

Design of Experiments Techniques Solve Difficult Production Problem

Design of experiments objectives addressed critical performance specifications and profitability considerations.

By Frank J. Kenny

This case study shows how design of experiments (DOE) successfully fixed a major production problem. The case study addresses a thermal transfer coating product which was relocated to a new production site and a new coating line. Successful manufacture was not reproducible at the new site. DOE methodology was employed to solve the problem and identify optimal processing conditions. Use of this technique not only

Figure 1
Thermal Transfer Ribbon

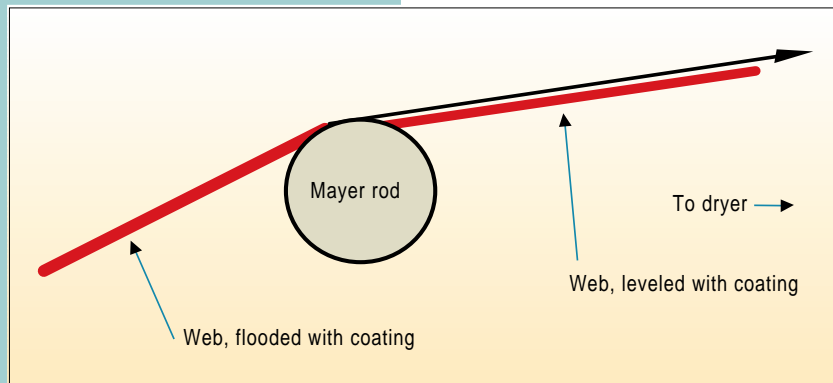
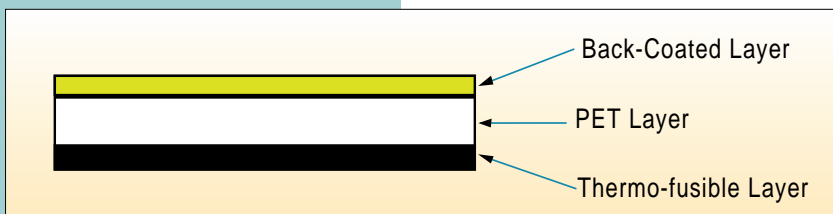


Figure 2
Mayer Rod Coating System

identified running conditions that exceeded specifications, but shattered certain myths about the product's runability and increased throughput by 33 percent. As a result, NCR expects to see double-digit growth in revenues from this product line.

Background

NCR Corporation (recently renamed after its trivestiture from AT&T) has created strategic business groups to focus on five key areas. One of these groups is NCR's Systemedia Group, which focuses on

information and transaction technologies. Systemedia is directly involved in the marketing, manufacture and distribution of products such as custom and stock paper rolls, ink ribbons, thermal transfer ribbons, business forms, laser forms, fax paper, thermal rolls, labels, label/form combinations and mailers — products, which take information and transform it into a printed image.

Thermal Transfer Ribbons (TTR) are typically used in bar code printers for consumer goods labeling and inventory control. The ribbon itself is typically composed of at least three layers: a protective back-coated layer, a PET layer, and a pigmented thermo-fusible layer (see Figure 1). When the ribbon is put into a TTR printer, a thermal printhead (a thin strip of resistive heating elements) melts the thermo-fusible layer and allows it to flow to a receiving substrate (typically a paper or synthetic label).

Manufacturing of TTR is a web-based converting operation. After the coating (typically a solvent/water-borne 30 percent solids mixture composed of resins, waxes and a pigment) is made, it must be applied to a 4.5 micron thick PET film. The coating is applied via a Mayer rod coater head (see Figure 2). The wet layer then passes through a two-zone forced-air dryer which evaporates the solvent or water vehicle. The dried, coated web is then wound up for later converting into smaller printer-size TTR rolls.

Specification Considerations

The final TTR product must have a Transparency above 6 percent at 900 nm, or the product may trigger an "out of media" error in most bar code printers. NCR transferred TTR production to a new production site which contained a new coating line. The product was not meeting the Transparency specification at the new production site using the new coating line.

The TTR product must also have a Residual Solvent of less than 2 percent. This second consideration historically affected the allowable line speed. It had been observed at the old production site that high residual solvent levels in the end product greatly reduced printing quality. Also, slow line speeds (typically 200 - 250 fpm) produced the fewest rejects in terms of residual solvent levels. This was a critical consideration, since slow line speed translates directly into decreased throughput and therefore decreased profitability.

