 17 measuring points, so these vectors have 68 components. We conclude that the linearity is satisfied for a location pair when we have at most one component of x whose absolute value exceeds 100 (μm). This threshold value was set because each component of the vector has measurement error up to $\pm 50\,\mu m$. The above criterion might seem rather subjective, but we acknowledged that it was acceptable since the absolute values of the components were not so large. After the test, we found that all location pairs satisfied the linearity criteria. As a matter of fact, our linearity test may not be complete since the number of location pairs is limited. However, we concluded that the test result was good enough to go further to the next process: modeling and test of misconvergence compensation.

3. MODELING

Using the linearity property, we can compute the vector of misconvergence change due to several ferrite sheets as the sum of the vectors due to each sheet. So, we consider an integer programming model to select the locations of sheets needed to compensate misconvergence among many candidate locations. We consider circular sheets of three sizes (they are classified as type 1, 2, and 3). Note that the locations of the sheets can be chosen over the continuous domain (inner part of DY), and with more locations, the model becomes more accurate. Here, we partitioned the inner part of the DY properly and selected a finite number of candidate locations for each sheet type (refer to the next section and Table 2).

The notation and decision variables used in the model are as follows.

N_k : Set of candidate locations for sheets of type k, $1 \le k \le l,\ l = 3$.

m : Size of misconvergence vector (or the number of parameters), $m = 102$.

x_j^k : 1 if a ferrite sheet of type k is attached to location $j \in N_k$ and 0, otherwise.

w : Vector of the misconvergence after the needed sheets are attached, $w = (w_1, w_2, \ldots, w_m)$.

a_j^k : Vector of the misconvergence change when a ferrite sheet of type k is attached to location $j \in N_k$, $a_j^k = (a_{1j}^k, a_{2j}^k, \ldots, a_{mj}^k)$.

b : Vector of the misconvergence for an empty DY, $b = (b_1, b_2, \ldots, b_m)$.

The mathematical formulation of the mixed integer programming (MIP) model can be stated as follows.

$$\text{Min} \quad \sum_{k=1}^{l} \sum_{j \in N_k} x_j^k \qquad (1)$$

subject to

$$w_i = \sum_{k=1}^{l} \sum_{j \in N_k} a_{ij}^k x_j^k + b_i \quad \text{for } 1 \le i \le m \qquad (2)$$

$$-T_A \le w_i \le T_A \quad \text{for } i \text{ in A zone} \qquad (3)$$

$$-T_B \le w_i \le T_B \quad \text{for } i \text{ in B zone} \qquad (4)$$

$$x_j^k \in \{0, 1\} \quad \text{for} \quad j \in N_k \quad \text{and} \quad 1 \le k \le l$$

The objective (1) is to minimize the number of ferrite sheets. Constraints (2) define decision variable w_i's. Constraints (3) and (4) state that components (parameters) of the misconvergence vector should satisfy the convergence criteria. Note that the variables w_i's have integer values in any feasible solution since both a_j^k and b are integer vectors.

Since we consider sheets of three sizes, we may obtain a solution such that two or three sheets of different sizes are attached to the same location. We did not test if the linearity property held in such a special case. However, since we assume that misconvergence is minor in this research as described in the previous section, possibility of such solutions appearing is very low. In fact, we obtained no such solutions in real implementation.

We may use the objective function, $\sum_{i=1}^{i=m} |w_i|$ (5) instead of the function (1) when near-zero misconvergence vector is definitely required. But, it may generate solutions requiring more ferrite sheets. Moreover, the time needed to find an optimal solution is expected to increase when using this objective function. We may consider two reasons for this phenomenon. First, the second objective function should be linearized to apply LP-based branch-and-bound algorithm. In this case, the number of variables remains the same by rewriting $w_i = \left| \sum_{k=1}^{l} \sum_{j \in N_k} a_{ij}^k x_j^k + b_i \right|$, but the number of constraints doubles itself as follows: $w_i \ge \sum_{k=1}^{l} \sum_{j \in N_k} a_{ij}^k x_j^k + b_i$ and $w_i \ge -\left(\sum_{k=1}^{l} \sum_{j \in N_k} a_{ij}^k x_j^k + b_i \right)$ for $1 \le i \le m$. Second, note that the optimal value of the problem with objective function (1) is integral. Hence, if $\bar{z}$ denotes the objective value of the current incumbent solution in the branch-and-bound tree, we can prune subproblems whose LP objective values are greater than $\bar{z}-1$. This can expedite the search procedure considerably since the optimal value is usually small (<10). However, we cannot expect this effect helps us much with the second objective function. We report computational results for these two objective functions in the next section. However, it should be noted that such near-zero misconvergence is not a main concern in the factory.

