Yield Improvement Efforts in Vinyl Siding Production

by

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Submitted to the Department of Mechanical Engineering and the Sloan School of Management in Partial Fulfillment of the requirements for the Degrees of:

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ABSTRACT

For this thesis, the research and experimentation was completed at ALCOA Building Products (ABP), in Denison, TX. This plant is a manufacturer of Vinyl Siding for the Home Construction and Remodeling markets. Due to anticipated volume growth and the competitiveness of the industry, maximizing the efficiency of the existing equipment is increasingly important. In line with this need, the overriding objective of the internship was to increase the yield rates for the manufacturing processes. The internship focused on three separate opportunities for improvement.

One approach to consider for improving process yield rates is tighter control of the raw materials. A section of this thesis discusses a production trial controlling resin particle size. Yield improvements averaging 2.3%, and approaching 10% for short runs, were achieved by using resin which was mechanically ground so it could pass through a 30-mesh screen. Annual savings exceeding $160,000 are predicted.

Another approach is to dynamically alter the process so as to adapt to the variation of the input materials. In the blending of PVC-based compound for extrusion, variation among different production lots of pigments influences the color of blended compound. One section of this thesis analyzes a model based on the Kubelka Munk equations for mixing opaque compounds. The model was intended as a means of predicting and compensating for the effect of pigment variation on the color of blended compound, but was found to be inadequate for this application.

Improved results can also come from reducing the variation of other process parameters, but which parameters should be given the most attention? The final portion of this thesis consists of designed experiments performed on the blending process for extrusion compound. These experiments determined the relative impact of various blending process parameters on the color of blended compound; pigment and TiO_2 levels were found to be the most critical. Future efforts at variation reduction can now be focused on these more significant parameters.

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I am grateful to the employees at ALCOA Building Products (ABP) for their support during my internship and for making my stay enjoyable. I am also grateful for the efforts of my MIT advisors, Dave Staelin and Vien Nguyen.

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My classmates in LFM also deserve some recognition. Not only have I learned tremendously from them during these two years, but they were kind enough to put up with me the same way I put up with them throughout the writing of all our theses.

Finally, and most importantly, I thank my soon to be wife Julie, and son Josh for sticking with me through it all.

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Chapter 1. Introduction

ALCOA Building Products (ABP) manufactures aluminum and vinyl siding, and window shutters for the home construction and remodeling markets. The company is a strong competitor in its markets, producing over 100 million pounds of aluminum siding products, over 300 million pounds of vinyl siding products, and almost 1.5 million pairs of shutters in 1994. The company has four manufacturing facilities:

1. Sidney, Ohio - this plant manufactures aluminum siding and accessories.
2. Princeville, Illinois - this plant manufactures vinyl siding and accessories for distribution through mass retailers such as Home Depot or Builder's Square.
3. Denison, Texas - this plant manufactures vinyl siding and accessories for distribution through wholesale chains.
4. Stuart's Draft, Virginia - this plant also manufactures vinyl siding and accessories for distribution through wholesale chains.

This thesis is the result of an internship spent within the vinyl siding sector of the business, working in the Central Engineering group in Denison, Texas. The focus of the work was on identifying and evaluating opportunities for improving production yield rates.

1.1 Terminology

There are many names and terms used in this thesis which may be unclear to readers unfamiliar with the business. For the reader's convenience, several of these are defined below, others are defined as they are used in the text.

1. Co-Extrusion - A process in which two extruders supply material to the same die. The melt from the extruders is combined in the die in a controlled manner to create two or more layers in the extruded product. The advantage

of this process for ABP is that only a thin layer of the more expensive material needs to be used on a panel and the other layer can be made from less expensive materials.

2. Topcap - the upper layer of the co-extruded panel which is the surface exposed when the panel is installed. It contains the pigments and materials critical to product color and weathering properties. The topcap layer on a panel has a nominal thickness of 0.006 inches.
3. Backply - The lower layer of the co-extruded panel. This layer is hidden from view and from exposure to weathering when the panel is installed. It does contribute greatly to the product's impact strength, but contains less pigments and very little weathering additives. The backply layer varies by product, ranging from 85-90 % of the panel thickness.
4. Microingredients - a general term for all additives other than the base resin (PVC or Geloy) and the stabilizer.
5. Salvage - Defective material produced by the extrusion process which has passed through the chill rollers and can be reground and processed again.
6. Scrap - Defective material produced by the extrusion process which cannot be reground. This typically refers to material that passed through the extruder but not the chill rollers. This material "wads" up in balls on the floor which cannot be processed by the grinders.
7. Spectrophotometer - This is a piece of test equipment used to measure the color of a sample. The machine generates a reflectance curve for the sample and uses this to calculate color coordinate values for the sample.
8. Brabender torque rheometer - This is a piece of test equipment used in preparing a test sample. The machine converts powder compound into a viscous, fused material which is then flattened into a pressout suitable for color testing.

1.2 Statement of the Problem

To remain competitive, ABP management recognizes the need to drive down manufacturing costs and to "do more with less." In response to this need, a Vinyl Steering Team was formed to initiate and direct activities for increasing asset utilization, product yield rates, interplant cooperation and coordination, and to define and pursue technological advances necessary for ABP to remain an industry leader

As part of the team, Scott Jacobsmeyer (LFM 94) saw an opportunity for an LFM intern to come to ABP to assist the Vinyl Steering team with their challenge. It was agreed that the focus for the internship would be on issues relating to production yields, both in determining those factors which currently limit yield rates and in looking for methods to overcome these limits.

1.3 Scope of the Project

After discussions with the Vinyl Steering Team and consideration of the timing constraints of the internship, three topics were chosen as the basis for this thesis: 1)Trial coordination and analysis for a proposed material change, 2) Analysis of a proposed model to reduce color variation, and 3) Studying the relative importance of the blending process variables. These efforts are independent of each other but they each fit into the common theme of pursuing yield improvements.

1.3.1 Geloy Trial

Concurrent with the beginning of the internship, the Central Engineering Group and the Denison plant engineers were just beginning to study the effect of Geloy particle size on yield rates. Geloy is a compound produced by GE Plastics which is used in the topcap layer of certain colored products. In most products, the topcap consists of a pure PVC base resin to which microingredients are added. These are referred to as "Rigid" products. However, some colors are more susceptible to weathering problems, such as fading. In these situations half of the PVC base resin is replaced with Geloy resin to provide increased weatherability. These are referred to as Geloy products.

There was a common feeling among this group that the variation in the Geloy particle size was influencing yield rates. Particularly, the presence of large particles is believed to make blended compound more susceptible to segregation during material transfer. Segregation is a phenomena in which a homogenous blend of material separates back into its various components. Additionally, experience indicates that the large particles of Geloy do not fuse at a rate comparable to the rest of the blend and that this results in high defect rates and more salvage material.

One of the areas of focus for the internship involved coordinating and analyzing a production trial to test this theory. Details of this study are presented in Chapter 4.

1.3.2 Analysis of Color Prediction Model

A second area of in-depth study during the internship involved researching the body of knowledge on color measurement and color mixing theory and applying this knowledge to the analysis of a color prediction model proposed to ABP by one of their suppliers. The purpose of this model was to reduce the negative impact of lot-to-lot pigment variation on the color of blended compound. A discussion of this research is in Chapter 5.

1.3.3 Blending Experiments

The final area of study for this project was experimental work to develop an understanding of the relative importance of various blending parameters to the color of blended compounds. This work was intended to highlight the major factors which contribute to the color of blended compounds, so that future efforts at variation reduction could be focused where they will yield the most benefit in terms of reducing the number off-color batches blended. This research is described in Chapter 6.

1.4 Significance of the Problems

The significance of these studies lies in their potential for cost savings as well as increased production flexibility. In the case of the Geloy trial, this material is approximately three to four times more expensive than PVC resin, so the cost of generating salvage material is more pronounced in Geloy products than in Rigid products. Any salvage material from the extrusion process (Geloy or Rigid) must be reground and either sold at a loss or reused as backply. Similarly, blending off-color batches of topcap compound results in material that must either be sold at a loss or used as backply material.

1.4.1 Selling at a Loss

If the material is sold outside the company, it has a market value of approximately \$0.20/lb for regrind material (this is salvage material from the extrusion process) and \$0.10/lb for blended compound (this has not gone through extrusion). In most topcap blends, the material cost, exclusive of the cost to process, is approximately \$0.50/lb. For Geloy products, the cost is closer to \$1.10/lb. Compound is typically blended in 1,000-lb batches, so the loss incurred from selling one batch ranges from \$400 to \$1000. Selling regrind results in a loss of between \$0.30 and \$0.90 for each pound of topcap sold, and \$0.20 per pound of backply sold as regrind.

1.4.2 Reusing as Backply Material

Preferable to selling it, the material may be used as backply, in which color tolerances are less stringent. However, even in this case ABP must use material costing \$0.50/lb (Rigid) or \$1.10/lb (Geloy) per pound when normal backply costs only about \$0.40/lb. This still results in a loss of \$100 to \$600 for each blended batch of topcap used as backply and \$0.10 (Rigid) to \$0.70 (Geloy) per pound for topcap reground and used as backply, excluding the cost to regrind.

Any progress towards reducing the amount of salvage produced or the number of off-color batches blended will not only reduce costs as described above, but will also increase the effective extrusion and blending capacity. The significance of capacity will increase in the coming years as ABP's growth strategy develops and they need more capacity than they currently have. ABP already faces capacity problems during their peak production times.

1.5 Organization of the Thesis

The remainder of this text is broken down into the following areas:

1. Chapter 2 contains the conclusions from each of the three areas of study.
2. Chapter 3 provides background on the product and manufacturing process for vinyl siding.
3. Chapter 4 is a discussion of the Geloy production trial.
4. Chapter 5 contains background material and the analysis of the proposed compensation model for pigment variation.
5. Chapter 6 is a discussion of the blending experiments conducted.

Chapter 2. Conclusions

The three areas of study each resulted in specific conclusions and recommendations; these are outlined in this chapter. Please refer to the respective chapters for the supporting analysis.

2.1 Geloy Production Trial

A trial was conducted in which Geloy resin was mechanically ground to restrict particle sizes such that all material was able to pass through a 30 mesh screen. The following was observed:

1. On average, a 2.3% increase in yield rates was observed.
2. On production runs of fewer than 100 cartons, the yield increase approaches 10%.

As a result of this trial, the company is currently implementing a change to restrict the particle size on all Geloy used in production. The change is expected to yield annual savings in excess of $168,000 as well as providing the flexibility to run shorter run lengths without suffering large yield penalties.

2.2 Analysis of Supplier's Model for Pigment Variation Compensation

In September of 1995, representatives of the Engelhard Corporation (a supplier of powder pigments) presented a model for predicting and compensating for the effects of lot-to-lot variation in their products.

Based on research of the theory behind color mixing, it has been shown that the assumptions used by this model are not sound from a theoretical viewpoint. Furthermore, the empirical data available thus far has demonstrated that the model is not capable of providing a level of accuracy which can justify its use.

2.3 Blending Experiments

A set of designed experiments was conducted to clarify the relative impact of several factors on the color of blended compound. These experiments led to the following conclusions:

1. Compound color variation is dominated by changes in TiO_2 and pigment levels.
2. Changes in blade speed have negligible effect on compound color.
3. Variation in resin inlet temperature has a negligible impact on compound color.
4. There is no advantage to metering in pigments slowly vs. the current method of charging as a lump mass.
5. The wide variation in dump temperature and microingredient addition temperature had negligible effect on compound color.

These results point toward control of pigment and TiO_2 levels as the best mechanism for reducing color variation. Currently great emphasis is placed on accurately weighing and charging pigments, but this is not true of TiO_2. It is recommended that methods for better TiO_2 control be pursued. An automatic weighing and dispensing system may be one such method, although further studies would be required to determine the cost and savings potential. The ergonomic benefits of an automatic weighing system should also be included in such studies.

Chapter 3. The Product And The Manufacturing Process

To aid in understanding the work and the results, a discussion of the product and manufacturing processes for vinyl siding follows.

3.1 Vinyl Siding

Vinyl (PVC) based siding has been used on home exteriors for well over 20 years, and at present it is produced in greater volumes than aluminum siding. As the market demand began to shift from aluminum to vinyl siding, ALCOA (through ABP) committed itself to becoming a major competitor in this growing field. Currently, ABP is the second largest supplier of vinyl siding in North America, with a 15% market share. The top player in the business is Certainteed, a division of St. Gobain. with a 23% market share.

The majority of ABP's business is in sales to wholesalers and distributors, who in turn sell the products to construction contractors. The remainder of vinyl siding sales are to lumber yards and retail stores. Currently, all of the retail production takes place in the smallest of the three plants, Princeville, Illinois.

The main characteristics which separate siding products are: 1) Color, 2) Surface Emboss Pattern, 3) Panel Thickness, and 4) Profile Design. By varying these attributes, the company is able to offer a wide product selection. ABP also sells a product with a thin film layer which provides exceptional weather resistance. This high-end siding comes with a life-time warranty, a service which no competitors currently provide.

3.2 ABP Production Processes

The manufacturing system for the vinyl siding plants can be broken into three main sections: 1) Batch Blending and Storing of Compound, 2) Co-Extrusion, and 3) Warehousing and Distribution. The functions are not identical from plant to plant, but they are similar. The following process descriptions are based on those from the Texas facility.

3.2.1 Batch Blending and Storing of Compound

There are several components that get blended together into a compound for extrusion. With the exception of the liquid stabilizer, all inputs are dry powders. The inputs are:

1. PVC resin - polyvinylchloride. This is the base resin to which other components are added.
2. Geloy resin - This is a compound used only in certain (darker) colors to provide additional protection against weathering. When used it replaces half of the PVC resin in the blend. This is only used in topcap compound.
3. Calcium Carbonate - This material is very low cost and is used as a filler material to lower total product costs.
4. Stabilizer - This is the only liquid component used in the blend. It is absorbed by the base resin and prevents PVC burning during extrusion.
5. Calcium Stearate - Adding this increases the friction during extrusion to promote melting.
6. Parrifin Wax - This is added as an external lubricant, providing lubrication between the powder and the equipment.
7. Polyethylene Wax - This is added as an internal lubricant, providing lubrication between molecules.
8. Impact Modifier - This is added to increase the impact strength of the siding.
9. Titanium Dioxide (TiO_2) - This is included as both a colorant (white) and for weathering properties.
10. Pigments - Various colored pigments are used to achieve the desired product color.

The blending of these components is produced in a high intensity, vertical mixer with the tip speed of the mixing blades exceeding 7,000 ft/min. The blend deck in Texas consists of three mixing stations: two of which blend 1100-pound batches of compound and a smaller one which blends 400-pound batches. The PVC and stabilizer are weighed automatically just prior to using, while all other components are pre-weighed manually and added at specific temperature points. A typical blending cycle is:

1. Charge blender with PVC and stabilizer.
2. At 150° F, add all remaining ingredients except TiO_2.
3. At 185° F, add TiO_2.
4. Continue mixing until the blend reaches 220° F, then discharge to the cooler.