Goals, Platform and Procedure

Due to the Transparency problem and the key considerations, the experiment goals at the new facility were:

1. Minimize Residual Solvent (target < 2 percent).
2. Maximize ribbon Transparency (target > 6 percent).
3. Identify maximum throughput for best product quality (target > 250 fpm).

The first two goals above addressed the critical performance-based product specifications. The third goal above addressed ultimate profitability. It required testing the prevailing wisdom regarding the upper limit imposed on line speed driven by the Residual Solvent specification.

The TTR coater has two dryers, each with independent temperature and air impingement controls (see Figure 3). Dryer inlet temperature is controlled via natural-gas fired heaters; air impingement is controlled by air dampers in supply ducts to each zone.

NCR knew that coater operating temperature and air impingement affected both Transparency and Residual Solvent. We also knew that the line speed interacted with temperature and air impingement.

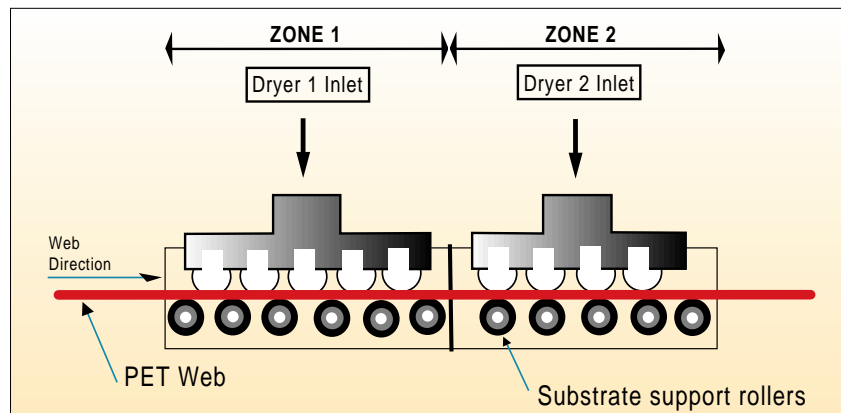


Figure 3: Coater schematic

| Experiment Variable | Low Level | High Level |
|------------------------------|-----------|------------|
| Line Speed (fpm) | 200 | 300 |
| Zone 1 Temperature (°F) | 200 | 260 |
| Zone 2 Temperature (°F) | 200 | 260 |
| Zone 1 Air Impingement (fps) | 1900 | 4900 |
| Zone 2 Air Impingement (fps) | 2200 | 4500 |

Table A: Experiment Variable List

| Independent Variable | Optimum level Setting |
|------------------------------|-----------------------|
| Line Speed (fpm) | 300 |
| Zone 1 Temperature (°F) | 260 |
| Zone 2 Temperature (°F) | 200 |
| Zone 1 Air Impingement (fps) | 1900 |
| Zone 2 Air Impingement (fps) | 2200 |

| Response Variable | Predicted Value |
|-------------------|-----------------|
| Transparency | 9.4 |

Table B: Optimziation Results

Therefore, the controllable study factors (independent experiment variables) that we chose and their respective ranges were:

For each experiment run we measured the Transparency and the Residual Solvent of the final TTR product. Transparency is measured using a Milton Roy Spectronic 21 at 900 nm. Residual Solvent is a weight by difference measure: a sample of the coated web is initially weighed, dried in a laboratory oven for 30 minutes, then reweighed. The Residual Solvent is the weight difference, expressed as a percent of the initial weight.

Experiment Design

To meet the experiment goals, NCR decided to use a Design Of Experiments (DOE) approach at the new facility. A

DOE approach was necessary for three important reasons. First, too much time would be required for a complete study using the historical one-variable-at-a-time experiment approach. Second, manipulating two or more experimental variables at a time in a successive-approximation approach can yield incremental improvement, but probably could not tell us what was best attainable performance or what were the optimum conditions for all goals. Third, the study variables were probably exhibiting both highly interactive effects and complex individual effects. Historical evidence suggested that the drying parameters were interrelated with respect to Residual Solvent and Transparency. For example, higher line speed coupled with lower temperature and lower air impingement (and therefore reduced heat transfer) would result in higher residual solvents and reduced product performance. The individual effects of the variables on both Residual Solvents and Transparency were not widely understood.