4. EXPERIMENTS

In this section, we describe how to obtain data of misconvergence change due to a single sheet and the procedure of finding locations of sheets to compensate misconvergence.

We consider three types of circular sheets with diameters of 6*mm*, 8*mm* and 10*mm*, respectively. In the factory, rectangular sheets are preferred since they provide more degree of freedom: location and orientation of a sheet. However, since attaching circular sheets requires only finding the accurate locations of sheets, they seem to be more suitable for the automatic attachment indication system.

4.1 Getting Data of Misconvergence Change

In order to get misconvergence change due to a single sheet, we place a sample DY without sheets at the measuring system and measure 102 parameters for misconvergence. Then we attach a sheet to one of the candidate locations of the DY and get the parameter values changed. Since the characteristics of DY's are identical for a model, we chose a sample DY to get data of misconvergence change.

Some parameter values (affected by a ferrite sheet) concerning misconvergence change becomes larger as the depth of the sheet location approaches to 1 and as larger sheet is used. If a parameter value changed is too large (200 μm or more) for a sheet attached to a certain location, the affected region is too wide and it causes unexpected side effects, which may require another sheet to compensate it. So we do not consider such sheet-location combinations here. Also, we do not consider some sheet-location combinations if all the values are too small (50 μm or less), which might come from measurement error. As a result, candidate locations in the first quadrant were selected as shown in Table 1. Using the geometrical symmetry of DY, we generated data for other quadrants by changing signs of them appropriately, and thus actually 370 sheet-location combinations were prepared.

Table 1. Candidate locations and sheet sizes used in the model

Angle	Diameter	Depth							Number
		1	2	3	4	5	6	7	
0	10	O	O	O	O	O	O	O	7
	8	O	O	O					3
10	10	O	O	O	O	O	O		6
	8	O	O	O	O	O			5
	6	O							1
20	10	O	O	O	O	O	O	O	7
	8	O	O	O	O	O	O		6
	6	O							1
25	10					O	O		2
30	10	O	O	O	O	O	O	O	7
	8	O	O	O	O	O	O		6
	6	O							1
35	10					O	O		2
40	10	O	O	O	O	O	O	O	7
	8	O	O	O	O	O	O		6
	6	O							1
45	10	O							1
50	10	O	O	O	O	O	O		6
	8	O	O	O	O	O			5
	6	O							1
60	10	O	O	O			O		4
	8	O	O	O					3
	6	O							1
70	10	O	O	O			O		4
	8	O	O						2
	6	O							1
80	8						O		1
90	8						O		1

It is very important to obtain accurate data of misconvergence change so that we obtain a realistic solution. We modified the data before it is used in the model as follows: 1) Since a parameter value changes slightly as time passes, we used the average after measuring it five times. 2) Some parameter values concerning the misconvergence change for the points far from the attached location are considered to be (or, almost near to) 0 but they are usually deviated from 0 a little in actual measurement. So we fixed them to 0. For example, when a ferrite sheet of size 10*mm* is attached at (1, 0), all the values of parameters at points except 3, 6, 9, 13 and 15 are set to 0.

4.2 Test of Misconvergence Compensation

We select a sample DY and read out misconvergence by placing it at the measuring system. If misconvergence occurs, we determine the types and locations of sheets to be used to compensate the misconvergence by solving the optimization model. If acceptable convergence cannot be accomplished after attaching the sheets, we repeat the procedure with the DY on hand without removing the attached sheets, which is another trial.