The temperature used for triggering the cycle is the material temperature as measured by thermocouples inside the mixer. The heat source involved here is not a chemical reaction, but rather it is generated from friction and mechanical shearing in the material. The length of the blending cycle varies seasonally, ranging from 5 to 7 minutes.

Once the compound is blended, it must be cooled. This is achieved in a Horizontal Plow type cooler. While some mixing does occur in the cooler, its primary function is to lower the material temperature down to about 120° F. The cooler capacity is much greater than that of the mixer, allowing the hot material to tumble freely within the chamber. Each batch is slowly tumbled and the cooling comes from material contact with the walls of the vessel, which are chilled with cold water.

From the Cooler, each batch of compound is passed through a screener to remove any contaminants or oversize particles which could cause extrusion difficulties. Finally, after having been blended, cooled, and screened, the material is pneumatically pushed through transfer lines to the storage locations. With the exception of lower volume colors, the material is stored in large silos which may hold as many as 80 batches. Lower volume colors may be stored in small flow bins which hold only two batches at a time. Figure 3.1 illustrates the Batch Blending process just described.

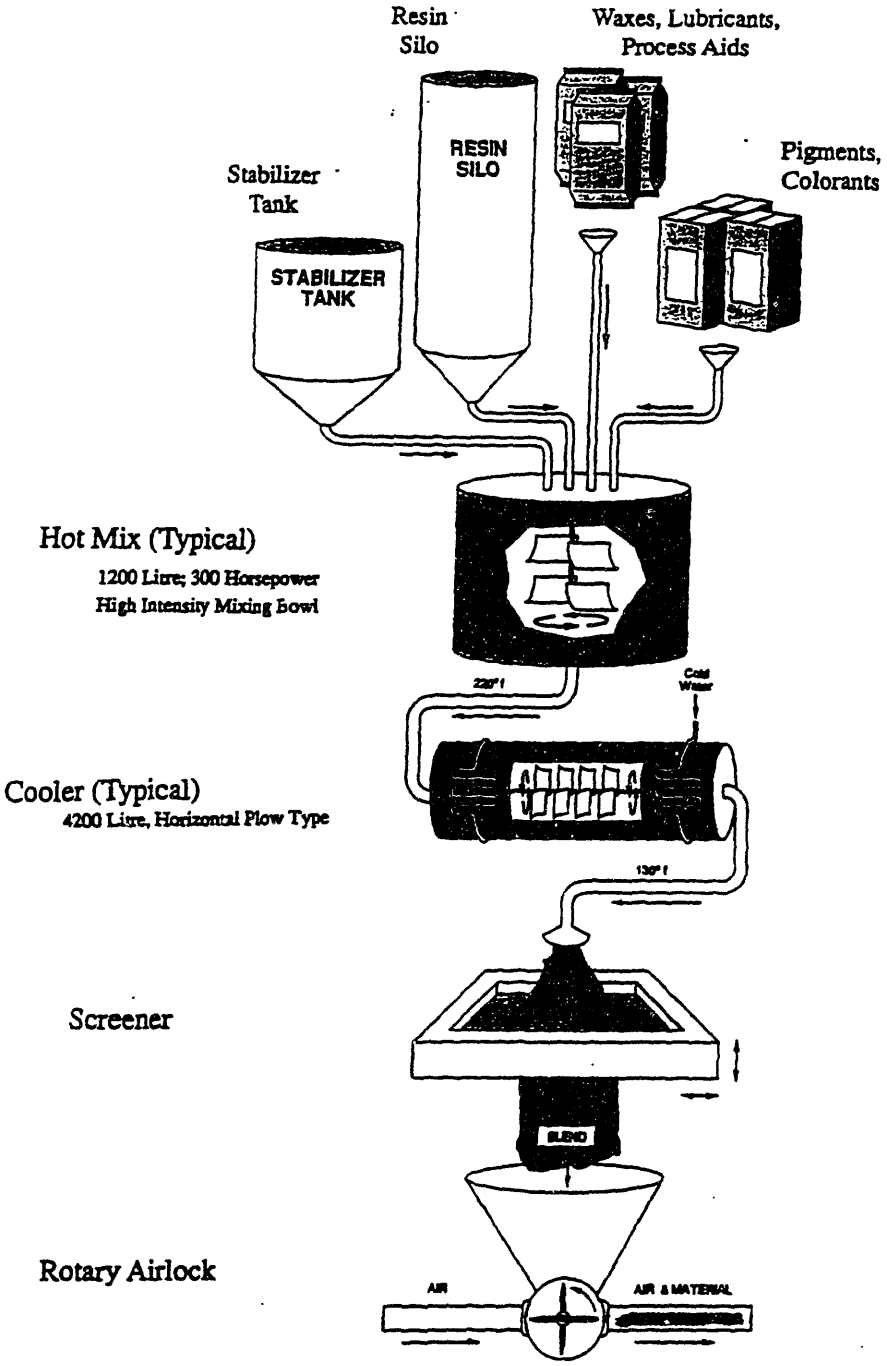

Figure 3.1 Batch Blending Process

3.2.2 Co-Extrusion

At an abstract level, the co-extrusion process converts the powder resin into siding panels. The siding actually consists of two layers, a topcap and a backply. The advantage of using co-extrusion instead of a mono-extrusion is that the expensive materials that provide coloring and weathering for the product are needed mainly near the surface of the panel. By producing two layers, one can use less expensive materials in the backply (which is 85 to 90% of the thickness) and reduce the overall panel cost. Figure 3.2 is a diagram of a typical extrusion line. The process is a continuous flow operation which can be broken down into the following functions:

1. Convert the powder resin to a melt and extrude as a two layer sheet.
2. Add an emboss pattern.
3. Form the flat sheet into a siding profile.
4. Cool the panel.
5. Punch nail slots for hanging.
6. Cut the extruded profile into 12 ft panels to be boxed.

The conversion of powder compound to a melt is achieved separately for the topcap layer and the backply layer. The backply compound is fed into the main extruder, which is a twin-screw machine. The extruder has two horizontal, co-rotating screws which cause the material to both mix and to travel along the extruder barrel. As the compound traverses, frictional heating causes it to transform to a viscous melt. By the time the melt exits the screws, it is at a temperature of 350 to 450 degrees Fareheit. The topcap material undergoes a similar process, but in the adjacent (or co) extruder. Upon leaving the screws, both the topcap and backply material are directed into the extrusion die. Each material follows its own flow path until entering the die cavity where they meet, with the topcap flowing on top of the other compound.

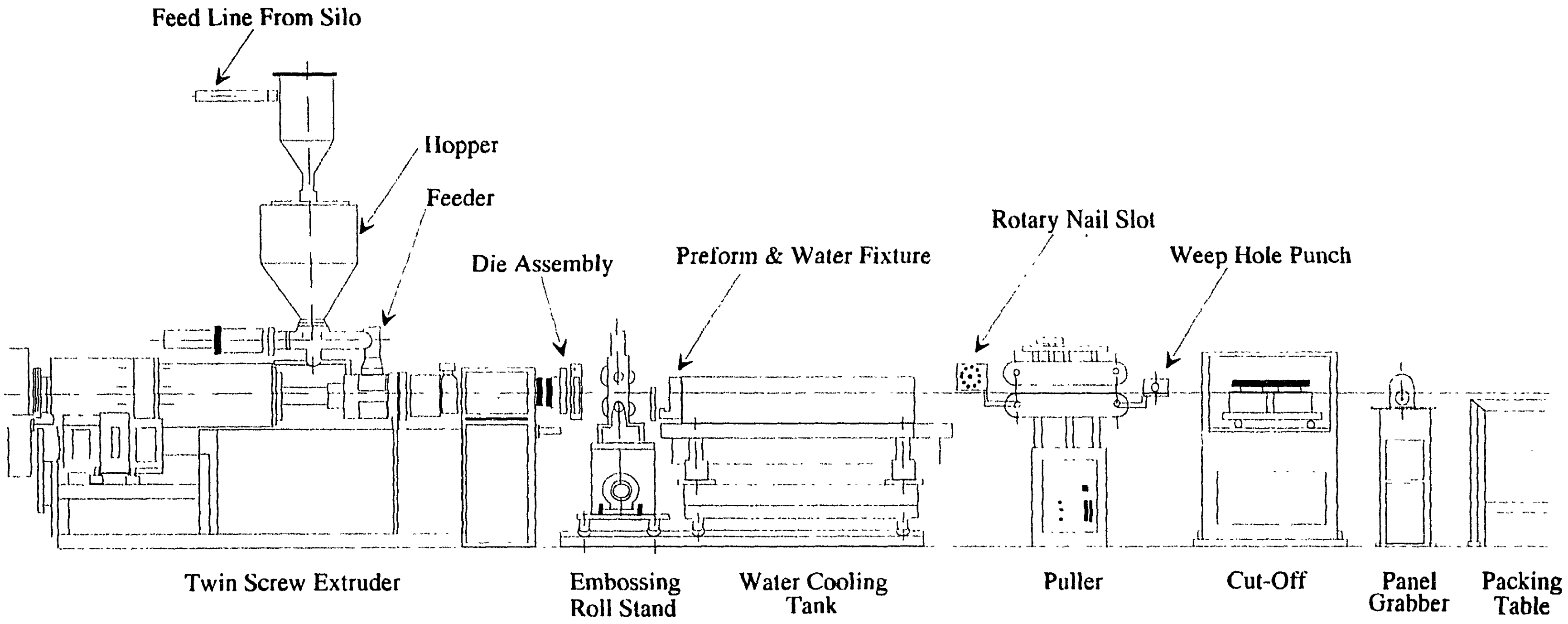

Figure 3.2 Coextrusion Process

This combined flow is then pushed through the die opening, or die lips, resulting in a two-layered, flat sheet. Because the main extruder runs at a much higher rate, around 1100-pounds per hour compared to a rate of 200-pounds per hour for the co-extruder, the main extruder provides more material to the die cavity, resulting in a sheet that is composed mostly of all backply. Immediately after leaving the extrusion die, the process switches from a push (driven by the extruders) to a pull system. The puller is located at the opposite end of the line, just before the cut-off machine, and it pulls the sheet through the rest of the line.

As Figure 3.2 shows, the flat sheet immediately goes through the set of rollers which presses an emboss pattern onto the top layer of the sheet. These rollers also begin to cool the hot sheet. After embossing, the flat sheet is pulled through a set of profile fixtures which give it the desired product profile. The siding then traverses through a cool water bath to complete the cooling process begun by the rollers. Upon leaving the bath, the siding is punched for nail slots, cut into discrete panels and then packed in boxes.

3.2.3 Warehousing and Distribution

The third section of the siding operation is the warehouse(s) and shipping. For a plant that produces as much as 380,000 pounds of siding a day, storage and distribution is a critical function. The company promises delivery of product within five days of order placement. To accomplish this, they build to a forecast, trying to keep enough material on hand to fill incoming orders on time. Because demand is very cyclical, the current strategy is to build up inventory during the slow season to be able to meet demand during peak times.

Chapter 4. The Geloy Trial

Coinciding with the start of the internship, the ABP Central Engineering group and the Denison Plant personnel were just beginning to undertake a study to quantify the effect of Geloy particle size on production yield rates. As this fit in well with the overall internship objectives, I became involved in the implementation and analysis for the study.

4.1 Background

Since 1988, ABP has been using Geloy as a major ingredient in certain topcap formulations. The material is manufactured by GE Plastics and is actually an ASA (Acrylate-styrene-acrylonitrile terpolymer) compound marketed under the Geloy name.

In formulations with Geloy, the material replaces approximately one-half of the rigid PVC base resin to provide increased weathering characteristics. It is used in darker colors which are more susceptible to weathering problems like fading. Currently, the siding colors using Geloy are Pebblestone Gray, Biscayne Blue, Mauve, and Musket Brown. These account for 17% of the total production volume.

The group's interest in focusing on Geloy, separate from Rigid products, stemmed from the higher cost and lower yields of products using Geloy. The cost of Geloy resin is currently three to four times greater than the cost of PVC resin. Since Geloy yields had historically been lower than Rigid PVC yields across all three vinyl plants, the group decided that an effort should be made to look specifically at Geloy products in addition to the other yield efforts being undertaken by the Vinyl Steering team.

4.2 Hypothesis

After discussions with manufacturing, engineering and R&D personnel, and reviewing available information, the group formed a theory that the Geloy particle size distribution was having a negative effect on yields. To test this theory, they decided to conduct a small trial in which the Geloy to be used must be able to pass through a 30 mesh screen. The 30 mesh screen was chosen as the upper limit on size because, during normal operation, the opening at the extruder die lips is 0.032 - 0.036 inches wide. The openings on a 30 mesh screen are approximately 0.033 inches wide, so the material should pass through this opening without sticking, even if some particles did not fuse properly. To meet this limit on Geloy particle size, GE had to send the material out to be mechanically ground as a secondary operation. Without this additional step, approximately 17% of the material would be above the 30 mesh limit.

4.3 Small Trial

The trial consisted of blending ten batches of PebbleStone Clay topcap using regular (unground) Geloy and ten batches using ground Geloy. Each set of ten batches was transferred and stored in a separate silo.

A single extrusion line was set aside for this trial. First, 12 hours of control material was run. Then, using the same set-up, the trial material was run for 12 hours. After the trial the results were compiled and analyzed. The areas where the group felt they might see differences were:

Topcap Distribution - The specification for topcap thickness on panels is six mils (0.006 inches). However, there is a problem with control of this thickness across the panel. There is a "crowning" effect such that the material is thicker in the middle of the panel than it is at the edges. Since the minimum allowable thickness is four mils, the coverage in the center is often as high as 9-11 mils thick just to get the edges above four.

Impact Strength - This quality characteristic is measured by dropping a weighted steel ball onto a panel. The measure of strength is a function of the panel thickness and the impact force the panel can withstand without cracking.

BB's, Scratches, Off-Color and Burnt Material - These are specific types of defects. A "BB" is a streak or line along the length of the panel in which there is no topcap coverage. BB's and Scratches are both caused by material which does not pass through the die lips, and subsequently blocks the opening. This material may be foreign debris or possibly unfused particles. Off-color material exceeds the allowable color tolerances as measured on the Hunter L,a,b scale[1]. The group felt that segregation may be one cause of this defect. Burnt material results from being overworked in the extruder.

Fixture Jams - This refers to a problem at the profile forming fixture. After the flat extruded sheet passes through the emboss rollers it should pass through a profile die which forms it into a siding profile. Failure to successfully pass through this fixture (e.g., tearing or buckling) is considered a jam.

Once the trial was complete it was apparent that there was insufficient data to draw sound conclusions. There were not enough defect occurrences in either 12-hour run to make a decision regarding the effect on extrusion yields.

On June 20th, 1995, a meeting was held with representatives from GE Plastics to discuss this trial and determine a plan of action. As a result of this meeting it was agreed that a much larger test be conducted to get enough data on the new material.

4.4 Large Trial

It was agreed that one month of production data should provide sufficient observations to conclude whether a yield change can be achieved by using ground Geloy. The first shipment of ground material arrived at the Denison plant on September 7th. At this time all non-blended Geloy that was in the plant was moved to an off-site location and the storage silos for Geloy topcap were emptied. The only exception was the color Musket Brown. This is a very small volume usage, so it was excluded entirely from the trial and the analysis. The remaining three Geloy colors: PebbleStone Clay, Biscayne Blue, and Mauve were studied in the trial.

