Practical Example of a Coating Process Quality Improvement through Designed Experiments

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The objective of this paper is to show how coatings quality improvements may be achieved using experimental design. Designed experiments are an empirical approach to solving quality-related problems. We present a successfully designed experiment for improving the performance of a laminated fiber board coating process. The objective was to eliminate the aesthetic defects that sometimes appeared on the surface of decorative laminated fiber boards. Eleven parameters were tested for significance. A 32-run designed experiment was employed. Live tests were performed to identify the factor settings (the set points at which a factor is placed during the designed experiment) that allowed the elimination of nearly all visual defects.

INTRODUCTION

Competition has forced the furniture industry to develop a systematic approach for continuous improvement of the quality of their products and processes. Quality improvement cannot be based only on the will to improve. Because of the complexity of current processes, quality often depends on the simultaneous influence of several factors. In such cases, designed experiments are an effective tool to identify the important parameters and to estimate their effect.

Unfortunately, designed experiments have often been viewed as a complicated and costly method that should be reserved for research laboratories. Traditionally, the setting of a single factor was changed one at a time until the response was improved. This one-factor-at-a-time approach is inefficient because no measures of the interaction effects are available and the precision of the effect estimates is usually poor. This paper reports on a successfully designed experiment for quality improvement that was performed on a very complex process in the furniture industry. It illustrates both the strengths of a designed experimental approach and the complexity that is involved.

Background

The furniture industry has been involved in significant quality improvement efforts. A segment of the industry is based on medium density fiber (MDF) compressed chipboards to reduce costs. The boards consist of aggregated wood fibers, which are machined to obtain the required shape. They are subsequently coated using decorative papers that provide the appearance of different types of woods. The aesthetic aspect of the coated chipboard is crucial to satisfy customers.

Problem Definition

We report on how a small company in this industry succeeded in solving a problem related to the presence of streaks and areas that lost adhesion after the coating process stage. Examples of these problems are shown in *Figure* 1. This problem was believed to be due to the fact that when the MDF boards are stockpiled, they usually fill with moisture, and tend to expand. During the coating process, much of the moisture content evaporates so that they shrink, causing streaks and crinkles on the coated paper. Little knowledge of the coating process was available; the degree of complexity of the physical and chemical phenomena that are involved is such that no one was able to indicate how this problem could be solved. A consequence of this was substantial quality losses including customer returns, warranty claims, and product recalls. Some defects became visible several months after the products were shipped, depending on local climate conditions. More specifically, large fluctuations in the amount of moisture appeared to significantly impact the presence of unadhered areas. The visual defects often appeared during the dry season in continental climate areas. To address this problem, management employed a designed experiment.

A DESIGNED EXPERIMENTAL APPROACH

Designed experiments are often performed to optimize process or product performance as well as for knowledge acquisition purposes (e.g., studies on cause/effect relationship and mechanism). Recently, designed experiments for quality and reliability improvement have become popular among manufacturing engineers.[1]

Selection of the Response

The response is the measured output variable (the quality characteristic) taken during an experimental run. Quality and reliability are often expressed in terms of the proportion of defects and survival times. Binary responses such as acceptable/defective, surviving/failed, result in information losses; moreover, the distribution of these binary responses is not normal so that data transformations are usually required. To prevent this, it is preferable to use a continuous response. In this case study, however, it was not possible to use a continuous response. Typically, streaks or unadhered areas are counted and are classified according to the resulting aesthetic damage.

