Improving Statistical Methodology with the SAS® System in an Industrial Environment

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INTRODUCTION

What are the responsibilities of a consulting statistician in an industrial organization, and how is SAS® statistical software useful in exercising those responsibilities? These are the questions to be addressed in this paper. The statistician's job could be viewed as waiting for a client to come along and then devising optimal experimental designs or methods of data analysis to address the client's problem. In industry, however, a more pro-active approach to the statistician's job is needed - one where the technology goals for the division or company are identified, and where programs are formulated to encourage the use of statistical methods in achieving those goals, not only by the consulting statistician but also by many other research and applied scientists in the organization. The first part of this paper will discuss this latter view of the statistician's job in more detail, and then, because the availability of good software is of critical importance, an example of using SAS software in support of organizational goals will be presented.

AN INDUSTRIAL STATISTICIAN'S JOB DESCRIPTION

The principle thrust for an industrial statistician was previously identified as encouraging the use of statistical methods toward the achievement of organizational goals. There are three main avenues for doing this: (1) personal involvement in projects, (2) providing statistical training for others, and (3) making available good software and hardware. Even in companies which are quite large, however, there may be only one or a few full-time statisticians, so that each one must be involved in all three areas. Let us now discuss each area individually.

Personal Involvement in Projects:

This category covers all of the statistics applications actually done by the statistician himself. At last year's Fall Technical Conference, Donald Marquardt (1) said that "a statistician can be viewed as a purveyor of the scientific method." To understand what Dr. Marquardt meant, it is instructive to examine the scientific method more closely. Unfortunately, there is no one sequence of steps which is followed by all technical disciplines. The Encyclopedia Britannica (2) contains a wide ranging discussion, but the steps followed by the operations researcher provide good insight for applied statisticians. These steps are as follows:

1. Formulate the problem:
   Observe the present system, identifying important independent variables and constraints, and devise an appropriate measure of performance.
2. Construct the model:
   Write an equation relating the performance measure to the independent variables. Take data by observing normal system operation or from a designed sequence of manipulations. Use the data to estimate model parameters and verify that assumptions are met.
3. Derive a solution:
   Use the fitted model to modify the present system in order to optimize the performance measure.
4. Test the model and the solution:
   Compare the actual performance of the present and modified system to insure that the model prediction is correct.
5. Implement and control the solution:
   Plan the implementation to avoid upset. Compare actual with predicted performance and find and correct discrepancies.

What is seen here is a comprehensive approach to problem solving which will result in better performance in meeting organizational goals. The statistician's involvement begins with the problem formulation and ends when the solution has been successfully implemented. This does not mean that he does all of the tasks himself, but that he is part of a team effort and is commited to the overall success of the project. Also, this is diametrically opposed to the concept of a consultant who just goes to a meeting or two, or who merely performs a statistical analysis on data to see which factors have statistically significant effects. In addition to total involvement, there are three other keys to project success which are discussed in a recent text by Boen and Zahn (3):

1. Implement the client relationship:
   A scientist or engineer who calls for statistical help should be treated like a new customer for a small business, because the statistician's salary and job security depend upon how satisfied this client is with the help he received just as the continued success of a small business depends on satisfied customers. Especially in the first few visits, be sure that the client feels he has made tangible progress toward his goals each time you meet, and that he knows what your commitments are and the timing associated with them. The client is not inferior because he or she is not a statistics expert, but rather the client is an expert in another field, and the success of the project depends upon integrating statistics into this other technology.
2. Avoid overly complex statistical methods:
   The important thing is success in meeting the company's organizational goals, not the

advancement of the field of statistics. You should use the least complicated statistical methods which will do the job, and these methods should be proven in prior use. This helps the project in two ways: (1) the statistical analysis takes less time and its completion date is more predictable, and (2) communication is enhanced because the client is more likely to understand the output of the analysis.