When the storage silos were empty, the plant blended fresh compound with the trial Geloy. Production was scheduled and the material ran according to normal practices. As of October 3rd, 1995, the plant had manufactured 1.3 million pounds of

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[1] Refer to Chapter 5, section 5.3 for a discussion of the Hunter color mapping system.

Geloy based products with trial material. Following is a discussion of the results from this time period and a comparison with the prior month's production of Geloy products with standard (unground) material. Areas of interest were Overall Yield, Topcap Distribution, Impact Strength, Defects, and Cost Implications.

4.4.1 Overall Yield

The average yield for Geloy products increased 2.3% during the trial period. A one tailed t-test was performed which confirmed that, with 98.9% confidence, the yield results from the two periods are from different populations. Equally important is the fact that for these same periods, the yield on Rigid PVC products (non Geloy) was virtually unchanged, dropping only 0.05%. The source of the increase in Geloy yields did not affect the rigid yields, supporting the group's theory.

Examination of the relationship between yield rates and run length revealed an interesting observation. As Figure 4.1 shows, the yield rate for production runs of less than 100 cartons was almost 10% higher[2] with the ground Geloy material than with the

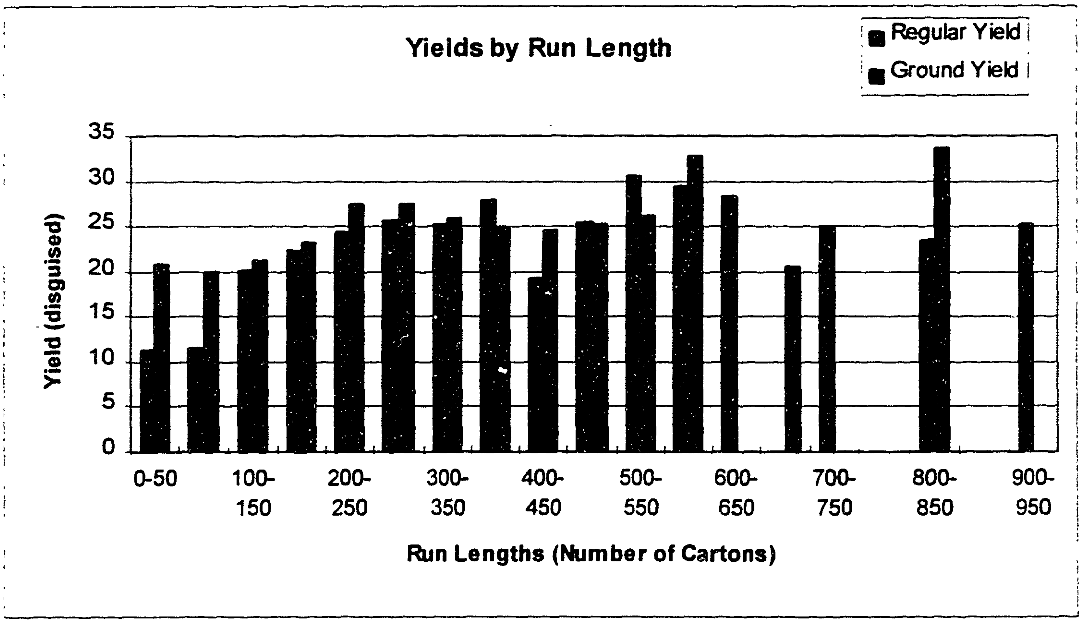

Figure 4.1 Geloy Yield Rate vs. Run Length

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[2] In the figure, all rates have been altered, but the relative differences shown are real.

August control material. While it can't be proven why this large increase was observed, one plausible explanation is that the process is stabilizing much faster with the trial material. This factor will have a significant impact in the future. As ABP increases their product diversity they will need the manufacturing flexibility to produce shorter runs without plummeting yield rates.[3]

4.4.2 Topcap Distribution

The crowned distribution of the topcap layer was described earlier. The cause of this problem is unknown, although efforts are in process to resolve this. Since it was expected that there would be a more consistent fusing of the material (no unfused particles in the die) this may have allowed for a more even flow of the topcap across the panel, reducing or eliminating the crowning problem. As can be seen from Figure 4.2, this was not the case. The trial material was subject to the same crowning pattern as the control material.

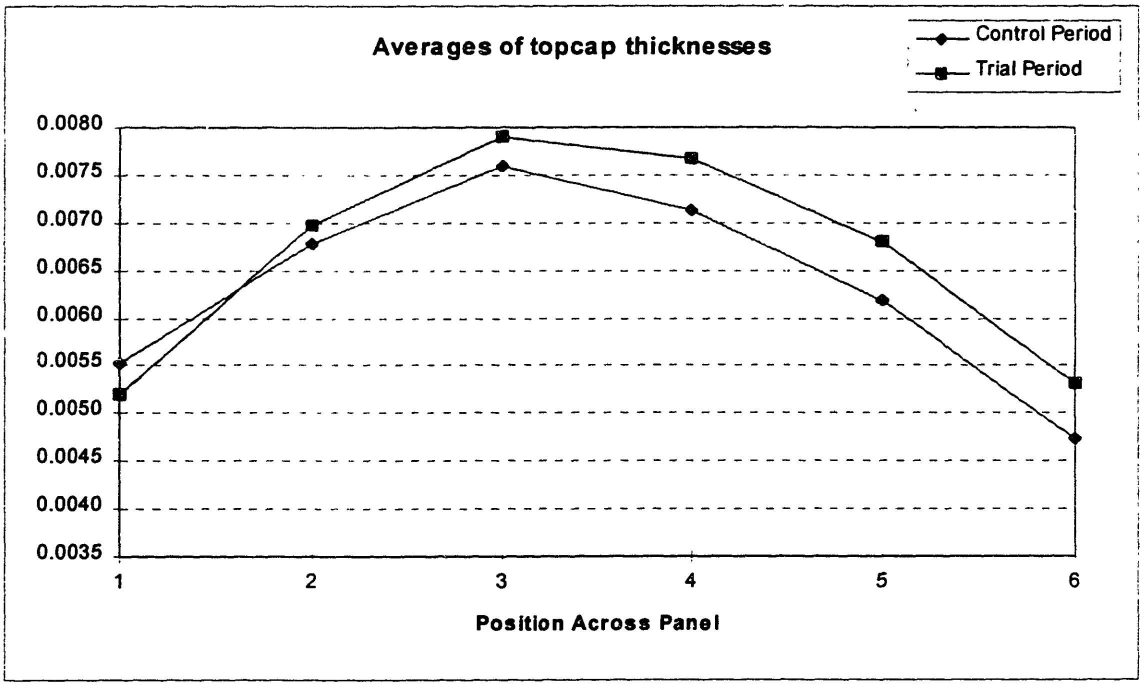

Figure 4.2 Distribution of Topcap Layer

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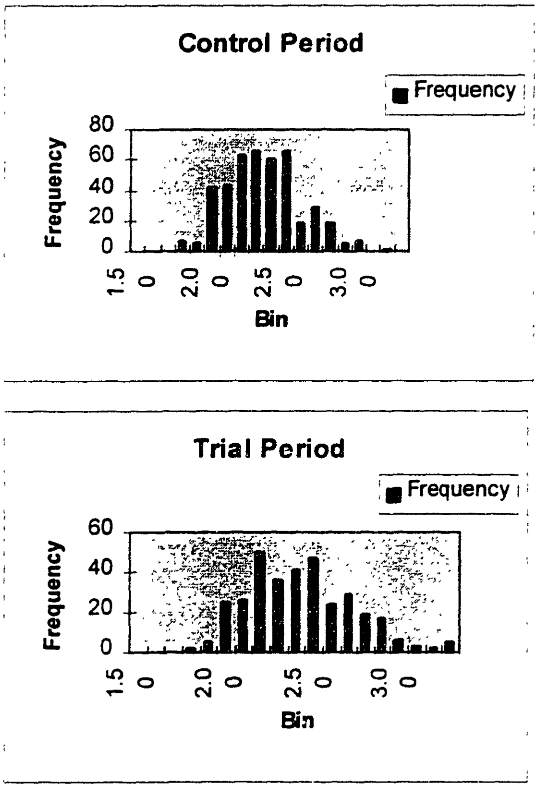
[3] ABP is introducing a new product line in 1996. In conjunction with this, the company wants to be able to implement shorter production runs.

4.4.3 Impact Strength

We were not anticipating much change in this characteristic. Since the backply layer is so much thicker than the topcap it tends to have the greatest influence on impact strength. Figure 4.3 shows that, as expected, there was no change in strength when using the trial material. Statistically, the 95% confidence interval for the control period impact strength is entirely contained within the confidence interval for the trial period.



Average Impact = 2.31, Std deviation = 0.25

Average Impact = 2.39, Std deviation = 0.30

Figure 4.3 Impact Strength During Control and Trial Periods

4.4.4 Defects

To gain a better understanding of why the yield rates were different between the two periods, a breakdown was made of the frequency of the different types of defects occurring. Some of the results of this breakdown are shown in Figure 4.4.

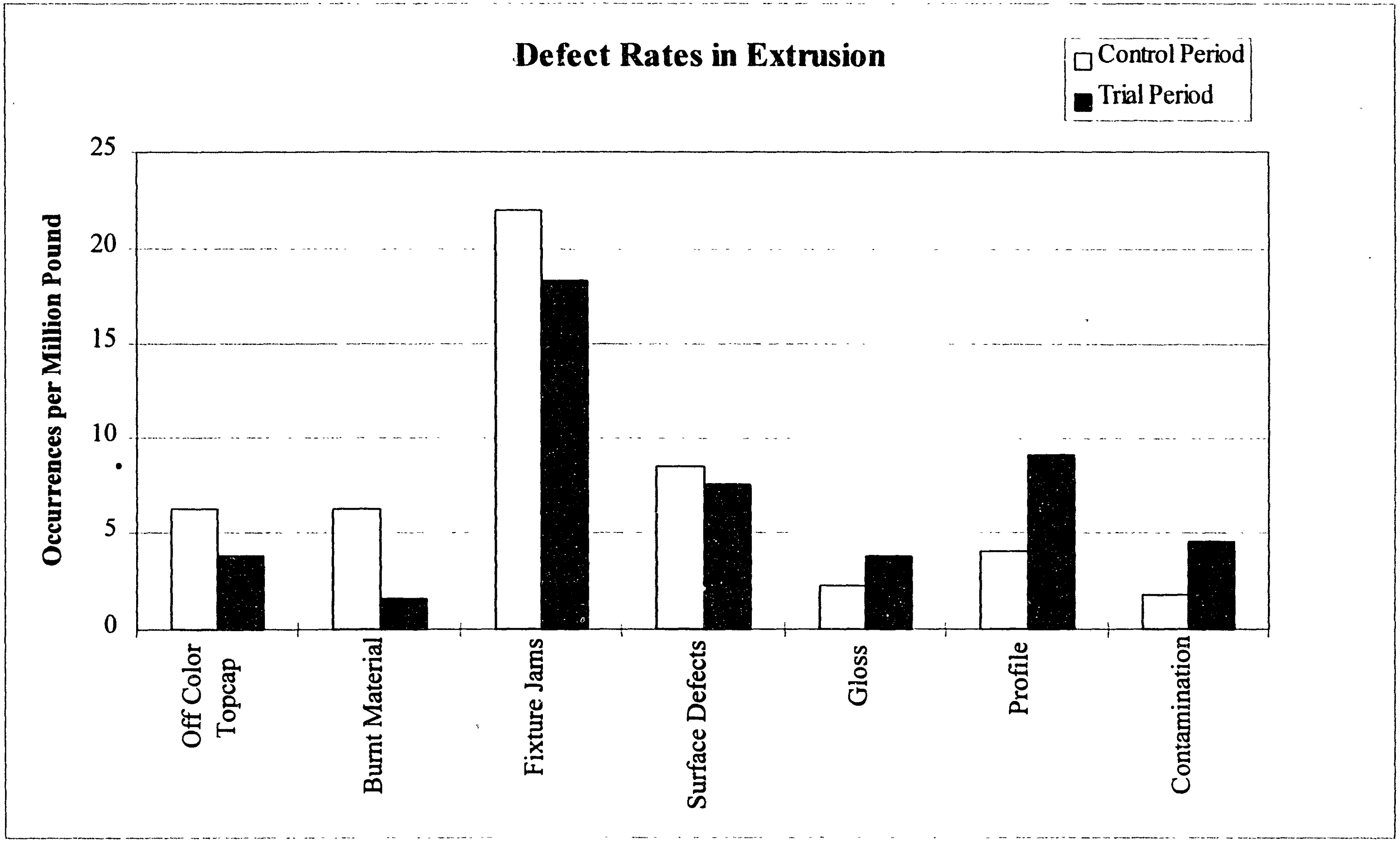


Figure 4.4 Defect Occurrences and Associated Downtime

From the table, we see reductions in the following relevant areas during the trial: 1)Off Color Topcap, 2) Burnt Material, 3) Fixture Jams, and 4) Surface Defects.

Of these, Off Color Topcap, Burnt Material and Surface Defects were expected to decrease according to the initial hypothesis. As the cause of fixture jams is unknown, we were unsure if there would be a change in this area, but it was encouraging to see an improvement. However, in changing from the control material to the trial production, there were increases in problem occurrences in the following areas: 1) Gloss, 2) Profile, and 3) Contamination in the Panel.

The increase in Gloss problems may be due to the fact that the operators are accustomed to running regular Geloy. Gloss is highly dependent on the coextruder temperatures, and if the ground material were fusing differently in the extruder it could alter the gloss characteristic. Similarly, there are fixtures in the waterbed which operators use to control the profile of the panels. Because the material warps upon cooling, creating what is called a bat-wing, operators induce a reverse bow so that upon cooling, the panel will straighten itself out. Since the ground material may have cooled differently, applying the same degree of compensation (reverse bow) as with regular material may not be appropriate.

While there is no evidence of the statistical significance of these specific changes, the data do provide some explanation of the causes of the total yield change, which has been shown to be statistically significant.

4.5 Cost Implications

As an effort to both improve the quality of their product and to promote additional demand, GE Plastics has agreed to supply all production material at particle sizes no greater than 30 mesh, and at no additional cost to ABP. GE is modifying the production process to include a grinding step for oversize material. An implementation date had not been set as of the end of the internship.

A cost model was developed to estimate the savings incurred from this change. The material savings were estimated from a pre-existing accounting model; energy and labor savings were estimated separately.

4.5.1 Accounting Cost Model

The accounting model can be manipulated to provide material savings estimates due to yield improvements, but it is limited by the following assumptions:

1. Labor is treated as a fixed cost - The time saved in generating, regrinding and handling salvage material is not claimed as savings.
2. There is no opportunity cost, or penalty for lost sales due to not producing at 100% yields.
3. Machine time/energy consumption is treated as a fixed cost.
4. All regrind material is assumed to be reprocessed, not sold.