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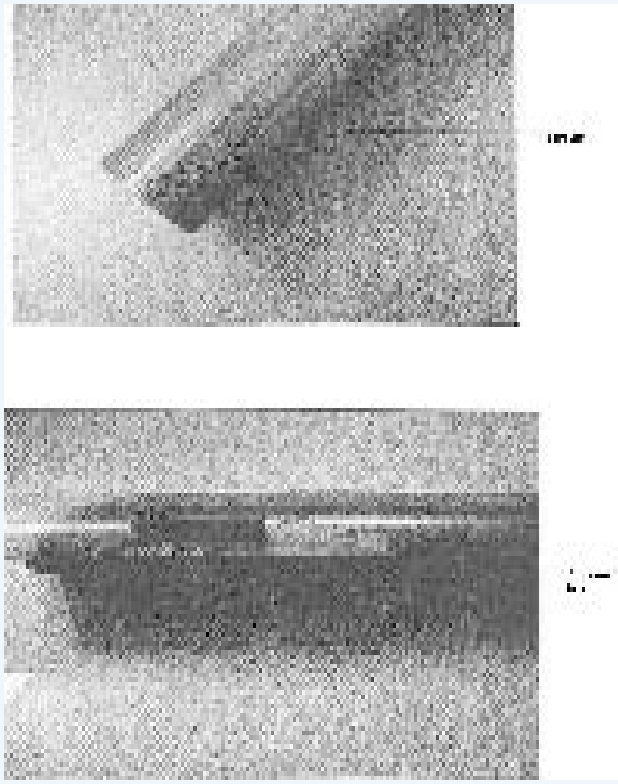

Figure 1—Examples of streaks (a) and adhesion loss (b) in coated MDF.

Taguchi's[2] accumulation analysis for studying the parameter design effects on different types of defects faces very serious practical limitations.[3] Instead, a simple scoring scheme, based on the seriousness of visual defects, was employed. A chamber test was available so that the visual defects were expected to appear very soon during the accelerated test phase, and the sample size did not need to be large.

Selection of the Orthogonal Array

An array is a table of rows and columns that is used to impose an order for efficient experimentation. The rows contain the individual experiments. The columns contain the experimental factors and their set points. A fractional array was used to reduce the number of runs, that is to say, all factor level combinations were not performed. Therefore, some effects are confounded with one another.

Two options were available: (1) a 16-run orthogonal design; and (2) a 32-run orthogonal design.

When a 16-run orthogonal design is used to study the effects of 11 factors and their interactions, some two-factor interactions are confounded with some main effect factors. The two factor interactions that have no influence on the response may be confounded without any risk with the main effect factors. Usually, however, it is difficult for the experimenter to accurately predict which interactions are likely not important. Misjudgement at this stage leads to misspecifications of real interactions and biases in some of the main effect factor estimates.

To prevent that, a 32-run design was performed, and the 11 factors were allocated to the array columns in such a way that the factor main effects would not be confounded with two factor interaction effects; however, two factor interactions were confounded with one another (resolution IV designs). Regate bed post profiles measuring 1.3 meters were selected for the experiments. The most important input in the experimental design process was provided by a team consisting of engineers and operating personnel. This team was responsible for choosing the right factors and for implementing the design. An essential step in the factor selection is constructing a cause and effect diagram illustrating all the parameters that may have an effect on the presence of defects. The objective was to distinguish between factors that have an actual effect and those factors whose apparent effect is only due to experimental errors. The "null" factors are adjusted to lower costs, and the "active"' factors are used to improve the results.

Choosing the potential causative factors and factor levels:

Amount of Adhesive: 70 to 80 g/m^2 are currently laid down on the decorative paper. To see if a change in the amount of adhesive has a real impact on the presence of visual defects, 50 g/m^2 of adhesive are laid down during half of the experimental runs and 100 g/m^2 during the other half.

Adhesive Temperature: The objective is to see if the adhesive fluidity has an impact on the coating adhesion. Below 180°C, the adhesive is not fluid enough to be properly laid down on the paper, above 195°C the adhesive is damaged. Therefore, the two chosen settings for adhesive temperature are 180°C and 195°C. These are the process specification limits.

Adhesive Supplier: An unloaded polyolefin adhesive was bought from one supplier. Half of the experiments are performed using an unloaded polyolefin adhesive from a lower-cost supplier, the other half using the adhesive from the original supplier.

Coating Process Speed: The paper may be bonded at either a fast speed or slower one. The velocity is modified depending on the type of profile to be coated. Two levels have been chosen: 25 m/s and 40 m/s speed.

MDF Supplier: One supplier sold long fiber resinous MDF boards, the other one short fiber folios MDF boards. These differences may have an impact on the bonding process.