3. Communicate
Communication must take place beginning with the problem definition phase and continuing throughout the project. This communication must include not only the client himself but also his management and those individuals who interface with the present system. You as the statistician must know that the work to be done is likely to result in progress toward organizational goals before investing the time. This can be done by discussing the formulation of the problem using "what if" scenarios to determine impacts on the present system if experimental results turn out in certain ways. If these impacts are slight or non-existent, then perhaps the problem should be re-formulated or the program abandoned.

The choice of statistical methods should be reviewed with the client to see if he will be comfortable discussing the results with his management. Then, once the data have been taken and the model solved, it is usually time for an oral presentation of the results. The purpose of this presentation is not to discuss statistical methodology but rather to gain support of the client's management for the test and implementation phases of the program. Therefore, the presentation should stress what has been learned from the model about the present system, and the predicted benefits associated with the system modification. If the client is willing, he should make part of the talk.

You as statistician tend to gain satisfaction from the creative aspects of applying a particular type of experimental design or data analysis technique, but this is probably not the case with your audience. If you are not extremely careful, those nods which you see will be courtesy nods rather than the assumed indication of comprehension and agreement. The appropriate place for a discussion of statistical methodology is in a separate section of the written report, or at a statistics conference such as this.

These are a set of "how to's", but the most important thing is that the program achieve results which are significant in the perception of the client and his management. If this is the case, the you as statistician will get repeat business.

Training of Others in Statistics:

It was concluded above that the statistical methods used on an industrial project should not be unnecessarily complicated, and that a key to achieving progress toward organizational goals is good communication between the statistician and his clients. Both of these suggest that the statistician can better leverage his time by training others, particularly his most frequent clients. This will not result in the statistician's working herself out of a job, but rather in more widespread productive uses of statistical methods.

Marquardt (1) looked at other scientific disciplines and concluded that their practicioners should use statistics for a large part of total work content. The subject matter will vary according to the work environment. For example, statistical process control is more useful for manufacturing engineers while regression analysis, analysis of variance, and design of experiments are more appropriate for engineers and scientists in research and development. In any of these subject areas, however, training can be provided which will realize benefits for the organization more than offsetting the training cost.

An important factor in successful training is to assure that it can be put to use immediately. In applied statistics, this means learning statistics principles and statistical software at the same time. Of course, the statistical software should be readily available to the course participants when they return to their jobs. SAS training meets these criteria. At Monsanto our employees have attended short courses at SAS Institute, and we just held the SAS Regression and ANOVA course at our Pensacola site last December with 25 participants.

Providing Adequate Tools - Software and Hardware:

The industrial statistician should lead the effort to choose the statistical software, and he should at least make a strong input into the choice of hardware. Regarding the choice of software, the statistician should be sufficiently knowledgeable about uses of statistics by others in order to understand their software requirements. Criteria for the choice of software could include the following:

1. Price
2. Ease of use for the occasional user
3. Ease of data transfer from other software
4. Breadth of statistical analysis capability
5. Graphics quality
6. Speed
7. Hard disk storage requirement
8. Utility of error messages
9. Availability of training
10. Quality of documentation

It may be that the best solution for the organization involves more than one software package. For example, the manufacturing engineer may need statistical process control software while others in the organization, including the statistician herself, will need software with a broader range of procedures. The software should be chosen to fit particular job requirements rather than changing requirements to fit a specific software package.

Hardware selection will usually be the responsibility of the Information Systems Department in all organizations large enough to afford a fulltime statistician, but the latter should have enough knowledge about job requirements to make a strong input. Hardware choices will involve such issues as (1) PC versus mainframe and (2) work centers versus a terminal on every desk. From a user point of view, however, the following factors are most important:

1. The hardware should work consistently and with reasonable speed.
2. There should be convenient access for all users.
3. Terminal and hard-copy graphics capability should be provided.
4. Mainframes and PC's must be linked together with a reliable communications network to facilitate data transfer.