The implication of these assumptions is that the only accounting savings recognized by an increase in production yields is material savings. These result from using less topcap material as backply after the regrinding operation. Since Geloy topcap costs much more than backply, a penalty is incurred for each pound of topcap reground into backply. The actual costs differ from product to product, since some topcap formulations are more costly than others; the cost model considers each product separately. Figure 4.4 is a schematic representation of the extrusion process used by the model.

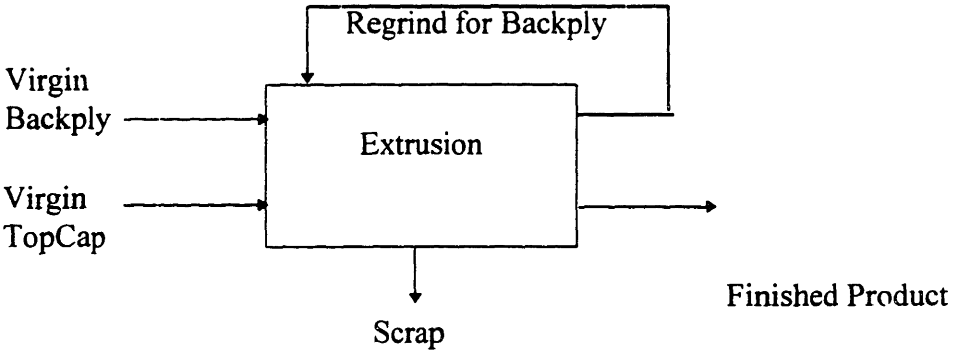


Figure 4.5 Model of Extrusion for Cost Accounting

Keep in mind that for every pound of siding that is reground, only a small portion is actually topcap material, the rest is backply for which there is no accounting penalty. The cost savings from a yield improvement is only the reduction in the amount of topcap recycled into backply, multiplied by the difference in cost between the topcap and the backply. For example, if a given product had a yield rate of 85%, and it experienced a 1% yield increase to 86%, the model determines the reduction in topcap material used as backply and calculates a savings per carton, based on this number.

As topcap formulas vary in cost, the savings per carton from a unit increase in yield will also vary by product. Material cost savings from a 1% yield increase were calculated for 27 (about 1/3) of the Geloy products. The per carton savings ranged from $0.09 to $0.17 for each 1% increase in yield rates, with an average of $0.117. Assuming this average as representative of the average for the entire Geloy product line, a 2.3% increase as seen in the trial will result in savings of:

$$\$0.117 \times 2.3 = \$0.269\,/\,carton$$

ABP consumes roughly three million pounds of Geloy a year[4], equating to 488,600 cartons/year[5]. Multiplying by the per carton savings, the total annual material savings from implementing the change is:

$0.269/carton × 488,600 cartons/year ~ **$130,734/year**

Recall that the effect of this change on shorter run lengths (less than 100 cartons) was closer to a 10% improvement. This provides savings of $1.17/carton, a significant factor since the company has expressed a desire to shift production to shorter run lengths.

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[4] Estimate based on companywide usage for first three quarters of 1995.

[5] The 27 products reviewed had an average of 6.14 pounds of Geloy per carton.

4.5.2 Energy and Labor Savings

In calculating both labor and energy savings, the following approximations were used:

1. Extruders operate at 1300 lb/hr (200 coex and 1100 main)
2. The average coextruder amp load is 30 amps.
3. The average main extruder amp load is 128 amps.
4. The average grinder (for regrinding salvage material) load is 100 amps.
5. A grinding machine processes 800 lb/hr.
6. A labor rate of $12/hr is applied.
7. The cost of electricity is the same at all three locations[6], $0.04621/KWHr
8. 39 million pounds of Geloy products made per year.
9. Material handlers can process 4,000 pounds of material into and out of grinding per hour.

4.5.2-1 Extrusion Savings

To determine the savings from the material change, electricity costs per pound of material must be calculated. Running on 480 volts, in one hour the Coextruder (@ 30amps) and Main extruder (@ 128 amps) consume 14.4 and 61.44 KW respectively, for a total of 75.84 KW/hr for each extrusion line. The cost to run the extrusion line per hour is:

$$1\text{Hr} \times 75\ \text{KW/Hr} \times \$0.04621/\text{KWHr} = \$3.4658/\text{Hr}$$

Running at 1300lb/hr, the electricity cost per pound is:

$$\$3.4658/\text{Hr} \times (1\text{Hr}/1300\text{lb}) = \$0.0027/\text{lb}$$

---

[6] Energy costs were estimated from the Denison plant's electric bills.

A 2.3% yield increase on 39 million pounds of finished products results in 897,000 fewer pounds of salvage produced. Thus, the electrical savings in extrusion are:

897,000 lb × $0.0027/lb ~ **$2,422 savings per year**

There is also a labor savings resulting from the yield increase. The time spent extruding salvage material will be reduced by:

897,000lb/(1300lb/Hr) = 690 Hours

Since extrusion requires one operator and one packer at $12/hr each, the labor savings in the extrusion department will be:

690 Hr × 2 people × $12/Hr/person ~ **$16,560 savings per year**

4.5.2-2 Grinding Savings

At 100 amps and 480 Volts, a grinder consumes 48KW in one hour. At a rate of 800 pounds per hour, the electrical cost to run a grinder is: Since 897,000 lb of salvage will be eliminated, this will eliminate:

1Hr × 48KW/Hr × $0.04621/KWHr = $2.22/Hr

resulting in a cost per pound of,

$2.22/Hr × (1Hr/800lb) = $0.00277/lb

and a yearly savings of,

$0.00277/lb × 897,000lb = **$2,487 savings per year**

The reduction in labor hours for grinding and material handling together are:

897,000 lb/(800lb/Hr) + 897,000lb/(4,000lb/Hr) = 1345 Hours

for a labor savings of,

1345 Hr × $12/Hr = **$16,140 savings per year**

Table 4.1 below summarizes the total savings from material, energy, and labor.

Savings Source:	**Annual Savings**
Implementation Cost:	($0)[7]
Material Savings	$130,734
Reduced Energy Consumption:	
Extrusion	$2,422
Grinding	$2,487
Reductions in Labor Hours:	
Extrusion	$16,560
Grinding & Mtl Handling	$16,140
Total Annual Savings:	**$168,343**

Table 4.1 Savings From a 2.3% yield improvement on Geloy Products.

4.6 Conclusion

The yield improvement demonstrated through this trial is representative of what can be expected in full production. In addition to the monetary savings described above, the large improvement evident in production runs of fewer than 100 cartons supports the company's plans to reduce run lengths and increase the number of products offered.

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[7] The supplier has agreed to absorb the cost of grinding the raw Geloy.

Chapter 5. Analysis of a Supplier's Model for Pigment Variation Compensation

5.1 Introduction to the Problem

On September 27, 1995, representatives of the EngelHard Corporation (a supplier of powder pigments), presented the results of some modeling work they had done for ABP. One of the areas of their work involved a predictive method for compensating the lot-to-lot variation of incoming pigment properties, as measured on the Hunter L,a,b color scale.

The employees of ABP are experts at the extrusion process, but they are not experts on color theory. As such, the level of comprehension of the EngelHard presentation was insufficient to understand the model. To aid the ABP group, I undertook a study of color measurement and the theory behind color mixing, both of which are needed to interpret the proposed model.

Sections one through seven of this chapter are intended to provide the background needed to analyze the model. Sections eight through ten present and analyze the proposed model.

5.2 The Inputs for Color Measurement

Before one can attempt to compensate for pigment variation, it is first necessary to understand how color is measured. Perceived color is a function of three inputs: the object, the viewer (man or machine), and the illuminating source. The same object may impart a different color to two different people, or it may appear different to the same person when viewed under a fluorescent light than if viewed under sunlight.

To deal with these differences, several standards have been developed over the years to put constraints on the inputs. An organization called the International Commission on Illumination (CIE) is the main force behind the development of such standards.

5.2.1 Illuminant

To remove variability of the illuminant source, CIE specified standard illuminants for use in color testing. Illuminants are quantified by their spectral power distribution curves. This curve is a plot of the relative amount of light emitted by the source at each wavelength along the visible region. The illuminant most commonly used to simulate normal daylight is called a D_{65} illuminant; its power curve is illustrated in Figure 5.1.

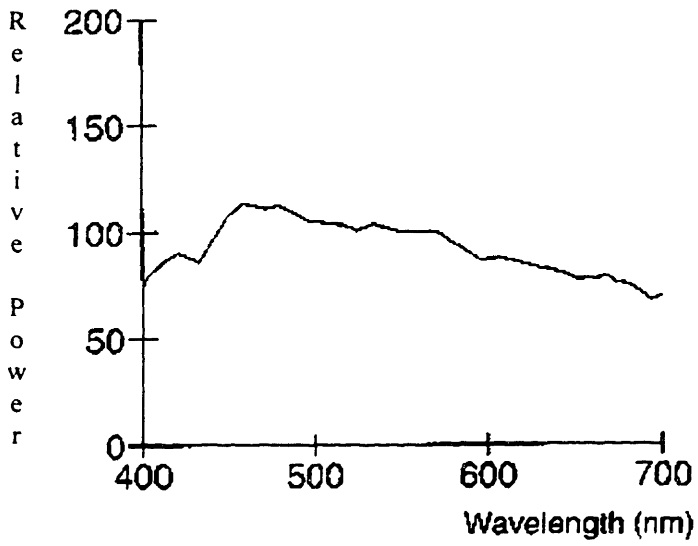

Figure 5.1 Power Curve of a D_{65} Illuminant Source

5.2.2 Observer

To remove observer variability from color measurement, CIE also defined a "standard observer", whose color vision is representative of the average person having normal color vision. This standard observer is defined by the color matching functions $\bar{x},\bar{y},\bar{z}$.

The development of the color matching functions was based on determining how to combine the three primary colors: red, green, and blue, to match a desired color. Red, green and blue lights were combined in varying intensities to achieve color matches with lights of different wavelengths along the visible spectrum. CIE conducted experiments with several people to obtain average intensity values for red, green and blue to match each of the desired wavelength lights. These intensity values are the tristimulus matching functions and are designated as $\bar{x},\bar{y},\bar{z}$. The $\bar{x}$ corresponds to the amount of Red, $\bar{y}$ to the amount of Green, and $\bar{z}$ to the amount of Blue needed to match the light at any given wavelength. For example, the $\bar{x},\bar{y},\bar{z}$ values for light with a wavelength of 500nm are 0.0049, 0.3230, and 0.2720 respectively. This means that if an average person were to combine 0.0049 units of red light, 0.323 units of green light, and 0.272 units of blue light, the resulting color would be the same as that of 500nm light waves.

The color matching functions are curves describing how much of each primary color needs to be used at each wavelength along the visible spectrum. The values for $\bar{x},\bar{y},\bar{z}$ will be different for different people, but by repeating these experiments with several people and averaging the results, CIE was able to establish standard $\bar{x},\bar{y},\bar{z}$ values, thus defining a "standard observer"[8]. Figure 5.2 is a plot of the values of the $\bar{x},\bar{y},\bar{z}$ functions across the visible spectrum.

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[8] Actually, there were two different observers defined, a 2° and a 10° observer. The two definitions vary in the viewing angle provided to the observer. For this study, the 10° observer is the standard.

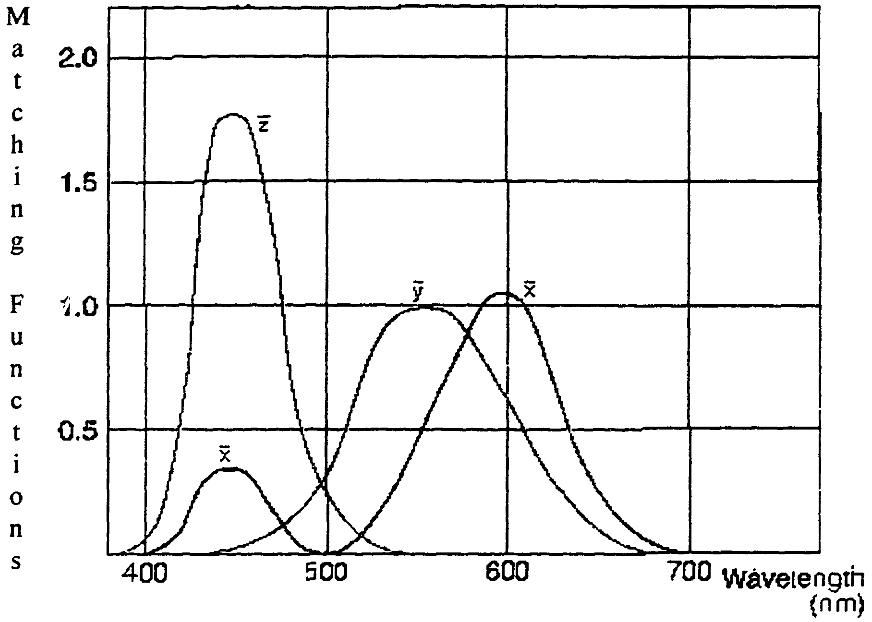


Figure 5.2 Color Matching Functions for 10° Observer

5.2.3 Object

Using the CIE standard observer and a standard illuminant, one can reduce the difference in observed color to differences caused by changes in the object. But what is it that changes in an object?

Reflectance is a measure of how much light is reflected from an object. If the object appears red to an observer, this is because it absorbs most of the short wavelength light but reflects most of the long wavelength (red) light. Since this red light is reflected and not absorbed, it is what the observer receives when viewing the object.

A reflectance curve for an object is a plot of the relative amount of light reflected at each wavelength in the visible region of the spectrum. For example, if 100 units of 500nm light is directed at an object and 60 units are reflected, that object has a reflectance of 60/100 = .6 at a wavelength of 500nm. Note that an object has a reflectance value associated with each wavelength of light in the visible spectrum. A spectrophotometer is a color measuring device. They have the observer matching functions and illuminant power values stored in memory, and they measure the color of an object by generating a reflectance curve for the sample.

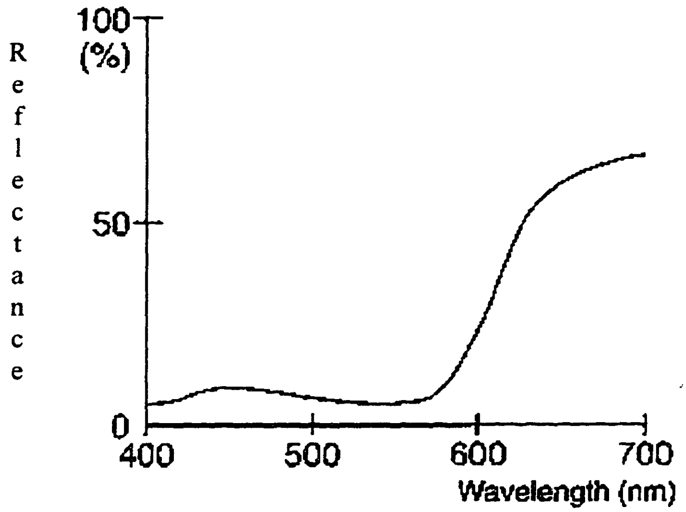


Figure 5.3 Possible Reflectance Curve for a Red Object

5.3 Combining Illuminant, Observer, and Object to Measure Color

Since the spectral power curve for a D_{65} illuminant is a constant and the $\bar{x},\bar{y},\bar{z}$ standard observer matching functions are also constants, only the reflectance curve of the object needs to be determined for its color to be quantified.