Surface Treatment: The boards are untreated. Once they have been coated, the amount of moisture in the boards may vary depending on the environmental conditions, which may cause some parts of the paper to separate from the boards. Therefore, a polyurethane-based solution was used to waterproof the MDF boards before coating.

Amount of Zinc Stearate in the Adhesive: Three doses of zinc stearate are poured in each bag of adhesive to prevent the adhesive granules from aggregating, so that they may reach the injection point. However, if too much zinc stearate is added, it can perturb the bonding process. The two levels for this factor are five doses per bag (high level) or no dose at all (low level).

Paper Weight: Different types of papers are used. Thinner papers are lighter, whereas thicker papers are heavier. This difference may have an impact on the bonding process.

Base Paper Color: Many colors are used, however, it was noticed that the number of defects tends to increase when black base papers are bonded to the boards.

Paper Type: The two most common types of papers are the impregnated papers and the pre-impregnated ones. This difference in paper type may influence the performance of the bonding process.

Impregnated Papers: They are imported from Germany and Italy and weigh around 80 to 120 g/m^2. They are manufactured, printed, and then impregnated with resin. Up to 50% of their final weight is made up of resin. After the polymerization and drying stage, the paper is varnished.

Pre-Impregnated Papers: They are imported from Germany, and weigh around 60 to 110 g/m^2. They contain approximately 20% of resin. The resin is integrated during the manufacturing stage. Then, the papers are printed and varnished.

Roller Pressure: The chosen profile allows one to modify the amount of pressure, however, this is not possible for all profile types.

Allocation of the design parameters to the array columns :

Adhesive: The amount of adhesive (A in the array) was allocated to column 6 of a standard L32 orthogonal array. Temperature of the adhesive (B) was allocated to column 4; supplier (C) in column 3; and amount of zinc stearate (G) in column 16.

Chipboard Profile: Supplier (E) in column 15 and surface treatment (F) in column 18.

Paper: Paper weight (H) in column 25; paper color (factor I) in column 8; and type of paper (J) in column 23.

Coating Process: Process speed (D) in column 13 and roller pressure (K) in column 1.

For confidentiality, the suppliers are not specified in this paper. Three uncontrollable factors were also identified: (1) the amount of moisture in the MDF board, (2) the amount of moisture in the paper, and (3) roller wear. After the chipboards were dry, they were cut into five sections and then subjected to large temperature and moisture changes to accelerate the appearance of streaks. During each cycle in the test chamber, the temperature and moisture settings were changed three times. After each one of the six cycles, the defects were counted, and their degree of seriousness was assessed. Three weeks were required to complete the accelerated tests. Most defects appeared between the first and the second cycle. Much of the moisture amount was lost at that stage causing

Table 1

Degree of Visual Damage	Score
Area showing adhesion loss	1
Presence of a streak	2
Defect which is detectable only by touch	3
Defect which is visible only using a grazing light	3.5
No defect	4