Summary:
The above discussion describes a methodology for statistical consulting in an industrial environment which will maximize the beneficial impact of statistics toward the achievement of company goals. The following text describes an application of these methods.

AN EXAMPLE OF APPLIED STATISTICS AT MONSANTO

Wear-Dated® is a Monsanto trademark which has existed for 25 years, and it stands for excellence in fabric performance. A carpet purchaser can see from the showroom display or by taking samples home whether a particular style meets her requirements for initial appearance; and if she purchases a carpet displaying a Wear Dated label, she knows that the rate of change in appearance will be no greater than what is normally expected. This is true because carpets which qualify for displaying Monsanto's Wear-Dated label have been tested at Monsanto's Technical Center in Decatur, Alabama and found to meet Wear-Dated performance specifications. At this time Monsanto is introducing Wear-Dated Gold Label carpet, a new product which offers protection against stains caused by pets or spillage of foods and beverages. The following example of applied statistics relates to the establishment of appearance retention standards to be used in conjunction with the Decatur testing of such carpets.

Problem Formulation:
During the testing of various styles, it has become apparent that appearance retention is affected by variables associated with carpet construction, such as the weight of fiber per square yard (face weight) and the height of the tufts (pile height). The objective for this work was to determine a set of carpet construction standards which, when used as criteria for Decatur testing, would insure that carpet styles carrying the Wear-Dated Gold Label have satisfactory appearance retention. these standards would be communicated to Monsanto's direct customers, the carpet manufacturers, to maximize their chances of passing the Decatur tests the first time.

To establish these construction standards would require the following:
1. An appearance retention test which could be run at Decatur at reasonable cost.
2. A response surface model relating appearance retention to carpet construction variables.
3. An acceptance criterion for this appearance retention test relating to a known level of in-home performance.

Direct measurement of in-home performance was ruled out for this appearance retention test because of cost and time, although any other procedure used at Decatur would have to be established as a predictor of in-home performance. Another procedure was to place carpet samples in a public place and use an electric eye to count the people passing by. This was a low cost test, but it was found to be unsatisfactory because the traffic count was not a good estimator of actual traffics. What is called the "Contract Walking Appearance Retention Test" was the procedure chosen. For this test, carpet samples are placed on the floor of a large room at the Decatur Technical Center, and people are hired under contract to walk on them in a controlled manner. Each time a person walks the entire circuit, he is required to step on a counter. Using this procedure with 6 walkers, 150 samples can be tested at once, and the equivalent of one year's wear in an average home can be administered in eight 8-hr. days.

The carpet samples are periodically taken up from the floor and graded for their appearance compared with original appearance. This "appearance retention" scale runs from .5 to 7, with increasing values representing greater departures from the original sample, as shown on Figure 1.

Construction of the Model - Phase I, Writing the Equation:
There are six important variables relating to carpet construction, and all of these were varied in this program.
1. Face weight (ounces of fiber per square yd.)
2. Pile height
3. Gauge (number of tuftlines per inch)
4. Singles cotton count (inversely related to yarn weight per unit of length)
5. Singles twist multiple (number of twists per inch divided by the square root of the singles cotton count).
6. Ply twist multiple (number of ply twists per inch divided by the square root of the doubles cotton count).

The number of tufts per inch in the length direction was used as a floating variable to achieve the desired combinations of these six. The result of this strategy is shown on Figures 2 to 4, which are pictorial representations of the construction changes when one variable is changed and the other five are held constant.