NCR used the CARD Design Of Experiments software by S-Matrix for the experiment design and the data analysis. CARD's Navigator Wizard guided us to a Screening design for our five variables that required 15 process runs. The design would enable us to quickly screen the experiment variables to determine (1) the strength of their individual and interactive effects within the experiment ranges, and (2) whether some combination of the variables

could provide a “fix” for the current problem. If the results showed us important opportunities, CARD could generate a next-cycle experiment that would enable us to efficiently build on the screening design.

Analysis and Discussion

In each of the 15 experiment runs, the Residual Solvent of the TTR product was below the specification upper limit of 2 percent. As a result, no data analysis was required for this response.

We used the CARD software program to analyze the Transparency data. The program’s ANALYSIS module automatically performs several interrelated analyses on the experiment data under one of two analysis modes: Automated or User Interactive. In the Automated mode CARD makes all the statistical “decisions” regarding the proper analysis settings and choices. In the User-Interactive mode, the Analysis Wizard sets up the analysis. The program then makes recommendations at each analysis decision point, but we can change the defaults if desired. CARD also creates a PlainTalk Report as part of the analysis output. The PlainTalk Report summarizes the key results of each analysis in plain English and includes specific recommendations on what to do next if further analysis is required.

We used the automated mode for the Transparency analysis and determined that the Transparency response was linear and did not have a relative or nonlinear measurement error. The report therefore defined that no transformation of the Transparency response data was required prior to regression analysis.

Proper DOE practice includes adding experimental error replicate run pairs to the design. A replicate is a run in which a set of experiment conditions is repeated at a different time during the course of the experiment. CARD’s 15-run design contained three replicate pairs. The program used the replicate run data to define the magnitude of overall experimental error. For the Transparency data the automated error analysis defined an overall (cumulative) experimental error of 0.10, with corresponding 95 percent confidence limits of 0.30. This is a very acceptable magnitude of error for the Transparency measurement. The report showed that the variation (run to run differences) in the Transparency data was larger than could be attributed to overall error alone, and analysis of the Transparency data was

therefore appropriate.

The experimental error was also automatically translated into regression analysis “targets” (numerical guidelines for data analysis). This additional analysis step is extremely important. Without targets the only regression analysis goal is a “perfect” model, i.e., one that perfectly re-predicts the observed test results for each experiment run. However, in regression analysis a perfect model can always be obtained by simply using a sufficiently large model. This is a common problem in regression analysis, usually with a disas-

multiple response optimization analysis defined the following results:

NCR carried out a verification production run at the optimum level settings. The TTR product obtained from this run had a Transparency of 9.2 and a Residual Solvents below 1.0.

We then used the final model in the GRAPHICS module to graph the variable effects in the area of the optimum level settings. An example 2D contour graph is shown in Figure 4. Contour graphs let us easily pinpoint optimum level settings within the plotted ranges of the variables.