Table 2—Scores

Run	Defect Score				Number of Cycles					Combined Scores					
1	1	1	2	1	1	7	4	4	4	4	7	4	8	4	4
2	1	1	1	1	1	2	1	2	1	1	2	1	2	1	1
3	1	1	1	1	1	1	1	1	2	1	1	1	1	2	1
4	2	2	2	2	2	2	2	2	5	2	4	4	4	10	4
5	2	2	2	2	2	2	2	2	2	4	4	4	4	4	8
6	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
7	1	1	1	1	1	2	1	1	1	2	2	1	1	1	2
8	2	3	2	3	2	2	2	4	3	3	4	6	8	9	6
9	1	1	1	2	1	2	1	1	2	6	2	1	1	4	6
10	2	2	2	2	2	2	2	2	3	3	4	4	4	6	6
11	2	2	2	2	2	3	7	7	3	6	6	14	14	6	12
12	1	1	1	1	1	2	3	3	2	1	2	3	3	2	1
13	1	1	1	1	1	1	1	4	4	2	1	1	4	4	2
14	2	2	2	2	2	3	3	5	2	2	6	6	10	4	4
15	2	2	2	2	2	2	3	4	2	7	4	6	8	4	14
16	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
17	1	2	1	2	2	5	3	5	2	4	5	6	5	4	8
18	2	3.5	3	4	3	7	4	4	7	4	14	14	12	28	12
19	2	2	2	2	2	5	6	6	4	6	10	12	12	8	12
20	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
21	1	1	2	1	1	2	2	2	2	2	2	2	4	2	2
22	2	2	2	2	2	2	2	2	3	3	4	4	4	6	6
23	3	2	3	2	3	3	6	3	7	3	9	12	9	14	9
24	1	1	1	1	1	2	2	2	2	1	2	2	2	2	1
25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
27	2	3	3	3	3	3	3	3	4	3	6	9	9	12	9
28	1	1	1	1	1	1	1	2	1	1	1	1	2	1	1
29	1	1	1	1	1	3	6	1	4	4	3	6	1	4	4
30	1	2	1	1	1	7	4	7	4	6	7	8	7	4	6
31	2	3	2	3	2	7	2	6	3	7	14	6	12	9	14
32	1	1	1	1	1	2	2	1	1	2	2	2	1	1	2

significant dimensional variations. The experiment was run in a split-plot way, i.e., some factors were more difficult to move than other ones. Therefore, the design array was set up in such a way that the number of level changes of the hard-to-change factors was minimized. The roller pressure factor was difficult to modify. Also, a change of the type of adhesive required a time lag of about 15 min. Therefore, for practical reasons, the runs were not set up in a random order; the aim was to reduce the number of level changes of the roller pressure and the type of adhesive factors.

Two responses were available: (1) seriousness of the aesthetic damage (see *Table* 1); and (2) number of cycles before a defect is visible.

The two responses were combined into one by multiplying them with one another. The five combined scores from each one of the 32 samples were then averaged. Some defects appeared immediately (cycle number 0), multiplying a defect score by zero would have resulted in biases. Therefore, the score was one when a defect appeared before the first cycle, two when it appeared after the first cycle, and so on (see *Table* 2). A higher score was clearly desirable.

These defect scores are designed to heavily penalize the presence of streaks or areas that lost adhesion. When large screening experiments are performed, the outcome is usually expected to be a "parsimonious model" (a model with few parameters). This is called the "effect sparsity" principle. All main effect factors were confounded with at least three-factor interactions. Because every two-factor interaction was confounded with several other two-factor interactions, it was difficult to identify which one among the aliased interaction effects was active and which one was not. Very often the active interactions are the ones in which active factors are involved (the so-called heredity principle). The reason for that is the following: suppose that we find that two factors significantly interact, whereas their individual effects are not significant. This would mean that the effect of one of these two factors is reversed when the other factor level is moved. In practice, however, such a situation is very unlikely to happen. Early results indicated that surface treatment had a major effect on the quality of the coated boards.

Since five samples were cut from each tested board, it was possible to estimate the within-board variance. Estimating the between-board variance was almost impossible because the experiments have not been repeated. Within-board variability is just a small component of all product variations.

Data Transformation

The averaged combined scores cannot be lower than one; therefore, the data were restricted on the lower side. When the boards were waterproofed, the combined scores were very low and quite close to the lower boundary (areas that lose adhesion often appear before the first cycle in the test chamber). In such situations, the effects of the other factors are difficult to assess since the results cannot be worsened by much. Therefore, the active factors have a very significant effect when the boards are not