The following empirical model was chosen to relate the above construction variables to appearance retention:

$$Y_{ik} = \mu + \alpha_i + \sum_{j=1}^{27} \beta_j X_{ij} + \sum_{k=1}^{5} \gamma_k (\ln T)^k$$

$$+ \sum_j \sum_k (\beta\gamma)_{jk} X_{ij} (\ln T)^k + \varepsilon_{ik}$$

In this model, Y represents appearance retention, X the levels of the coded (zero mean and unit standard deviation) construction variables and their squares and cross products, and T the traffic level. There are a total of 289 parameters in this model, with the following meanings:

- μ is the overall mean appearance retention
- α_i are the effects of the individual carpet items not explained by carpet construction or traffic level. These are random effects distributed NID $(0,\sigma_\alpha^2)$.
- β_j are the slope parameters for the full quadratic model showing the the effects of carpet construction on appearance retention. These effects are independent of traffic level as shown on Figure 5.
- γ_k are the linear thru fifth order effects of the natural log of traffic level on appearance retention, independent of carpet construction. These parameters determine the shape of the curve in Figure 6.
- $(\beta\gamma)_{jk}$ are the interaction parameters which show how carpet construction effects the shape of the curve relating appearance retention to traffic level, as shown on Figure 7.
- ε_{ik} are the appearance retention measurement errors for each carpet item at each traffic level, distributed NID $(0,\sigma^2)$.

Construction of the Model - Phase II, Experimental Design:

There are 170 parameters of interest in the above model, including μ, 27 β_j's, 5 σ_k's, 135 $(\beta\gamma)_{jk}$'s, σ_α^2, and σ^2. This seems to be contradictory to the earlier advice for statistical consultants concerning the avoidance of unnecessarily complicated statistical methods, but an understanding of all of these parameters was required because a series of earlier smaller scale tests gave conflicting information about main effects.

The details of the experimental design will not be discussed here, except that there were 121 different carpet constructions covering the ranges of interest in the six construction variables, each of which were evaluated at six traffic levels selected such that the logarithm of traffic level was about equally spaced. After estimating the slope parameters, therefore, there were 93 degrees of freedom for estimating σ_α^2, and 465 for estimating σ^2.

Construction of the Model - Phase III, Using the SAS System for Data Analysis:

Flow diagrams for the data analysis are shown on Figures 8 and 9. On these diagrams the rectangles represent data sets with variables as columns and observations as rows. The ovals represent operations on the data, and the SAS procedures used are noted along side. On the top of Figure 8, W is the matrix of construction settings, and Y is the matrix of appearance retention grades with each column representing a different traffic level. Using SAS data statements, the W matrix is coded to have zero mean and unit standard deviation and then expanded to include the squared and interaction variables, resulting in the X(LQI) matrix as shown.

Because the appearance retention measurements for each traffic level are made on samples cut from one carpet for each item, this experiment could be considered to have repeated measures on traffic level. For this situation, the REPEATED statement in PROC GLM had two major advantages. First, the POLYNOMIAL transformation was made on the Y matrix in order reduce the number of columns containing essential information and to make these columns more orthogonal. This was done by multiplying Y by the M transformation matrix, which is generated by the REPEATED statement, in order to form the Z matrix which has the same dimensions as Y but whose columns have the following meanings:

Column 1: The average appearance retention grade for each test item across all traffic levels.

Column 2: For each item, the log-linear effect of traffic level on appearance retention.

Column 3: For each item, the log-quadratic effect of traffic level on appearance retention.

Columns 4-6: Higher order effects of traffic level.

The second advantage of the REPEATED statement is that a complete analysis of variance is done on both between and within subject effects and their interactions without having to rearrange the data to make different observations for the traffic levels or adding a class variable denoting test item. Using the output obtained from the SHORT and SUMMARY options, variable selection can be done as shown on Figure 8 to reduce the number of columns needed in the X matrix and to replace some columns of Z with the column mean if there are no significant between-within subject interactions or with a column of zeros if in addition the column mean is not significantly different from zero. The Zr matrix, then, contained the significant information about between subject effects in column 1 and about between-within interactions in the other columns. The columns of C contained information about the curvature of the traffic level main effect only.