5.3.1 Tristimulus Values

Using these three inputs, CIE defined a system for quantifying color. An object's color is defined by its X,Y,Z Tristimulus values. To calculate X,Y, and Z:

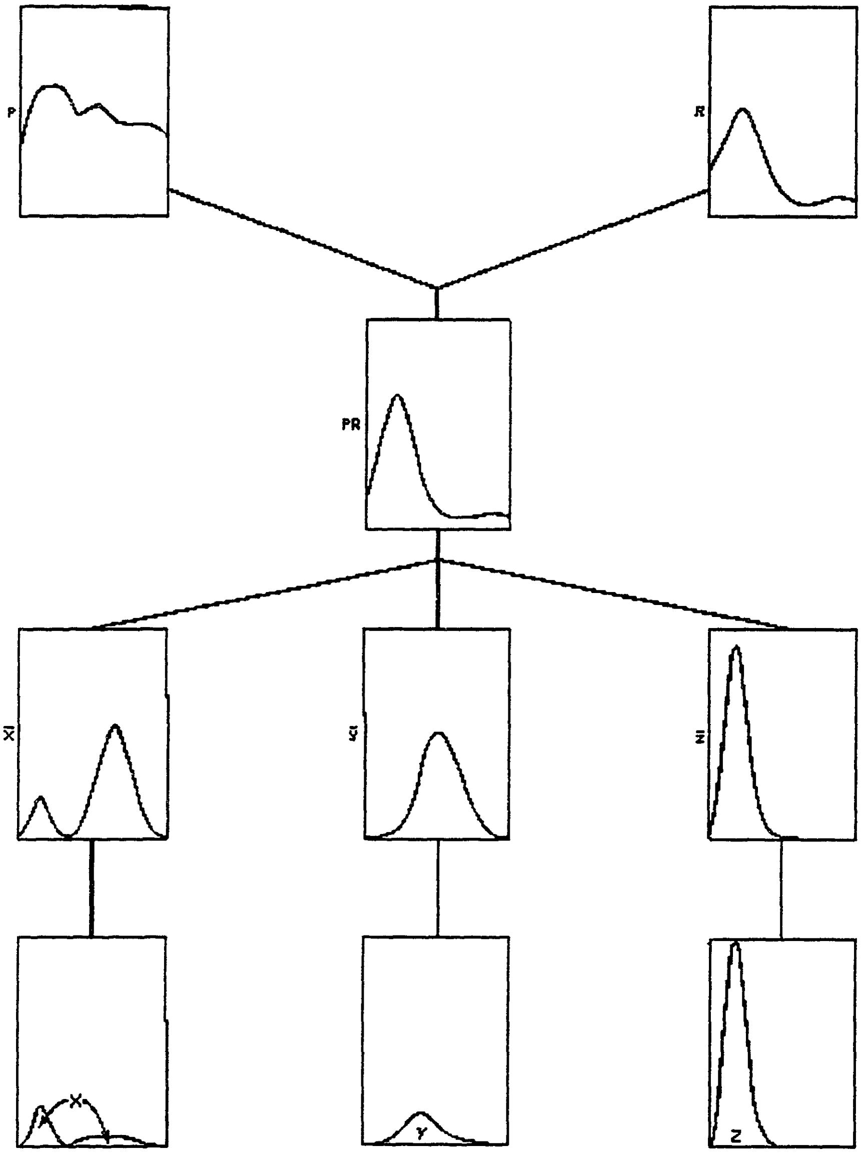
1. Calculate the product of the Reflectance (R), the relative Power (P) of the illuminant and the matching functions $\bar{x},\bar{y},\bar{z}$ for each wavelength. $RP\bar{x}$, $RP\bar{y}$, $RP\bar{z}$.
2. Sum (Σ) each of these values over all wavelengths to obtain the Tristimulus values:

$$X = \Sigma\ RP\bar{x}$$

$$Y = \Sigma\ RP\bar{y}$$

$$Z = \Sigma\ RP\bar{z}$$

Figure 5.4, taken from *Principles of Color Technology, 2nd ed.,* Billmeyer and Saltzman, shows these steps graphically.



P = Illuminant power curve; R = Object reflectance curve; $\bar{x},\bar{y},\bar{z}$ = matching functions

Figure 5.4 Flow Diagram for Calculating X, Y, Z Tristimulus Values

As mentioned previously, color is a function of the illuminant, the observer, and the object. The Tristimulus values quantify an object's color as its response (reflectance curve) to an illuminating source, across all visible wavelengths, as seen by an observer.

5.3.2 Converting X,Y,Z Tristimulus Values to Hunter L,a,b color Coordinates

Alcoa Building Products does not record color in the X,Y, Z tristimulus system. Instead their color specifications are based on the Hunter L,a,b color space. The Hunter system, and others such as chromaticity coordinate diagrams, CIE L* a* b*, L* u* v*, etc., were all developed to provide systems for mapping color in either 2-D or 3-D color space.

Chromaticity coordinate diagrams were the first system for visually representing color space. These diagrams are difficult to interpret because they are only two dimensional and because they are non-uniform in the sense that a one-unit shift at a given location on a chromaticity diagram may not correlate to the same degree of color change as a one-unit shift from a different location.

The Hunter L,a,b color space, developed in 1942, is simply a different mapping system intended to provide a more visually uniform color space. It is based on the same X,Y, Z tristimulus values that are used in chromaticity coordinate mapping. The difference is in the way that the Hunter approach transforms the tristimulus values into color space coordinates. Through his experiments, Hunter developed the following equations for mapping X,Y,Z tristimulus values into a 3-D L,a,b space:

$$L = 100\sqrt{\frac{Y}{Y_n}}$$

$$a = \left[175\sqrt{\frac{0.0102\,X^{n}}{(Y/Y_n)}}\right] \times \left[\left(\frac{X}{X_n}\right) - \left(\frac{Y}{Y_n}\right)\right]$$

$$b = \left[70\sqrt{\frac{0.00847\,Z^{n}}{(Y/Y_n)}}\right] \times \left[\left(\frac{Y}{Y_n}\right) - \left(\frac{Z}{Z_n}\right)\right]$$

In these equations, X_n , Y_n , and Z_n are the Tristimulus values of a reference white color. For the standard D_{65} illuminant, these values would be 94.83, 100.00, and 107.38 respectively.

In Hunter space, *a* and *b* are plotted along the horizontal axes, with *L* values on the vertical axis. This is an opponent color system in which the *a* axis is called the Red-Green axis and the *b* axis is the Yellow-Blue axis. The basis for the opponent approach is that a color can contain blue or yellow, but not both blue and yellow. Likewise, it can contain red or green, but not both red and green. An increase in red is in the positive *a* direction and an increase in green is in the negative *a* direction. An increase in yellow is in the positive *b* direction and an increase in blue is in the negative *b* direction.

From its equation, one can see that *L* is a function of only the Y tristimulus value. As a result of the careful selection of which combination of color matching functions ($\bar{x},\bar{y},\bar{z}$) to choose for the standard observer, the function $\bar{y}$ was chosen such that the Y tristimulus value provides all the information on a color's lightness.

The implication of this to the Hunter scale is that *L* is a measure of the Lightness of the color of an object. The scale for *L* ranges from zero (black) to 100 (white).

5.3.3 Summary of Color Reading at ABP

In the case of ABP, the color readings used for quality control are obtained in the following manner: A sample of colored material is placed on the spectrophotometer and is exposed to a light source. The instrument records the reflectance curve of the object and uses this curve, along with the stored functions for a standard illuminant and a standard observer, to calculate the tristimulus values of the color. The spectrophotometer then transforms the tristimulus values into L,a,b readings by using the Hunter equations. These readings are then be used to compare the color to the desired standard.

5.4 Methods for Color Measurement/ Reporting

A major obstacle in color measuring is the differences in the sample preparation and reporting techniques. The techniques which are relevant to ABP's situation are:

5.4.1 Supplier Pigment Testing

5.4.1-1 EngelHard

Following is the procedure used by EngelHard for reporting the color properties of their products. First a sample of a pigment is placed in a PVC base and dispersed via a 2-roll mill. A reflectance curve is then generated for the sample using a spectrophotometer. The machine then converts the data to Hunter L,a,b numbers.

EngelHard does not report the Hunter numbers directly; they report the differences, or delta's, between the actual sample readings and those of a standard material. For the same material, the 2-Roll process will yield slightly different results from day to day, so each time a new lot of pigment is tested, they also retest the standard material and use this result for determining the delta L,a,b values to report for the lot.

5.4.1-2 TiO_2 Supplier

The sample preparation and measurement method for TiO2 are not known at this time. What is reported is an absolute value for L* (different from Hunter's L)[9].

5.4.1-3 Shepherd

Some pigments come from a supplier other than EngelHard. Shepherd reports absolute L*,a*,b* readings for both a standard and the sample lot. It is believed that Shepherd uses a 2-Roll mill for sample preparation, similar to Engelhard.

5.4.2 ABP Pigment Testing

Each time a new lot of pigment is received, the QC department performs a color test to determine L,a,b values for the lot. To prepare a sample, the pigment is mixed at a

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[9] L*,a*,b* is a CIE color space applying different transformation equations to the X,Y, Z tristimuli.

specified concentration in a standard base. The mix is then processed in a Brabender torque rheometer to disperse and fuse the mix. A press out is then made by immediately placing the material between two thin aluminum sheets and flattening in a press. The press outs (with sheets) are then placed between two aluminum plates to cool.

As with the 2-Roll mill, this method will give different results from day to day, so each time a new lot is tested, the standard material is also retested. Repeatability and reliability studies have been discussed, but not implemented, to learn why these results vary from day to day. It may be due to process variation or the capability of the measurement devices.

After cooling, the press outs are checked on a spectrophotometer to determine Hunter L,a,b and delta values.

5.4.3 ABP Blend Batch Testing

These are checks performed on production blended compounds. Samples are taken from the cooler after a blend cycle, and are processed on a Brabender. The press outs are made similarly to those for QC testing, except that steel sheets are used instead of aluminum, and they are placed in a cooler to speed up the cooling process.

The press outs are then checked on a spectrophotometer to determine Hunter L,a,b readings which are compared to a stored standard.

5.4.4 ABP Extruded Material

The last color check is made on extruded siding at the end of the process. This material has been dispersed by an extruder. It has also been embossed with a pattern. Samples are measured by a spectrophotometer to calculate Hunter L,a,b readings for comparison to a stored standard.

5.4.5 Results from the Different Techniques

Data has shown that the same material tested on a 2-roll mill yields different results than if tested on a Brabender rheometer. Reasons for this include: normal process variation, differences in the PVC base used, differences in the standard used for calculation of delta's, or differences in how each process disperses the pigment within the blend. Tom Edwards, of EngelHard, feels that it is differences in dispersion which cause variation in the results.

Dispersion is one of two types of mixing that occurs in the process; the other is distribution. In simple terms, dispersion means breaking down relatively large pigment agglomerates (clumps of particles) into separate particles so that they can be distributed evenly throughout the blend. The breaking down is caused by shearing forces being applied to the material. The more dispersed the pigment is, the greater its coloring capability is, or the more fully developed the color will be. Tom Edwards feels that the dispersion achieved via the Brabender is less than that achieved by a 2-Roll mill, and that an extruder may disperse more than a 2-Roll mill. This concept is depicted graphically in Figure 5.5. It is believed that in time, each process reaches a dispersion plateau beyond which additional blending time will have no added effect.

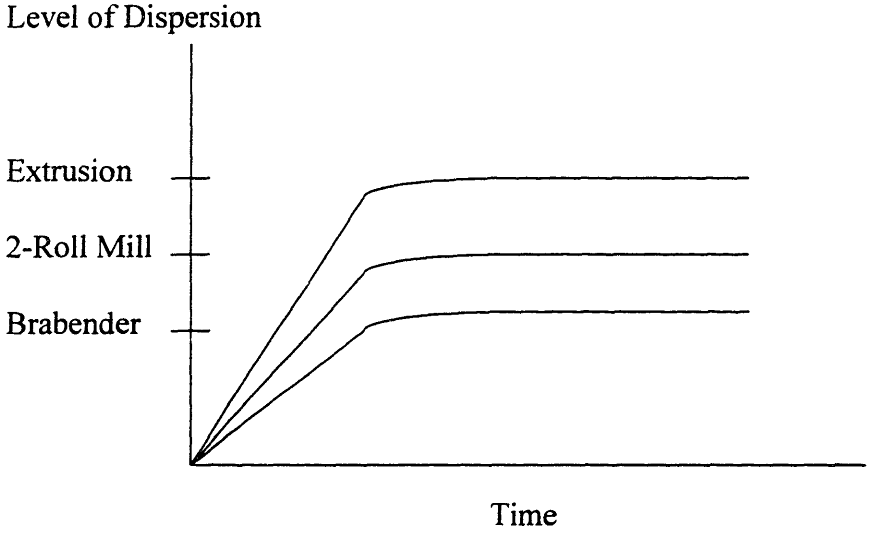

Figure 5.5 Concept of Different levels of Dispersion for Different Processes

In a continuous, unchanging environment, consistency is most important. As long as the extruders are providing consistent dispersion, the color should not fluctuate if the mixed blend does not change. Experience suggests that the extruders are consistently achieving the maximum dispersion they are capable of. However, when the inputs change, as in new lots of pigments, problems can arise from mixing the results of the different testing methods above.

5.5 Color Mixing Laws

The type of color mixing in which the colorants both *absorb* and *scatter* light is referred to as complex subtractive mixing. ABP's mixing falls into this category. Due to the high degree of complexity involved, the mixing laws which describe the process have been approximated by simplified equations. The most common approximation equations in use are those derived by Kubelka and Munk. For opaque samples, these equations are:

$$K/S = (1 - R)^2 / 2R \qquad \text{(Equation 5.1)}$$

$$(K/S)_{mix} = K_{mix}/S_{mix} = \frac{c_1K_1 + c_2K_2 + \ldots c_nK_n}{c_1S_1 + c_2S_2 + \ldots c_nS_n} \qquad \text{(Equation 5.2)}$$

In these equations:

K = a measure of how much light the material absorbs at the specified wavelength.

S = measures how much light is scattered at the given wavelength

c's = the concentrations of each colorant, and

R = the reflectance of the object at the given wavelength.

As is the case in color measuring, the mixing is a function of reflectance. The measured reflectance (at a given wavelength) of an object is related to the ratio of the object's ability absorb light to its ability to scatter light. For light of different wavelengths, this ratio will change, i.e., the object may absorb more light at 430nm than it does at 650nm.

The second equation above shows that the K/S ratio of a mixture (like blended compound) is a function of the K/S ratios and the concentrations of the various input colorants. The implication of this equation is that if the K and S values across the visible wavelengths, and the concentrations, are known for each input, K/S values for the mixture can also be calculated at each wavelength. Once these values are known, the reflectance at each point can also be derived from the first equation, thus generating a reflectance curve which can be used to calculate the tristimulus X, Y, Z values of the blend. However, there is a difficulty in working backwards to solve the first equation for reflectance since the quadratic equation which must be used can result in two possible solutions. Knowing which to choose is not obvious.