Table 3—Design and Data

K	C	B	A	I	D	E	G	F	J	H	Data	Std	Transformed data
1	1	1	1	1	1	1	1	1	1	1	5.4	1.949	0.732
1	1	1	1	1	1	1	–1	–1	–1	–1	1.4	0.548	0.146
1	1	1	1	–1	–1	–1	1	1	1	–1	1.2	0.447	0.079
1	1	1	1	–1	–1	–1	–1	–1	–1	1	5.2	2.683	0.716
1	1	–1	–1	1	–1	–1	1	1	–1	1	4.8	1.789	0.681
1	1	–1	–1	1	–1	–1	–1	–1	1	–1	2.0	0.000	0.301
1	1	–1	–1	–1	1	1	1	1	–1	–1	1.4	0.548	0.146
1	1	–1	–1	–1	1	1	–1	–1	1	1	6.6	1.949	0.820
1	–1	1	1	1	1	1	1	–1	1	1	2.8	2.168	0.447
1	–1	1	1	1	1	1	–1	1	–1	–1	4.8	1.095	0.681
1	–1	1	1	–1	–1	–1	1	–1	1	–1	10.4	4.099	1.017
1	–1	1	1	–1	–1	–1	–1	1	–1	1	2.2	0.837	0.342
1	–1	–1	–1	1	–1	–1	1	–1	–1	1	2.4	1.517	0.380
1	–1	–1	–1	1	–1	–1	–1	1	1	–1	6.0	2.449	0.778
1	–1	–1	–1	–1	1	1	1	–1	–1	–1	7.2	4.147	0.857
1	–1	–1	–1	–1	1	1	–1	1	1	1	2.0	0.000	0.301
–1	–1	1	1	1	–1	–1	1	1	–1	–1	5.6	1.517	0.748
–1	–1	1	1	1	–1	–1	–1	–1	1	1	16.0	6.782	1.204
–1	–1	1	1	–1	1	1	1	1	–1	1	10.8	1.789	1.033
–1	–1	1	1	–1	1	1	–1	–1	1	–1	2.0	0.000	0.301
–1	–1	–1	–1	1	1	1	1	1	1	–1	2.4	0.894	0.380
–1	–1	–1	–1	1	1	1	–1	–1	–1	1	4.8	1.095	0.681
–1	–1	–1	–1	–1	–1	–1	1	1	1	1	10.6	2.302	1.025
–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	1.8	0.447	0.255
–1	1	1	1	1	–1	–1	1	–1	–1	–1	1.0	0.000	0.000
–1	1	1	1	1	–1	–1	–1	1	1	1	4.0	0.000	0.602
–1	1	1	1	–1	1	1	1	–1	–1	1	9.0	2.121	0.954
–1	1	1	1	–1	1	1	–1	1	1	–1	1.2	0.447	0.079
–1	1	–1	–1	1	1	1	1	–1	1	–1	3.6	1.817	0.556
–1	1	–1	–1	1	1	1	–1	1	–1	1	6.4	1.517	0.806
–1	1	–1	–1	–1	–1	–1	1	–1	1	1	11.0	3.464	1.041
–1	1	–1	–1	–1	–1	–1	–1	1	–1	–1	1.6	0.548	0.204

waterproofed; however, their effects are smaller when the boards are waterproofed, due to restrictions on one side. Consequently, a data transformation was necessary to cancel these spurious interaction effects. The standard deviation in each sample of five pieces of a single board was strongly dependent on the average combined score. The within-test variance was much smaller when the average was close to the lower limit and much larger when the average score was increased. Data heteroscedasticity (dependence of the variance on the mean) was clear evidence of the fact that a data transformation was required. The objective of the data transformation was to expand the area close to the lower limit to better assess the factor effects when the boards are waterproofed.

A plot of the logged within-board standard deviation versus the logged averages (see *Figure* 2) for the combined scores (employing 32 groups of five values) indicated that the linear coefficient of the regression, which describes the relationship between logged within-board standard deviations and logged averages, was 1.14. So, a logarithmic transformation was called for to simplify the final model and to eliminate the dependence of the within-board variance to the average value. The results of the design were not dramatically modified after the data were transformed. However, the effects of many hard-to-explain interactions were reduced.