Figure 9 covers the steps for (1) conducting a residuals analysis (1) to evaluate the validity of the above analysis of variance and (2) generating predictions of appearance retention for various traffic levels and carpet constructions of interest. First, a DATA step using DO, OUTPUT, and END statements generated the Wp matrix covering the carpet constructions for which predictions were desired. This matrix was then coded and concatonated with Xr, and the resulting matrix was then merged with Zr to form the data set which would be used for model fitting. The superscript p is used to identify the rows of this data set for which appearance retention measurements were not made, none of which contained carpet constructions which were outside of the experimental region. PROC REG was used with an OUTPUT statement to generate the model predictions, which were expressed in terms of the transformed variables in Zr. After mergeing this matrix with C and O, these prediction data were transformed back into the original appearance retention dimensions. A residuals analysis was conducted by comparing the predictions with the observed data, and the remaining predictions, YHATp, were used to achieve a better understanding of the effects of the various construction variables and to set specifications on carpet construction for licensing future WEAR-DATED grades.

Deriving a Solution to the Model - Setting Proposed Wear-Dated Carpet Construction Standards

The residuals analysis was undertaken prior to any effort to draw conclusions from model predictions, in order to be sure of a good model fit. This was confirmed when plots of residuals against model predictions and construction (independent) variables using the PLOT procedure in SAS software gave no evidence of patterns.

One important conclusion was drawn directly from the residuals analysis, however. Figures 10, 11, and 12 are output from PROC GPLOT showing the observed data plotted against the model predictions for 5,000, 20,000, and 80,000 traffics. The correlation is best for 20,000 traffics because the data have more spread, indicating that there is more "signal". It was concluded from this that at low traffic levels there is not sufficient appearance change to be distinguished by the human eye, while at high traffic levels most of the carpets had changed so much in appearance that they were again difficult to judge. This finding was important because differences in appearance retention could now be found at a moderate traffic level thereby lowering the cost of the Contract Walker Appearance Retention Test. From other appearance retention data obtained on carpet grades with known field performance, it was decided to set the acceptance criterion at an appearance retention grade of 4.0 for 20,000 contract walker traffics.

The model predictions showed that the three most important construction variables are singles cotton count (Figure 13), ply twist per inch (Figure 14), and face weight (Figure 15). Figure 13 is a plot of predicted appearance retention (YHAT) versus traffic level on a logarithmic scale for different singles cotton counts. It shows that higher cotton counts (finer yarns) give lower (better) appearance retention grades. This relationship is about the same for all traffic levels, except for the aforementioned difficulties with distinguishing differences at either end of the traffic scale. Figure 14 is a similar plot for different ply twist multiples at a singles cotton count of 3.0, showing that better appearance retention is associated with higher levels of twist. Finally, Figure 15 shows that higher face weight gives better appearance retention, especially for the higher traffic levels. The higher face weight carpets are generally more expensive, of course, because of the cost of the nylon, but these results suggest a corresponding benefit.

The process of setting Wear-Dated Gold Label carpet construction standards consisted of identifying those constructions for which the predicted appearance retention is less (better) than or equal to 4.0. This is shown on Figure 16, which was made using PROC GCONTOUR from a subset of the prediction data with face weight equal to 27 oz. On this plot the horizontal axis is singles cotton count, the vertical axis is ply twist multiple and the contours represent appearance retention. The minimum value for ply twist multiple is 3.4 because yarns below this level are unacceptable for Wear Dated carpets for other reasons. Any 27 ounce carpet with a combination of plytwist multiple and singles cotton count to the right of the 4.0 contour is acceptable. Similar contour plots were made for a range of heavier face weights.

Conclusion:

The test and implementation phases for these carpet construction specifications are now in progress. This has been a rewarding statistical consulting experience which reflects most of the values discussed in the first section of this paper.

ACKNOWLEDGEMENT

Special thanks are extended to G. H. Hill, J. E. Knight, B. I. Thompson, and O. B. Tyler, all of whom are employed at Monsanto Chemical Company's Textile Technology Division in Decatur, Alabama.