5.6 Using the Mixing Laws to Predict Color

From the preceding discussion. the following process could be used as a method for predicting the color of a blend:

1. For each pigment involved, determine K and S at each wavelength in the visible spectrum (400 to 700 nm).
2. For the specified concentrations (e.g. 5lbs pigment A, 3.4lbs pigment B, etc.), calculate the K/S ratio for the mixture for all wavelengths from 400 to 700 nm.
3. For each wavelength, solve for the estimated reflectance, R, of the mixture.
4. Using the derived reflectance curve, and the known data for the standard observer and standard illuminant, calculate the estimated tristimulus values X, Y, Z for the mixture.
5. Apply the Hunter transformation equations to obtain predictions for the L,a,b mixture values.

As mentioned previously, there is a problem in the calculation of R. This derivation requires the use of the quadratic equation to algebraically solve equation 5.1. In doing this, there will be two possible roots (solutions) to choose from as the answer. In some cases, the choice may be obvious (e.g. a root that is negative or imaginary would be discarded), but not always.

5.7 Color Matching Software

There is a more significant technical problem than just picking the correct root, which prevents such easy prediction of color. The spectrophotometers used for color measuring are limited by the fact that they cannot provide separate values for K (absorption) and S (scatter). They can only provide values for the ratio, K/S, which is derived from its relation to the reflectance which a spectrophotometer does measure. Without these values, no simple theoretical predictor can be developed to use the standard Kubelka-Munk mixing equations.

Keep in mind that these equations were not developed to predict how color would change when the inputs changed (i.e., pigment variation). They are intended to predict the output color when using defined inputs. These inputs are defined through making several pressouts of each pigment, all at differing concentrations, and mapping their reflectance behavior to estimate K and S. In modern practice this is done by a color matching software program. There are several companies which specialize in color matching software and the exact technique used for calculating K and S varies from one company to another. with each company having a proprietary method[10].

The drawback of these approaches is that to define an input requires several tests to be conducted. This is not a practical approach to dealing with lot-to-lot variation in pigments, as ABP does not have the resources to allocate to such work for every lot of pigment.

5.7.1 Using Color Matching Software Without Testing each Lot

Color matching software programs are in use reactively, or as corrective action estimators. In this role (for ABP), a batch of material would be run through the blender using whatever pigment lots are available on the given day, using the standard formulation. Once the batch is blended, a pressout needs to be made and the reflectance curve determined on a spectrophotometer. Using this data, and assuming that the pigments being used are actually the standard (no variation) pigments, the software

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[10] Per Phil Ruggiero, Applied Color Systems (ACS). The Denison plant actually has a system from ACS, but has never fully utilized it as intended.

suggests weight changes to bring the color back on target[11]. Of course, if the blend is on color, no changes need to be made. This approach typically works well, provided the lots of pigments do not vary much from the standards.

The obvious drawback of this method is that if the first batch is off color, it must be discarded, which is precisely the event we are trying to avoid by using a predictor. The results of this method are similar to the experienced-based "judgment call" approach currently in use.

Having read this, and previous sections, one should rightfully be skeptical of any proposed method for variation compensation which does not require iterations. The remainder of this chapter apply this background material to an analysis of the model proposed by Engelhard.

5.8 EngelHard Model for Color Changes due to Lot-to-Lot Pigment Variation

If a new lot of pigment is to be used which has slightly different Hunter L,a,b values reported with it, this means that it also has a slightly different reflectance curve. Therefore, according to the Kubelka Munk mixing laws (equations 5.1 and 5.2), use of the pigment will yield a mix with a different reflectance curve as well. As described previously, this change in reflectance may result in a change in perceived color.

Lot-to-Lot variation in the pigments may result in perceived color changes, but this depends on how much variation exists. If the variation is small enough, the change in reflectance would be minor enough to not cause the blend to be "off color", or out of the specification range. Unfortunately, this is frequently not the case, and changing pigment lots during a run or between runs often results in color problems.

Since the level of lot-to-lot variation does not appear to be shrinking in the near future, ABP called upon its main pigment supplier, EngelHard, to help them find a method for proactively addressing this problem. On September 27th, 1995, Tom Edwards and Vahe Karayan presented the results of modeling work they had done on the ABP blending process. Their model was developed using data from the 400 pound

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[11] Per Norm Demers, Applied Color Systems

blender at the Stuart's Draft, VA plant. Their study looked at factors beyond pigment variation, but part of their work included a color prediction model which looked exclusively at the effect of pigment variation. A discussion of this predictor model follows.

5.8.1 EngelHard Predictor

To understand how the model works, one needs to recall the relationship between Hunter L,a,b values and the tristimulus values of a material as well as the Kubelka Munk color mixing equations discussed previously.

The predictor is an Excel spreadsheet designed for the Pebblestone Clay topcap. This blend has the following colorants: Yellow (buff), Black, and Green pigments supplied by EngelHard, Brown pigment from Shepherd, and TiO2 from Dupont.

According to the Kubelka Munk mixing equations for opaque compounds, the absorption over scatter ratio (K/S) for the topcap blend, at each wavelength, is a function of the K/S ratios of each of the input colorants above and their concentrations in the blend. The K/S ratios of the mixed compound can also be derived from its reflectance curve. One of the simplifications of the EngleHard model is that it considers only the Yellow and the Black pigments, excluding the others from the prediction calculations. (Follow-up work is being done to incorporate the Green and Brown pigments too.)

A second premise of the model is that it alters the Kubelka Munk (K-M) equation for the K/S ratio of a mixture from:

$$(K/S)_{mix} = K_{mix}/S_{mix} = \frac{c_1K_1 + c_2K_2 + \ldots c_nK_n}{c_1S_1 + c_2S_2 + \ldots c_nS_n}$$

Equation 5.1 (standard)

to:

$$(K/S)_{mix} = \frac{c_1\left(\frac{K}{S}\right)_1 + c_2\left(\frac{K}{S}\right)_2 + \ldots c_n\left(\frac{K}{S}\right)_n}{c_1 + c_2 + \ldots c_n}$$

Equation 5.3 (modified 5.1)

Additionally, the EngelHard model also makes the following substitution for the other Kubelka Munk equation, replacing:

$$K/S = (1 - R)^2 / 2R \qquad \text{Equation 5.2}$$

where R is the reflectance of a pigment, with the following three equations:

$$K/S = \left(1 - \frac{X}{100}\right)^2 / 2\left(\frac{X}{100}\right) , \qquad \text{Equation 5.4A (modified 5.2)}$$

$$K/S = \left(1 - \frac{Y}{100}\right)^2 / 2\left(\frac{Y}{100}\right) , \text{ and} \qquad \text{Equation 5.4 (modified 5.2)}$$

$$K/S = \left(1 - \frac{Z}{100}\right)^2 / 2\left(\frac{Z}{100}\right) \qquad \text{Equation 5.4C (modified 5.2)}$$

where X,Y, and Z represent the tristimulus values for each pigment.

5.8.2 Using the Modified Equations

Tom Edwards uses these modified equations to predict color difference due to pigment variation. An outline of the methodology is as follows (refer to Figure 5.6):

1. Using the Hunter L,a,b values for the standard lots of yellow and black pigment, solve the Hunter transformation equations to derive the X,Y,Z tristimulus values for each of the pigments.
2. Substitute these values into the equations above to determine three K/S values for each pigment, one in terms of X, one for Y, and one for Z, i.e., $(K/S)_X$, $(K/S)_Y$, & $(K/S)_Z$. At this point, the X,Y, and Z absorption over scatter ratios are treated independently.
3. Use the Modified K-M equation for mixing to determine $(K/S)_{X(mix)}$, $(K/S)_{Y(mix)}$, and $(K/S)_{Z(mix)}$.

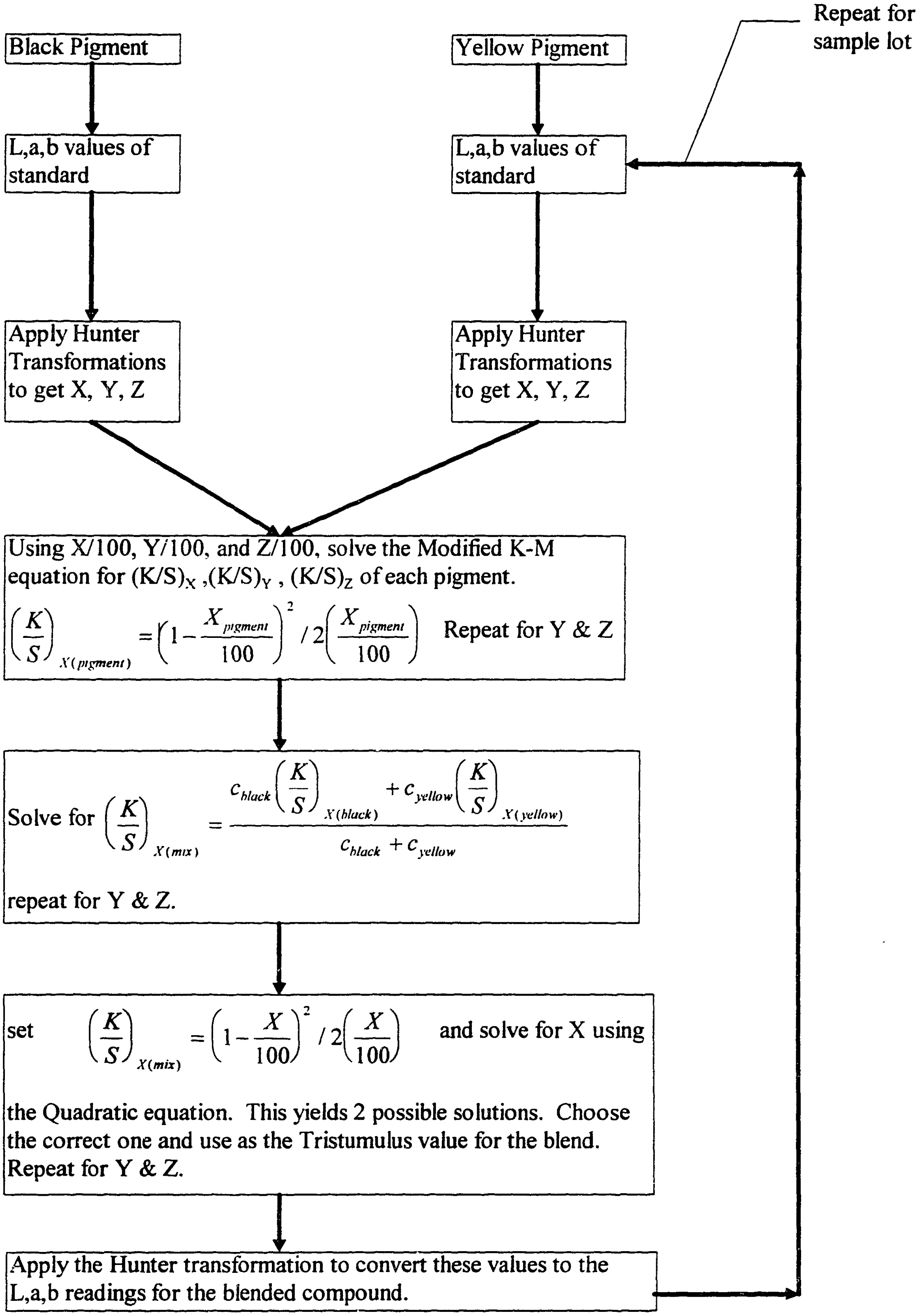

Figure 5.6 FlowChart of the color prediction method proposed by EngelHard

4. Reverse the process of step 2 by using the value of $(K/S)_{X(mix)}$ and solving for the X tristimulus of the mixture by using the quadratic equation. There will be two possible answers to choose from. Repeat this for $(K/S)_{Y(mix)}$ and $(K/S)_{Z(mix)}$.. finding Y and Z.
5. Use the Hunter transformation to convert the three calculated tristimulus values into L,a,b values.
6. By repeating steps 1-5 for the sample lot, the predicted L,a,b values of the sample and standard can be compared.

To use this model for finding the ideal weights for use with a given set of pigments, one must try varying the concentrations of the yellow and black pigments until a match can be achieved between the L, a, b prediction for the sample lots and that for the standard lots at their standard weights.

5.9 Analysis of the EngelHard Approach

There are some problems associated with the EngelHard model which throw doubt on its validity/feasibility. In no specific order, the items in question are:

5.9.1 Exclusion of several pigments

As mentioned, the predictive model assumes that the effect of TiO2, Brown, and Green pigments are not significant when dealing with changes in only Black and Yellow pigments. This assumption is in violation of the mixing laws being used.

5.9.2 Modifying the K-M Mixing Equation

The original mixing equations defined by Kubelka and Munk are approximations of more complex equations. The reasoning for modifying these equations as suggested by the EngelHard model is that, to solve the standard K-M equation for a mix requires knowing <u>both</u> K and S for each of the individual pigments. In using equation 5.1 to solve for the ratios for the individual pigments, a single number is obtained for the value of K/S, but one cannot determine the value of each. By modifying the equation for mixtures as was done, having a single value for the K/S ratio of each pigment is sufficient.

5.9.3 Replacing Reflectance (R) with Tristimulus values (X,Y,Z)

Recall that the tristimulus values were previously defined as functions of reflectance curves, illuminant power curve, and the standard observer matching functions. They are integrative functions, meaning that a single tristimulus value is derived from all the reflectance values across the visible spectrum. The K-M equations were developed to apply at individual wavelengths across the spectrum; replacing the reflectance with tristimulus values (divided by 100 to make fractions) requires validation to determine if the relationship remains feasible. While researching color theory literature, I came across the following statement regarding the mixing of the Kubelka Munk equations and tristimulus values:

> ". . . Calculations with the Kubelka-Munk equations must be made at many wavelengths across the spectrum; they cannot be applied to tristimulus values. . ." (*Principles of Color Technology, 2nd Ed.*, Billmeyer and Saltzman, John Wiley & Sons, p. 140)

5.9.4 Whose L,a,b Data to use

This concern applies not only to this approach, but to all predictions or comparisons which rely on data from different sources and/or sample preparation techniques. The different methods of sample preparation and color checking were discussed previously; recall that these techniques may yield different results for the same pigments. The implication of this is that, even if the EngelHard model were accurate, it is based on pigment L,a,b values generated with their 2 Roll mill. Recall that this method is believed to have a different level of dispersion than the mixer/Brabender technique or the extrusion lines at ABP.

The Kubelka Munk equations do not address dispersion, they simply assume that all colorants are equally dispersed during mixing. Also, the dispersion obtained during the sample preparation of each pigment is assumed to be the same as its dispersion in the blend, meaning that the K/S values of the sample will be applicable to the pigment when used in the blend.

If the differences between the supplier testing processes and the ABP processes are real, then a difference reported by the supplier may not be representative of the difference which will actually be seen by ABP.

The best way to get around this dilemma is to eliminate or minimize comparisons between non-similar methods. Provided the ABP testing method can be controlled to provide consistent results, this method should be used for generating pigment data for use in any predictive environment.