ANALYSIS OF THE RESULTS FROM THE EXPERIMENTAL DESIGN

The effect estimates (see *Table* 3 and *Figure* 3) from the L32 orthogonal array appeared to indicate the following:

Main Factor Effect Estimates: Surface treatment had a very large impact on the coating quality. The experimenters believed that by waterproofing the board they could minimize the variations in the amount of moisture and, thereby, reduce the number of defects. This assumption proved to be wrong. It is preferable not to waterproof the boards. This was a welcomed conclusion as this would have increased the manufacturing costs. Other conclusions include:

- The amount of adhesive had a significant impact. A greater amount of adhesive improves the results.
- The adhesive supplier was the third most important factor. One of the suppliers (supplier 2) performed significantly better.
- Board supplier: Folio boards (short fibers) allow one to achieve better results than resinous boards (long fibers).
- Roller pressure: A higher pressure tended to improve the results.

Two-Factor Interaction Effect Estimates: During the preliminary meeting, the operators and engineers made a list of seven potentially important two-factor interactions. They expected these seven pre-specified two-factor interactions, out of the 55 possible interactions between the 11 factors, to be significant. However, in screening resolution IV designs, we found that the interactions that were expected to have a greater impact were not important, whereas unexpected interactions eventually turned out to be significant. An analysis of the largest contrasts was carried out to detect the important interactions.

Roller Pressure/Board Supplier Interaction: Roller pressure seemed to have a greater effect when the boards from the second supplier were used. Therefore, when a higher roller pressure is combined with the boards from supplier 2, the results are improved.

Surface Treatment/Base Paper Color Interaction: There seemed to be an interaction between base paper color and surface treatment (board waterproofing). Although base paper color had no significant effect by itself, when a non-black base paper was used, the effect of the surface treatment seemed to be increased. Therefore, it is better not to waterproof the boards and to use a base paper whose color is not black.

A larger roller pressure and a greater amount of adhesive increase the degree of adhesion of the MDF boards to the decorative papers. Further studies are required to study why the adhesive sold by one of the suppliers and the short fiber boards perform better. The experiments also confirm the fact that non-black base papers improve the degree of adhesion, which had already been noticed by the operators in normal production conditions. These results are valid only for the particular process under study. Moreover, since the tests were carried out in a small company and little scientific knowledge was available, improving the process was more important than understanding the complex

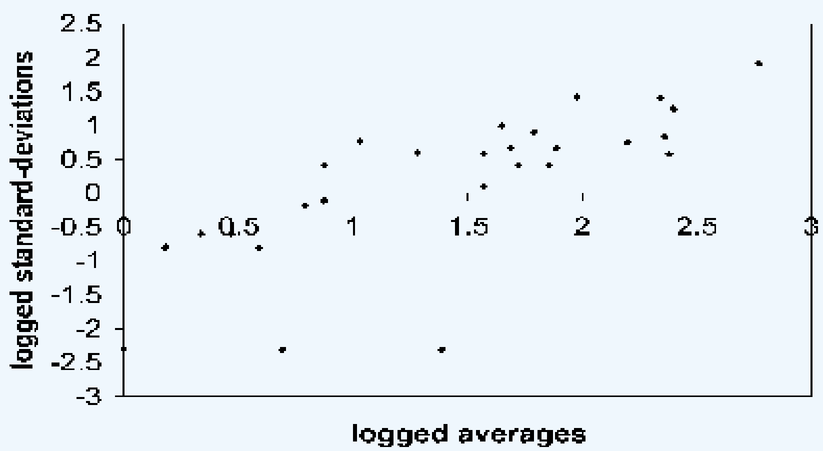

Figure 2—Plot of the logged within-board standard deviation vs. the logged averages.

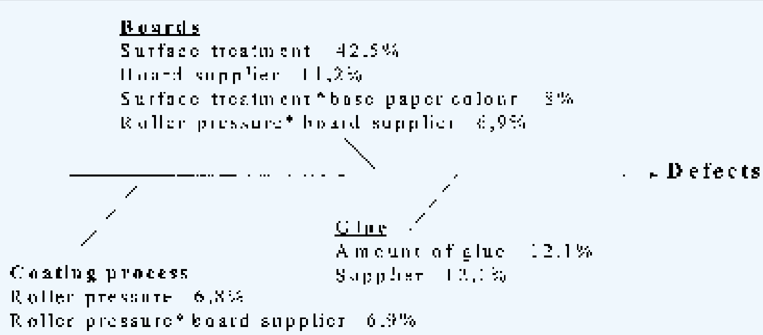

Figure 3—Active factors and interactions are their estimated effects in percentage of the sum of all significant effects.