4.3 Results

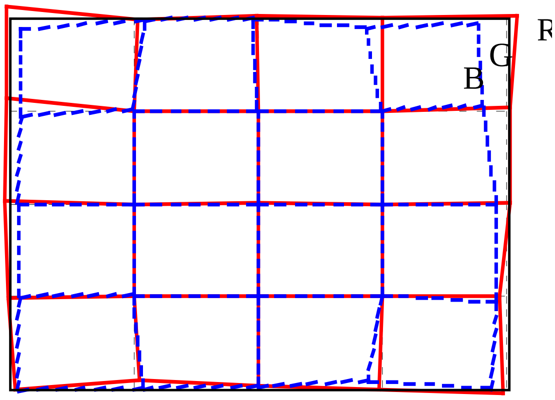
Total of 81 DY samples of a 19-inch CDT model taken from the production line were tested. Among them, five DYs satisfied convergence criteria initially, so they were excluded from the test. Thresholds in convergence criteria for A and B zones to meet the DY specifications are 200 μm and 300 μm , respectively.

As a result, we succeeded in adjusting convergence for 70 (93%) DYs within three trials. The numbers of successes were 59, 9 and 2 in the first, second and third trials, respectively. Thus we can conclude that two trials of adjustment are sufficient for most DYs. More than three trials, however, were not helpful. Figure 4 shows an example of convergence adjustment for a sample DY for which we succeeded at the first trial. We can see that the adjustment result (c) and the result of the algorithm (d) are almost identical.

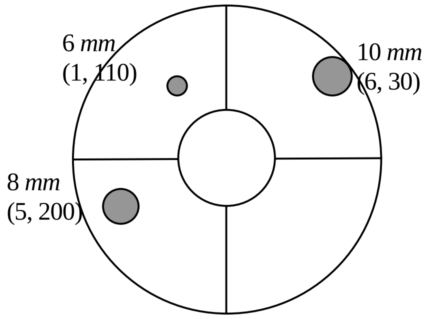
Among five DYs for which we failed to compensate misconvergence, three DYs were identified as inadequately prepared samples. The difference of sizes between the red and blue cross-hatch patterns was too big and could not be diminished enough by a single ferrite magnet bar (applying more than one bar is not recommended). For the rest of three DYs, we could not identify the reason of the adjustment failure. More research is needed for this problem. It is recommended that small number of DYs for which misconvergence could not be corrected by our algorithm should be delivered to skilled workers.

Table 2 compiles the data for the number of ferrite sheets used to correct misconvergence. Misconvergence was successfully corrected for 77% of DYs with no more than 4 sheets. On average, 3.2 sheets were used for misconvergence compensation, whereas workers in the factory usually use four or more sheets. About 80% of them were of 8*mm* and 10*mm* diameters.

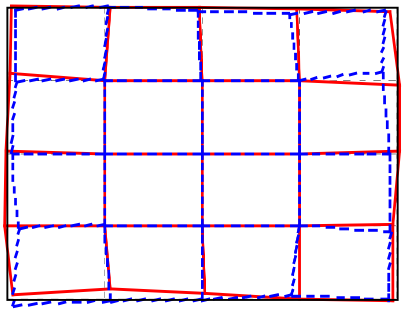
We used ILOG CPLEX^{TM} 6.5 to solve the optimization model. It took at most three seconds on



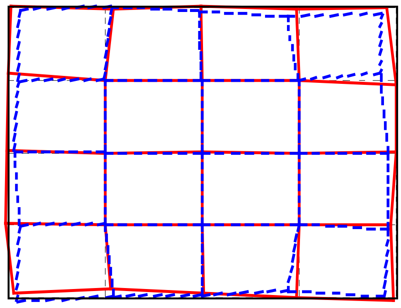
a) Empty DY sample



b) Attachment of sheets



(c) After adjustment



(d) Result obtained by the algorithm

Figure 4. An example of convergence adjustment

average to get an optimal solution for an adjustment trial on a Pentium III PC with clock speed of 500MHz. One may also develop his/her own package to solve the problem while not using commercial packages if desired.