5.9.5 Empirical Results Using the EngelHard Predictor

In addition to the issues regarding the theoretical validity of the approach proposed by EngelHard, a comparison of the K/S predicted color deviation and the actual color deviation was done on data from production batches[12]. This comparison is illustrated in Figure 5.7. In the figure, DL_Pred, Da_Pred, and Db_Pred are the estimates based on the K/S prediction of the EngelHard model. Out_DL, Out_Da, and Out_Db are the actual deviations which occurred in the data sets.

From the 38 data sets used in the study by EngelHard, the K/S prediction was only within 0.10 L units of the actual output 9 times. The predictions for changes in the "a" value were closer, but the actual changes in "a" were typically smaller than 0.05 units. It appears that for larger variations the model is a poor predictor of the "a" values. Of the 8 points in the data where the "a" value varied by more than 1 unit, the model was off by greater than 1 unit in its prediction. The K/S prediction was accurate within 1 unit for "b" values 23 out of 38 times in the data. About half of the time it was within 0.05 units of the actual change in "b".

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[12] The data for the comparison was from the Stuart's Draft plant and had been provided to Engelhard during their development period.

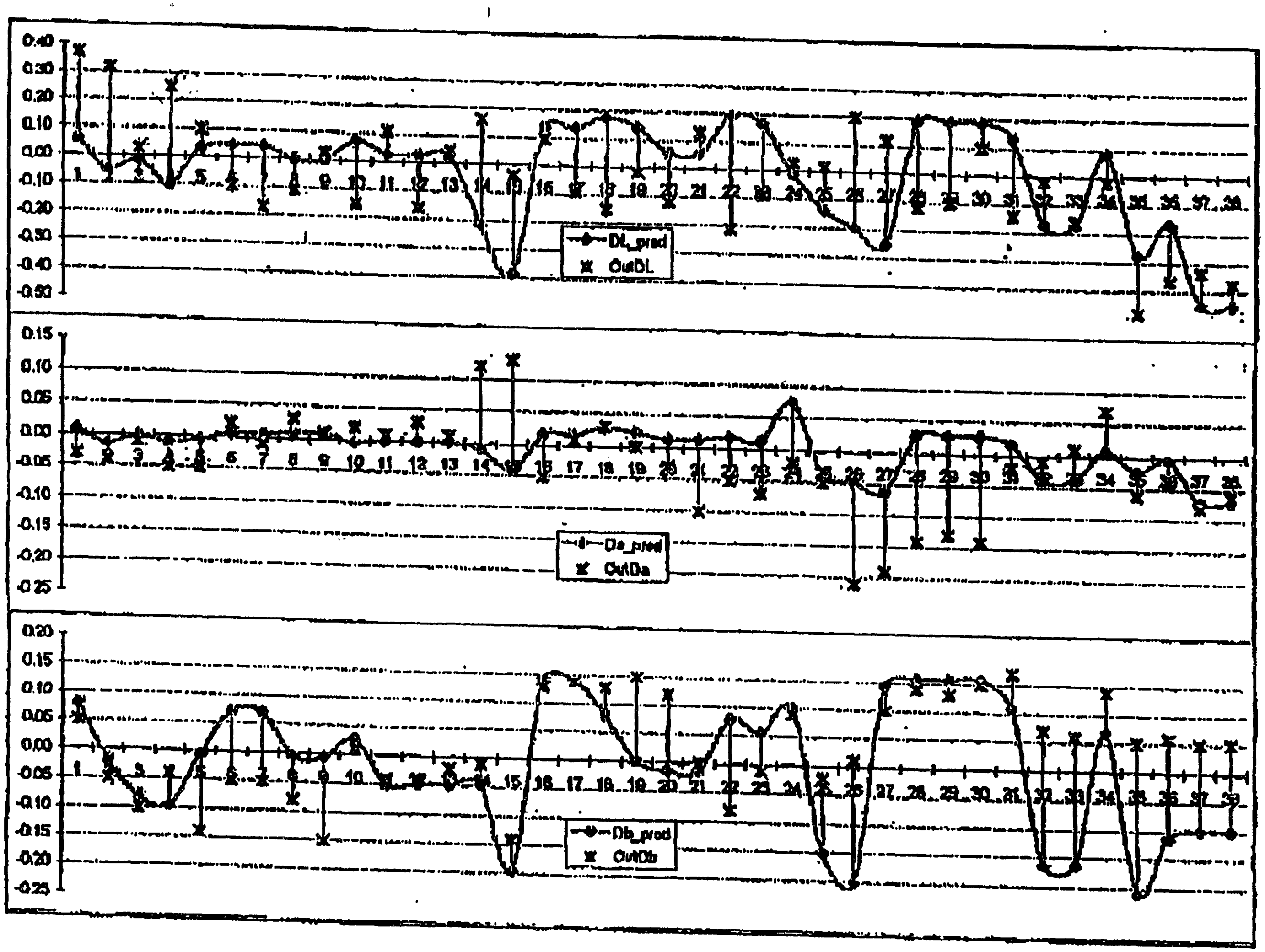

Figure 5.7 Model Predictions vs. Actual Results

5.10 Conclusions

Based on consideration of color mixing theory, the assumptions used by this model are not theoretically sound. Furthermore, the empirical data available thus far has demonstrated that the model is not capable of providing a level of accuracy which can justify its use.

Chapter 6. Blending Experiments

Off color product is one of the major defect factors in ABP's extrusion process. Variation in color may be driven by 1) the extrusion process itself, 2) the transfer of material - possibly via the segregation phenomena discussed earlier, or 3) color variation of the compound resulting from the blending process. Considering these three potential sources, an effort was undertaken which focused on the color output of the blending operation. Achieving greater color consistency at this stage should result in overall yield improvements in extrusion.

For this study, experiments were conducted using the Conformal Design techniques developed at MIT. These experiments clarified the relative impact of several factors on the color of blended compound, and it is hoped that the results of this work can be used to focus future efforts at variation reduction where they will yield the greatest benefit.

6.1 Limits of the Experiments

For the blending operation (described in chapter 3, section 3.2.1), a brainstorming session was conducted with engineers from the Denison plant which generated more than 40 factors which could potentially impact the color of the final compound. Due to equipment availability and the cost of experimenting in the production environment, it was decided to conduct the trials in a lab environment. The equipment used was a Henschel high speed mixer, with a 5 pound capacity as opposed to 1000-pound batches on the production equipment. Unlike the production process, the blended compound was not tumbled in a cooler, instead it was allowed to air cool.

6.2 Determining Control Factors and Levels

Of the original list of variables, six were chosen by the group for inclusion in a designed experiment. This selection was based partly on the ability to manipulate the variables in an experiment and partly on the group's judgment of their perceived importance. Also, a single compound color, Sandtone, was chosen and used as the basis for all experiments. The variables are:

Var1 = Microingredient Addition Temperature
Var2 = TiO_2 Loading Level
Var3 = Pigment #1 Loading Level
Var4 = Other Pigment Loading Levels
Var5 = Dump Temperature
Var6 = Pigment Metering

Recall that a typical blending mixing cycle is consciously designed with temperature as a triggering mechanism. The microingredient addition temperature and the blend dump temperature were included because there had been considerable intuitive discussion regarding their respective impact on color. Inclusion of these variables yielded more quantitative evidence of their significance.

A literature search of existing industry practices revealed a tremendous overlap in temperature driven additions. Table 6.1 lists the microingredient addition schedules as recommended by various sources and Figure 6.1 graphically depicts the overlapping effect. After review of this data, it was decided that the levels for microingredient addition (including TiO_2) would be (+) at the current standard, and (-) immediately after adding the stabilizer. The dump temperature settings used were (+) standard and (-) standard minus 25 degrees F.

Addition Temperatures and Conditions						
	PVC	Stabilizer	Lubricants	Pigments/TiO2	Modifier	Dump
Tom Resing[13]	Ambient At high Speed	140	160	195	185	220
Roesler & Shah[14]	Ambient At high Speed	180-200	220	220	220	260
Linder & Worschech[15]	Ambient At high Speed	150	near the end			
Gerson & Graff[16]			Pigments - Never at Beginning. Preblend w/ a portion of compound @ low speed			
Eric Kushon[17]	Ambient At high Speed	170	Mix until adequate dispersion/drying and add remaining components.			
P. Verrier[18]	Ambient At high Speed	140	140		Ambient	230
P. Verrier[19]	Ambient At high Speed	140	160	195	185	220-230
P. Verrier[20]	Ambient At high Speed	after resin	after stabilizer		after stabilizer	195
GEON[21]	Ambient at <u>Low</u> speed	Shift to high, add after resin	160	140	140	190

Table 6.1 Microingredient Addition Schedules

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[13] Resing, Tom The Technology of High Intensity Nonfluxing Mixing

[14] Roesler & Shah - Mixing and Compounding Equipment

[15] Linder & Worschech - Lubricants for PVC

[16] Gerson & Graff - Colorants

[17] Kushon, Eric - Optimization of the Compounding Operation in PVC Dry Blend Preparation

[18] P. Verrier - 30 Dry Blending

[19] P. Verrier - 30 Dry Blending

[20] P. Verrier - 30 Dry Blending

[21] Geon Technical Service Report #8

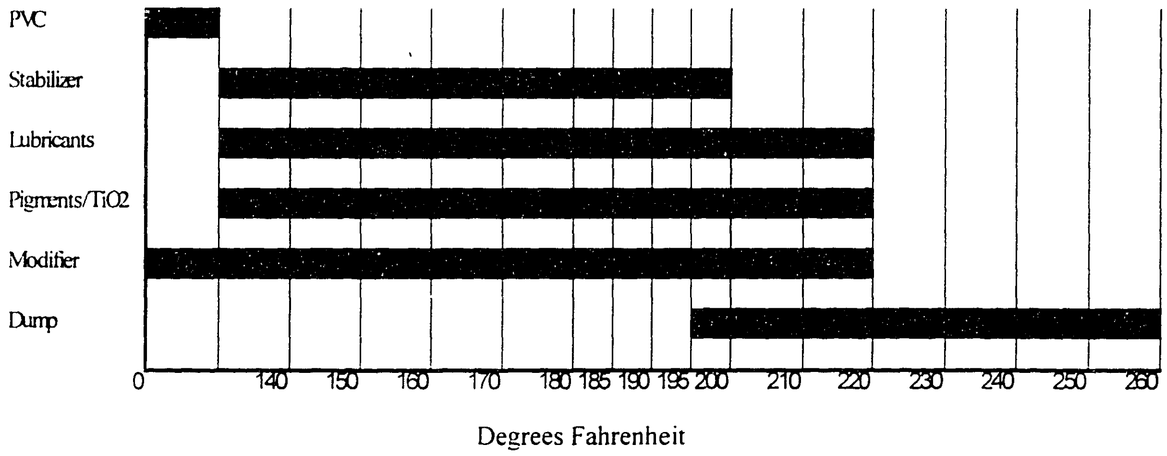

Figure 6.1 Temperature Addition Ranges of Blend Components

Inclusion of pigment and TiO_2 levels was done because their primary function is to impart color to the compound (and provide weathering in the case of TiO_2). The (+) and (-) settings were reasonably selected to yield a measurable change in output.

In normal production. TiO_2 is added separately, but all the other pigments are pre-weighed in a plastic bag and added as a lump amount (bag and all). It was suggested that this method may limit the effectiveness of the mixing operation. To test this hypothesis, pigment metering was used as a control factor. The (-) level represented standard practice and the (+) level consisted of metering the pigments into the blender over a 15 second interval.

6.3 Setting Up The Experiments

Using the Conformal Design Software developed at MIT, a 16 trial experiment matrix was generated based on the six control factors outlined above. The reader may at this point question how a 16 trial experiment can be relied upon when varying 6 factors at two levels each; the following explanation is intended as a brief introduction to the method of conformal design, for a more thorough explanation of the software tool, please refer to [Conformal Design of Experiments: an Automated Tool Supporting Experiment Design and Analysis for Efficient Improvement of Products and Processes, Fieguth, Spina, and Staelin, 10 March 1994].

Conformal Design is a useful technique for creating robust experimental designs using ~2N experiments, with N being the number of factors. The approach takes advantage of pre-existing process knowledge and creates an experiment matrix which "conforms" to the problem. The tool decreases the number of required experiments by relying on the user's input of the relative significance of possible interactions. In the experiment matrix, less significant interaction effects are overlapped with main effects (or important interactions) to reduce the required number of experiments. If these interactions are correctly presumed unimportant, they will not confound the other effects. If the expert guesses are in significant error, this will usually be evident from the model's failure to fit the data well. For this experiment, only the following four interactions were included in the analysis:

Int 2,3 = TiO_2 and Pigment 1
Int 2,4 = TiO_2 and Other Pigments
Int 2,3,4 = TiO_2 , Pigment 1, and Other Pigments
Int 3,4 = Pigment 1 and Other Pigments

6.4 Conducting The Experiment

In conducting the experiment, one batch of compound was blended for each row in the matrix. Since color is the quality characteristic of interest, Hunter L,a,b values were chosen to be the measurable attributes. The relationship between Hunter values and perceived color is described in chapter 5, section 5.3.2.

Two pressouts were made from each test batch. A pressout is a flat, thin piece of fused and solidified compound. These pressouts were all created with the same model Brabender torque rheometer as is used on production compound; the fusion process involved here is representative but not identical to the production extrusion process.

The color of each pressout was then measured via a spectrophotometer in the Quality Control lab. The readings from the two pressouts per batch were averaged to obtain L,a,b values for each of the 16 experimental settings. These values were then compared to the standard values for the compound being studied. Table 6.2 shows the conformal design matrix and lists the output delta's, or differences from the defined standard values. The standard is the Hunter L,a,b coordinates which characterize the nominal, or ideal color for this particular compound.

Addition Temp	TiO2	Pigment 1	Other Pigment	Dump Temp	Pigment Metering	Delta L	Delta a	Delta B
1	1	1	1	1	1	-1.945	-0.08	-0.38
1	1	1	-1	1	1	-0.385	-0.195	-0.91
1	1	-1	1	1	-1	-1.895	0.15	0.005
1	1	-1	-1	1	-1	0.1	-0.12	-0.77
1	-1	1	1	-1	1	-2.685	0.125	-0.07
1	-1	1	-1	-1	1	-0.885	-0.08	-0.62
1	-1	-1	1	-1	-1	-2.38	0.275	0.165
1	-1	-1	-1	-1	-1	-0.72	0	-0.565
-1	1	1	1	-1	-1	-1.695	0.035	-0.215
-1	1	1	-1	-1	-1	0.075	-0.195	-0.89
-1	1	-1	1	-1	1	-1.61	0.105	-0.075
-1	1	-1	-1	-1	1	0.245	-0.105	-0.645
-1	-1	1	1	1	-1	-2.745	0.215	0.12
-1	-1	1	-1	1	-1	-1.07	-0.09	-0.595
-1	-1	-1	1	1	1	-2.38	0.225	0.185
-1	-1	-1	-1	1	1	-0.88	0.015	-0.435

Table 6.2 Lab Trial Experiment Matrix and Results

These outputs were then regressed against the input matrix in an Excel linear regression. Three regressions were run, one each for L, a, and b. The summary statistics are shown in Figures 6.2, 6.3, and 6.4.