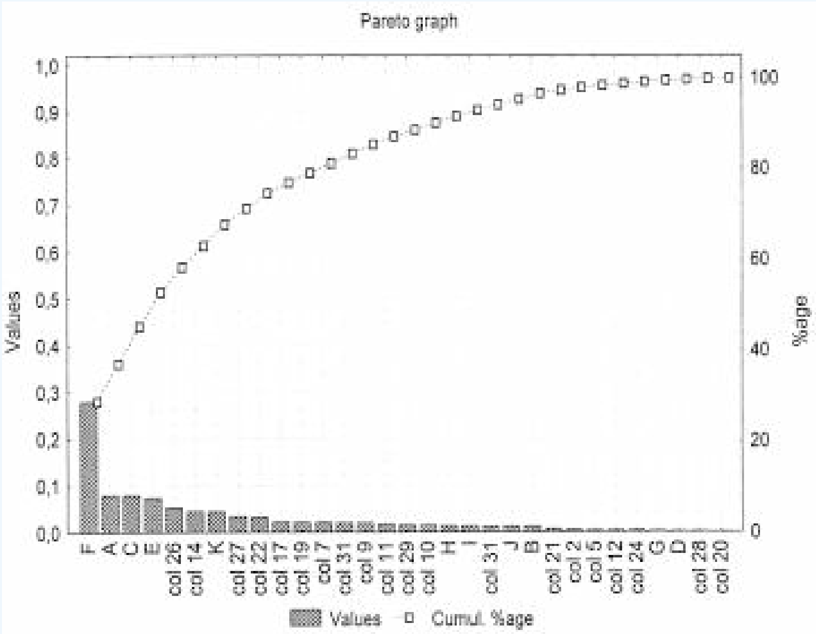

Figure 4—Pareto graph

Table 4—ANOVA Table

	Effects	SS	d.f	V	F
K	–0.045	0.002	1.000	0.002	5.307
col 2	0.006	0.000	1.000	0.000	—
C	–0.080	0.006	1.000	0.006	16.742
B	0.012	0.000	1.000	0.000	—
col 5	0.004	0.000	1.000	0.000	—
A	–0.080	0.006	1.000	0.006	16.485
col 7	0.021	0.000	1.000	0.000	—
I	0.013	0.000	1.000	0.000	—
col 9	0.020	0.000	1.000	0.000	—
col 10	0.015	0.000	1.000	0.000	—
col 11	–0.017	0.000	1.000	0.000	—
col 12	–0.004	0.000	1.000	0.000	—
D	–0.002	0.000	1.000	0.000	—
col 14	0.046	0.002	1.000	0.002	5.499
E	–0.074	0.005	1.000	0.005	14.168
G	0.003	0.000	1.000	0.000	—
col 17	0.022	0.001	1.000	0.001	—
F	0.280	0.078	1.000	0.078	203.922
col 19	–0.021	0.000	1.000	0.000	—
col 20	–0.001	0.000	1.000	0.000	—
col 21	–0.007	0.000	1.000	0.000	—
col 22	0.033	0.001	1.000	0.001	2.767
J	–0.012	0.000	1.000	0.000	—
col 24	0.004	0.000	1.000	0.000	—
H	–0.014	0.000	1.000	0.000	—
col 26	0.053	0.003	1.000	0.003	7.190
col 27	–0.034	0.001	1.000	0.001	3.002
col 28	–0.002	0.000	1.000	0.000	—
col 29	0.015	0.000	1.000	0.000	—
col 30	0.020	0.000	1.000	0.000	—
col 31	–0.012	0.000	1.000	0.000	—

physical and chemical phenomena that are involved. The process speed and paper weight do not have a significant impact on product quality. This allows a substantial productivity improvement by increasing the process speed and using more robust (heavier) papers that cannot be torn easily at a higher process speed. The degree of adhesive fluidity does not seem to have an effect on quality, therefore, the amount of zinc stearate and the temperature may be set in such a way that costs are reduced and process speed is increased. Also, it is not necessary to pre-impregnate the decorative papers, as this does not lead to better results.