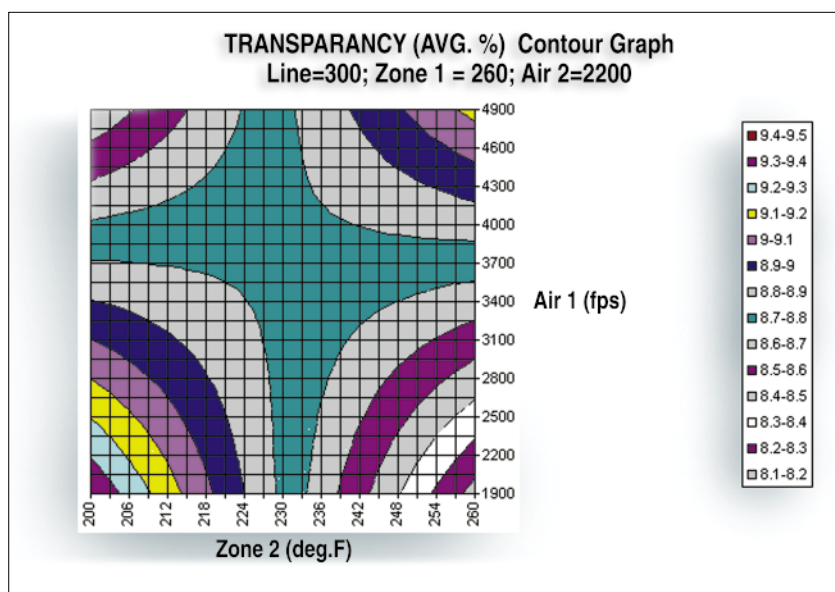


Figure 4: Transparency Contour Graph

trous side effect: the perfect model re-predicts the observed data perfectly, but fails miserably when used to predict results at untried settings. Also, given that experimental error is always greater than zero in the industrial world, we know we should get a less than perfect model. CARD’s targets tell us exactly how much less than perfect is an acceptable final model.

CARD performed an automated step-wise regression analysis on the Transparency data. The analysis yielded a model that met the analysis targets, and the report therefore defined it as an acceptable final model.

We then used this model in the program’s OPTIMIZATION module to identify the variable level settings which would meet or exceed all experiment goals. Using the Optimizer Wizard we set goals of maximizing the Transparency response while simultaneously achieving a line speed of at least 300 fpm. The mul-

The optimum point obtained from the multiple response optimization analysis corresponds to the lower left corner of the contour graph.

The 3D response surface graph corresponding to the 2D contour plot is shown in Figure 5 on page 4. Response surface graphs let us visualize the variable effects within the plotted ranges of the variables. The optimum point obtained from the multiple response optimization analysis corresponds to the left front corner of the response surface graph.

It is important to note the steepness of the response surface in the area of the optimum point. This means that the Transparency response is sensitive to fluctuations in both temperature and air impingement at the corresponding optimum level settings. However, the flatness of the response surface in the middle portion of the graph indicates that mean Transparency is much less sensitive to

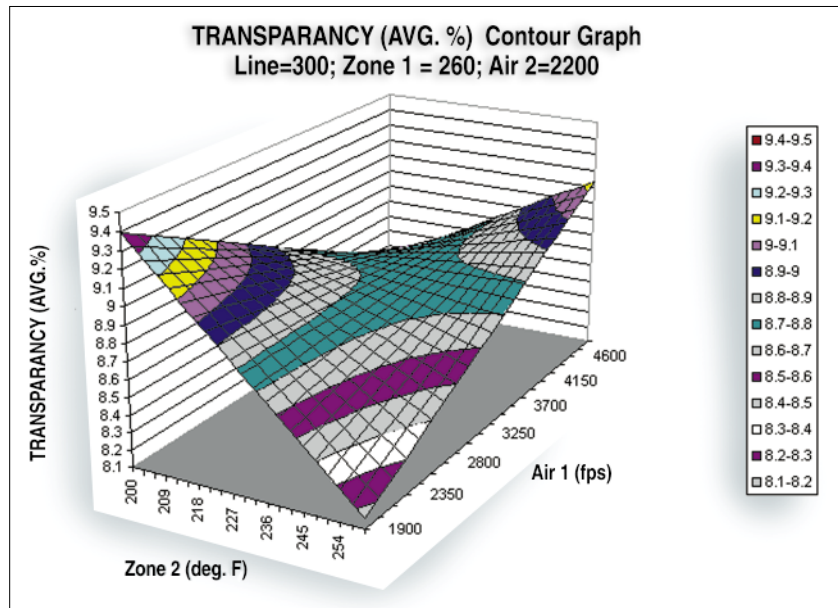


Figure 5: Transparency Response Surface

temperature and air impingement fluctuations in this region. Also, the height of the surface in this region corresponds to a mean Transparency of 8.7-8.8 percent,

which is well above the minimum specification limit of 6 percent. The graph therefore presents that changing the Zone 2 and Air 1 level settings to 230 °F and

3,700 fps, respectively, will safely improve the robustness of the process in terms of mean Transparency.

Conclusions

S-Matrix's CARD software program enabled NCR to efficiently apply Design Of Experiments methods in the plant environment. The DOE approach resulted in a speedy solution to a difficult production problem. Most importantly, the answer translated into a greater than 33 percent increase in productivity, which in turn yielded a double digit increase in profitability. This wholly unexpected result went against the conventional wisdom, and therefore may never have been achieved with a more conventional development approach.

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Companies mentioned in this article:

NCR Corporation - **Write in 329**
S-Matrix - **Write in 330**