Table 2. Compiled data for the number of ferrite sheets used

Number of sheets	Number of DY samples	Percentage	Accumulated percentage
1	14	20.0	20.0
2	12	17.1	37.1
3	16	22.9	60.0
4	12	17.1	77.1
5	7	10.0	87.1
6	6	8.6	95.7
7	2	2.9	98.6
8	1	1.4	100.0
Total	70	100.0	

We finally report a comparative tests for the two objective functions presented in section 3. Table 3 shows the results for eight DY samples: the objective values (and the number of sheets in case of the second objective function), the number of branch-and-bound nodes generated, and time in seconds. We limited the number of nodes to be generated up to 100,000. As we expected in section 3, the problem with the objective function (1) for the number of sheets yields much shorter times than the other function (5) for the sum of the absolute values of the expected misconvergence. Actually, we could not obtain optimal solutions for all test problems with this objective function within the node limit. Consequently, we can conclude that employing the alternative objective function is impractical in terms of the number of sheets as well as the running time.

We can consider another model that adopts the objective function (5) and also limits the number of attached sheets to a number N. This model may seem attractive but we prefer the first model introduced in section 3 for the following reasons: 1) the main objective should be to minimize the number of sheets since the adjust time is proportional to the number and 2) CDT is qualified as good if each parameter value is between the upper and lower limits. After the tests of the new model with $N = 3, 5,$ and 10 for the DYs in Table 3, we found that all DYs required N sheets and the running time mainly depended on the value of N. For example, setting $N = 5$ resulted in 20.6 seconds on average and it is well compared with 2.2 seconds for tests of the first model in Table 3.

Table 3. Comparative tests for the two objective functions

a) Objective function: $\sum_{k=1}^{l} \sum_{j \in N_k} x_j^k$ (1)

DY No.	Optimal values	No. of B&B nodes	Time (sec)
1	1	3	0
2	3	1,599	10
3	1	6	0
4	3	280	2
5	3	271	2
6	3	295	2
7	1	6	0
8	3	344	2

b) Objective function: $\sum_{i=1}^{i=m} |w_i|$ (5)

DY No.	Objective values	No. of Sheets	No. of B&B nodes	Time (sec)
1	4,476	15	100,000	633
2	4,974	19	100,000	689
3	4,196	16	100,000	613
4	5,226	20	100,000	701
5	5,084	17	100,000	564
6	5,176	14	100,000	523
7	4,832	15	100,000	662
8	4,752	16	100,000	717

5. CONCLUSIONS

We suggested and tested an optimization model for the adjustment of convergence on CDT and succeeded in adjusting for more than 90% of DY samples. It is noticeable that we did not use rule bases or fuzzy models as in the previous studies, which had not provided successful results.

The success seems to result from the following factors. First, the automated measuring system for DY developed recently was very useful in data acquisition process and the specially designed fixture for ferrite sheet attachment made the experiment easy to perform. Second, we could solve the optimization models in short times. The optimization model was designed to minimize the number of sheets instead of minimizing the misconvergence ($\sum |w_i|$). The time to get optimal solutions is much less with the first objective than the second. Moreover, with the second objective, we may need to use more sheets to correct misconvergence. Since error between expected misconvergence change due to a sheet and true one is accumulated as the number of sheets increases, final convergence performance predicted by the optimization model and the real performance may not coincide exactly.

When thresholds in convergence criteria become tighter, we may need more candidate locations where ferrite sheets can be attached. In our experiment, the time needed to obtain data of misconvergence change was about four hours for a DY model (in fact, the time is rather long and some approaches may need to be suggested to reduce it further). To use more candidate locations, we may need to estimate convergence changes for some locations while not measuring them directly. It may be possible by using neuro-fuzzy models (Chung *et al.*, 1995b) or regression models.

We expect that the guidance system developed in this research will be applied to real production line in order to increase efficiency of the convergence adjustment process and eventually, to increase productivity of color monitors.

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