Analysis of Variance

An analysis of variance (ANOVA) was performed (see *Table* 4). We were unsure as to whether or not the value of the effects (the contrasts) associated with column 22 and with column 27 of the L32 design was statistically significant. It was rather difficult to explain why the column 22 and 27 contrasts were so large. This could be due either to a three-factor interaction or to an interaction between two inert factors. These, of course, are unlikely events. The 22 remaining effects were pooled to estimate the residual variance. The critical value for the Fisher-Snedecor ratio ($F(1.22;0.05)$) is 4.3. Therefore, only the effects that were larger than 0.04 were considered to be active. The confidence limit beyond which an effect is considered to be active is 0.04. We chose a large confidence limit (95%) because the number of contrasts is relatively high. Had we selected a confidence limit of 90%, it is very likely that at least two inert contrasts would have been erroneously identified as being active.

The column 22 and 27 contrasts are smaller than 0.04. The effects of the surface treatment, board supplier, adhesive supplier, amount of adhesive, roller pressure factors, the surface treatment/base paper color (column 26 contrast), and roller pressure/board supplier (column 14 contrast) interactions were clearly statistically significant. These seven effects account for approximately 70% of all effects (see *Figure* 4).

The final model (y) is the following :

defect scores $= 0.571 + 0.28\, x_1 - 0.08\, x_2 - 0.08\, x_3 - 0.074\, x_4 - 0.045\, x_5 + 0.046\, x_4x_5 + 0.053\, x_1x_6$

with x_1 : surface treatment
x_2 : adhesive supplier
x_3 : amount of adhesive
x_4 : board supplier
x_5 : roller pressure
x_6 : base paper color

We have performed several x,y graphs for each variable from the 32-run data. For each active factor, a coefficient of correlation (r) has been calculated. The results are the following :

$r(x_1,y) = 0.84$ $r(x_2,y) = -0.2432$
$r(x_3,y) = -0.2404$ $r(x_4,y) = -0.222$
$r(x_5,y) = -0.1364$

The coefficients of correlation of x_2, x_3, x_4, and x_5 are rather small. Visually, from the x,y graphs, it was not easy to see that y was correlated with these variables (x_2, x_3, x_4 and x_5). One strength of the designed experimental approach is that it allows one to detect such relationships.

Follow-Up Experiment

An experiment was performed at the factor settings recommended after the initial design of experiment. The results were consistent with the conclusions drawn from the design of experiments.

Analysis of the Residuals

The residuals did not appear to be time related, therefore the fact that the tests were not run in a random order was not a cause for concern. Although eight runs were performed some days after the initial 24 runs had been carried out, this did not seem to have resulted in biases. The degree of moisture in the MDF boards was measured throughout the experimentation process. It did not appear to vary significantly.

SUMMARY

In the furniture industry, decorative papers are often bonded to fiber boards to reduce costs. In this case study, a designed experiment was employed to solve a quality-related problem in a coating process. The objective of this experiment was to eliminate the streaks that sometimes appeared after several months of use. Two responses were available: the defect scores and the number of cycles before a defect appears. Five factors and two interactions turned out to have a statistically significant effect. This study resulted in a substantial quality improvement. Most of all, it resulted in an increased understanding of this complex process. The degree of adhesion between the coating decorative papers and the MDF boards was significantly increased. The recommended levels were easy to implement. This factorial experiment showed the engineers and the firm management how efficient such an experimental approach may be.

Fortunately, this design was not only helpful in improving the furniture quality, it also allowed cost reductions. The adhesive from the second supplier was notably less expensive. Before the experiment, the engineers believed that the boards from the first supplier had to be used in order to achieve a higher degree of quality. The good results obtained with the boards from the second supplier came as a surprise. Waterproofing the boards would have resulted in a very large cost increase.

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