Regression Statistics	Delta L
Multiple R	0.9988606
R Square	0.9977225
Adjusted R Square	0.9931676
Standard Error	0.0831358
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	15.13928	1.51393	219.0428	0.00001
Residual	5	0.03456	0.00691		
Total	15	15.17384			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.3034375	0.02078	-62.71365	0.00000	-1.35686	-1.25001
Addition Temp	-0.0459375	0.02078	-2.21024	0.07808	-0.09936	0.00749
TiO2	0.4146875	0.02078	19.95229	0.00001	0.36126	0.46811
Pigment 1	-0.1134375	0.02078	-5.45794	0.00281	-0.16686	-0.06001
Other Pigments	-0.8634375	0.02078	-41.54347	0.00000	-0.91686	-0.81001
Dump Temp	-0.0965625	0.02078	-4.64601	0.00560	-0.14999	-0.04314
Pigment Metering	-0.0121875	0.02078	-0.58639	0.58309	-0.06561	0.04124
TiO2, Pig1	0.0146875	0.02078	0.70668	0.51133	-0.03874	0.06811
TiO2, Other Pig	-0.0340625	0.02078	-1.63888	0.16216	-0.08749	0.01936
TiO2, All Pigments	0.0521875	0.02078	2.51095	0.05377	-0.00124	0.10561
Pig 1, Other Pig	0.0128125	0.02078	0.61646	0.56457	-0.04061	0.06624

Figure 6.2 Summary Statistics for Regression on delta L, First Trial

Regression Statistics	Delta A
Multiple R	0.9884538
R Square	0.9770408
Adjusted R Squar	0.9311224
Standard Error	0.0395443
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	0.33273	0.03327	21.27778	0.00175
Residual	5	0.00782	0.00156		
Total	15	0.34055			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.0175	0.00989	1.7702	0.1369	-0.0079	0.0429
Addition Temp	-0.008125	0.00989	-0.8219	0.4486	-0.0335	0.0173
TiO2	-0.068125	0.00989	-6.8910	0.0010	-0.0935	-0.0427
Pigment 1	-0.050625	0.00989	-5.1208	0.0037	-0.0760	-0.0252
Other Pigments	0.11375	0.00989	11.5061	0.0001	0.0883	0.1392
Dump Temp	-0.0025	0.00989	-0.2529	0.8104	-0.0279	0.0229
Pigment Metering	-0.01625	0.00989	-1.6437	0.1612	-0.0417	0.0092
TiO2,Pig1	-0.0075	0.00989	-0.7586	0.4823	-0.0329	0.0179
TiO2, Other Pig	-0.010625	0.00989	-1.0747	0.3316	-0.0360	0.0148
TiO2,All Pigments	-0.01	0.00989	-1.0115	0.3582	-0.0354	0.0154
Pig 1, Other Pig	-0.006875	0.00989	-0.6954	0.5178	-0.0323	0.0185

Figure 6.3 Summary Statistics for Regression on delta a, First Trial

Regression Statistics	Delta B
Multiple R	0.993879
R Square	0.987796
Adjusted R Squa	0.963388
Standard Error	0.072035
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regression	10	2.10002	0.21000	40.47004	0.00037
Residual	5	0.02595	0.00519		
Total	15	2.12596			

	Coefficient	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.35594	0.01801	-19.7647	0.0000	-0.4022	-0.3096
Addition Temp	-0.03719	0.01801	-2.0650	0.0938	-0.0835	0.0091
TiO2	-0.12906	0.01801	-7.1666	0.0008	-0.1754	-0.0828
Pigment 1	-0.08906	0.01801	-4.9455	0.0043	-0.1354	-0.0428
Other Pigments	0.322813	0.01801	17.9253	0.0000	0.2765	0.3691
Dump Temp	0.008438	0.01801	0.4685	0.6591	-0.0379	0.0547
Pigment Metering	-0.01281	0.01801	-0.7115	0.5086	-0.0591	0.0335
TiO2, Pig1	-0.02469	0.01801	-1.3709	0.2288	-0.0710	0.0216
TiO2, Other Pig	-0.00406	0.01801	-0.2256	0.8305	-0.0504	0.0422
TiO2,All Pigment	-0.00344	0.01801	-0.1909	0.8561	-0.0497	0.0429
Pig 1, Other Pig	-0.01406	0.01801	-0.7809	0.4702	-0.0604	0.0322

Figure 6.4 Summary Statistics for Regression on delta b, First Trial

As the data shows, the variables 1) Addition Temperature, 2) Dump Temperature and 3) Pigment Metering all either had negligible impacts on L,a, or b variation (the regression coefficients are quite small), or they were not statistically significant (the absolute value of the t-stat is less than 2) over the ranges used in the experiments. The same is true of the interaction effects. These results were accepted with some caution because of the extremely high correlation coefficient (R^2), even after adjusting for degrees of freedom. The concern was that the fit may be "too good to be true".

6.5 A Second Trial

It was surprising that the initial trial suggested the weights, or pigment loadings, were the only significant factors within the range of settings used. It was decided that a second trial should be conducted to further consider the relative impact on color of changes in non-pigment factors. This experiment was also conducted on the Henschel mixer and the four factors studied were:

Var1 = Mixer Blade Tip Speed (RPM)
Var2 = Dump Temperature
Var3 = Microingredient Addition Temperature
Var4 = Resin (PVC) Input Temperature

No interactions were believed to be significant so none were included in designing the experiment.

The ability to control Mixer Blade Tip Speed was not recognized during the first trial, but once discovered it was agreed that it should be studied. This factor was controlled by changing the blade RPM, with (-) set at 2900 and (+) set at 3900. The settings for Dump Temperature and Microingredient Addition Temperature were the same as in the prior experiment. PVC input temperature was selected because there are considerable seasonal temperature variations in production; the settings used were (-) 34° F and (+) 74° F.

The experiment consisted of only 8 runs but was conducted on the same equipment, and with the same input materials as the first trial. Press outs and L,a,b values were obtained the same as in the first trial. The conformal experiment matrix and the L,a,b output variations are shown below in Table 6.3.

Tip Speed	DumpTemp	AddTemp	PVCTemp	Delta L	Delta a	Delta b
1	1	1	1	-0.94	-0.09	-0.34667
1	1	1	-1	-0.98667	-0.07667	-0.30667
1	-1	-1	1	-0.93667	-0.11	-0.39
1	-1	-1	-1	-1.07	-0.11667	-0.30333
-1	1	-1	1	-1.03667	-0.13	-0.37
-1	1	-1	-1	-1.22333	-0.13	-0.33333
-1	-1	1	1	-0.93333	-0.07667	-0.41667
-1	-1	1	-1	-0.85333	-0.08333	-0.45333

Table 6.3 Lab Trial Experiment Matrix and Results, Second Trial

As before, three Excel linear regressions were performed, one each for delta L, delta a, and delta b. Figures 6.5, 6.6, and 6.7 show the summary statistics for each.

Regression Statistics	for Delta L
Multiple R	0.87958784
R Square	0.77367477
Adjusted R	0.4719078
Standard Err	0.08231601
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	0.069488889	0.017372	2.563815	0.232625
Residual	3	0.020327778	0.006776		
Total	7	0.089816667			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*ower 95%*	*pper 95%*
Intercept	-0.9975	0.029103105	-34.2747	5.46E-05	-1.09012	-0.90488
RPM	0.01416667	0.029103105	0.486775	0.659765	-0.07845	0.106786
DumpTemp	-0.0491667	0.029103105	-1.6894	0.189725	-0.14179	0.043452
AddTemp	0.06916667	0.029103105	2.376608	0.097917	-0.02345	0.161786
PVCTemp	0.03583333	0.029103105	1.231255	0.305949	-0.05679	0.128452

Figure 6.5 Summary Statistics for Regression on delta L, Second Trial

Regression Statistics	for Delta A
Multiple R	0.9814225
R Square	0.9631902
Adjusted R Squa	0.9141104
Standard Error	0.0066667
Observations	8

ANOVA

	df	SS	MS	F	Significance F
Regression	4	0.003488889	0.000872	19.625	0.017266
Residual	3	0.000133333	4.44E-05		
Total	7	0.003622222			

	Coefficients	Standard Error	t Stat	P-value	ower 95%	pper 95%
Intercept	-0.1016667	0.002357023	-43.1335	2.74E-05	-0.10917	-0.09417
RPM	0.0033333	0.002357023	1.414214	0.252215	-0.00417	0.010834
DumpTemp	-0.005	0.002357023	-2.12132	0.124027	-0.0125	0.002501
AddTemp	0.02	0.002357023	8.485281	0.003437	0.012499	0.027501
PVCTemp	4.163E-17	0.002357023	1.77E-14	1	-0.0075	0.007501

Figure 6.6 Summary Statistics for Regression on delta a, Second Trial

Regression Statistics	for Delta B
Multiple R	0.8955319
R Square	0.8019774
Adjusted R Squa	0.5379473
Standard Error	0.0360298
Observations	8

ANOVA

	df	SS	MS	F	Significance F
Regression	4	0.015772222	0.003943	3.037447	0.194124
Residual	3	0.003894444	0.001298		
Total	7	0.019666667			

	Coefficients	Standard Error	t Stat	P-value	ower 95%	pper 95%
Intercept	-0.365	0.012738466	-28.6534	9.33E-05	-0.40554	-0.32446
RPM	0.0283333	0.012738466	2.224234	0.112599	-0.01221	0.068873
DumpTemp	0.0258333	0.012738466	2.027978	0.135608	-0.01471	0.066373
AddTemp	-0.0158333	0.012738466	-1.24295	0.302177	-0.05637	0.024706
PVCTemp	-0.0158333	0.012738466	-1.24295	0.302177	-0.05637	0.024706

Figure 6.7 Summary Statistics for Regression on delta b, Second Trial

The regression fits were not as good, as evidenced by the lower R^2 values, but more importantly, there was very little movement in color values regardless of the control factor settings. These results provided a strong indication that variation in these inputs during normal production should have a negligible impact on color variation in the blended compound - provided the process model developed in the lab is consistent with production equipment.

6.6 Confirmation of Initial Trials with Lab Blender

Since lab trials are much less expensive than a production trial, it was decided to conduct some confirmation runs to check the accuracy of the linear regression models derived in the two experiments. The following table summarizes how the confirmation trial was conducted:

Run #	**RPM**	**Micro Add Temp**	**Dump Temp**	**TiO_2 Level**	**Pigment 1 Level**	**Other Pigments**
Base	+	+	-	+	0	0
2	+	+	-	-	0	0
3	+	+	-	+	+	0
4	+	+	-	+	0	+
5	-	+	-	+	0	+
6	+	+	+	-	0	0

Table 6.4 Confirmation Runs on Lab Blender

The runs were conducted in the above order, and then repeated. Brabender pressouts were made for each batch and the color was checked using a spectrophotemeter. Since the purpose was not to determine relationships, but to confirm them, the trial settings were chosen by the experimenter's judgment.

In general, the actual results tracked very well with the predicted results for changes in L, a, and b. This information supported the decision to scale up the confirmation trials to a production mixer to see if the model established on the lab scale equipment would hold true in a production environment. Runs five and six, which had more than one variable change at a time, did not track as well as the others. Table 6.5 shows how closely the regression predictions and the results correlate.

Run #	**Delta-L Predicted**	**Delta-L Actual**	**Delta -a Predicted**	**Delta-a Actual**	**Delta-b Predicted**	**Delta-b Actual**
1	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
2	-0.83	-0.87	+0.14	+0.09	+0.26	+0.30
3	-0.11	-0.09	-0.05	-0.02	-0.09	-0.10
4	-0.86	-0.78	+0.11	+0.10	+0.32	+0.34
5	-0.88	-0.57	+0.11	+0.07	+0.26	+0.22
6	-1.02	-1.0	+0.13	+0.09	+0.27	+0.34

Table 6.5 Correlation Between Predicted and Actual Results

6.7 Confirmation Trial in Production

The lab confirmation provided sufficient confidence to warrant a production test of the regression model. The experiment settings were the same as in the lab confirmation except that RPM could not be changed without considerable effort, so there was only a baseline and 4 trial batches as shown in Table 6.6.

Run #	**Micro Add Temp**	**Dump Temp**	**TiO_2 Level**	**Pigment 1 Level**	**Other Pigments**
Base	+	-	+	0	0
2	+	-	-	0	0
3	+	-	+	+	0
4	+	-	+	0	+
5	+	+	-	0	0

Table 6.6 Confirmation Runs for Production

Only one batch was blended at each of the settings (no repetition). The high and low levels for each variable were also the same as in the lab trial (microingredient levels were the same on a percent of total weight basis). In conducting the trials, samples were made from each batch and the color measured (on the Hunter L,a,b scale) with the spectrophotometer. Table 6.7 illustrates that the actual results failed to track with the predictions as well as they did in the lab trial. In run five, the error in the L values was as much as 0.27 units, which is over one third of the tolerance band of +/- 0.40 units. The "a" values tracked well, but the "b" values did not, with errors as high as 0.32 units (This is over half of the b tolerance band of +/- 0.20).

Run #	**Delta-L Predicted**	**Delta-L Actual**	**Delta -a Predicted**	**Delta-a Actual**	**Delta-b Predicted**	**Delta-b Actual**
1	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
2	-0.83	-0.94	+0.14	+0.08	+0.26	+0.32
3	-0.11	-0.15	-0.05	-0.03	-0.09	-0.02
4	-0.86	-0.93	+0.11	+0.15	+0.32	+0.52
5	-1.02	-1.29	+0.13	+0.16	+0.27	+0.59

Table 6.7 Production Correlation Between Predicted and Actual Results

While the actual results vary in magnitude from the predictions, the direction of the change (in each L, a, and b) was the same as the regression predictions in every case. If time and funding can be obtained, a second production confirmation trial is recommended, which should include repetition of runs. The results in Figure 6.7 are based on single batches for each of the five settings and are therefore fully exposed to normal (common cause) process variation. Blending multiple batches for each setting and averaging the results will filter out the influence of common cause variation and provide a more reliable estimate of the true effect of each change made. This will provide a better basis for judging the accuracy of the regression model in a production environment.

6.8 Conclusions

These experiments led to the following conclusions regarding color control of blended compound:

1. Compound color variation is dominated by changes in TiO_2 and pigment levels.
2. Changes in blade speed have negligible effect on compound color.
3. Variation in resin inlet temperature has a negligible impact on compound color.
4. There is no advantage to metering in pigments slowly vs. the current method of charging as a lump mass.
5. The wide variation in dump temperature and microingredient addition temperature had negligible effect on compound color.

These results point toward control of pigment and TiO_2 levels as the best mechanism for reducing color variation. Currently great emphasis is placed on accurately weighing and charging pigments, but this is not true of TiO_2. It is recommended that methods for better TiO_2 control be pursued. An automatic weighing and dispensing system may be one such method, although further studies would be required to determine the cost and savings potential. The ergonomic benefits of an automatic weighing system should also be included in such studies.

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