This facility is equipped with latest versions of commercial equipment for processing fiber and yarn into fabrics and carpets, and it is staffed with experts in operation of this equipment and in performance testing of finished products. Monsanto is therefore able to conduct evaluations on finished carpet with its own facilities under closely controlled conditions -- a big advantage for the type of testing discussed in this paper.

REFERENCES

(1) D. W. Marquardt, Presentation at the 30th Annual Fall Technical Conference, Charlotte, N.C., October 24, 1986.

(2) Encyclopedia Britannica, 15th Edition, 1981, Vol. 13, p. 596.

(3) J. R. Boen and D. A. Zahn, The Human Side of Statistical Consulting (Wadsworth, Inc.: 1982).

Figure 1.

(Not available)

Figure 2.

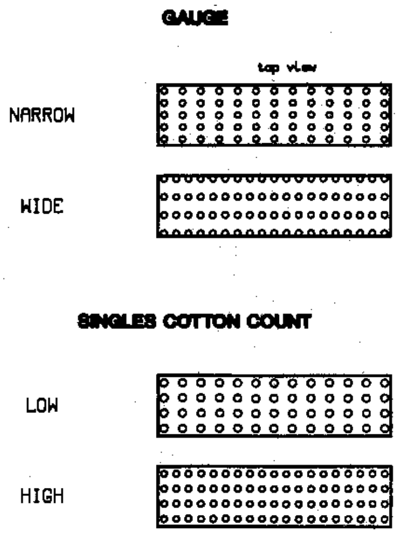

Figure 3.

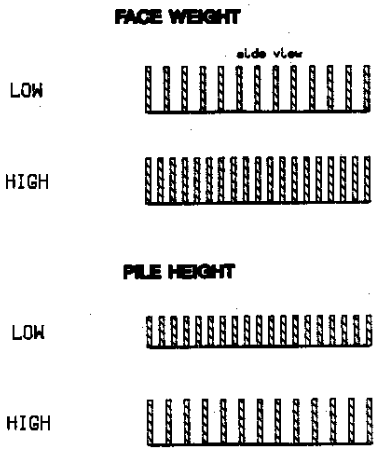

FIGURE 4.

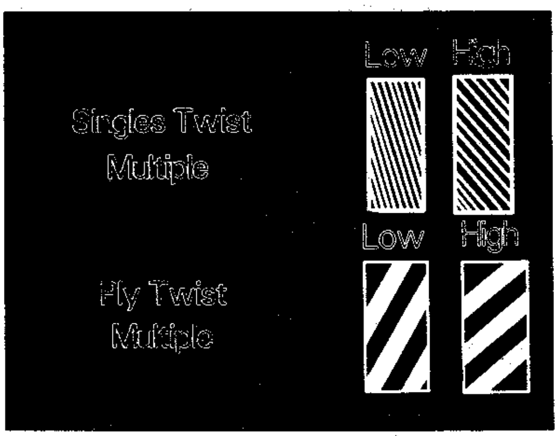

Figure 5.
CARPET CONSTRUCTION MAIN EFFECT

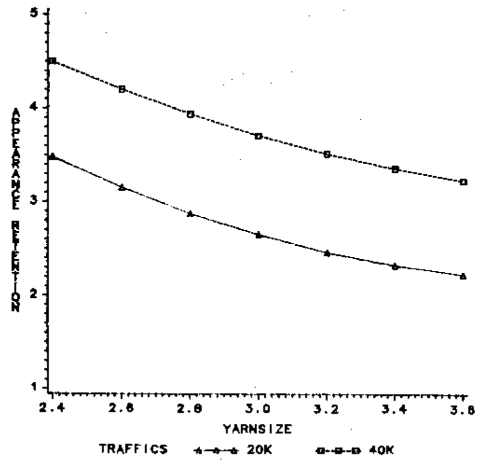

Figure 6.
MAIN EFFECT OF TRAFFICS

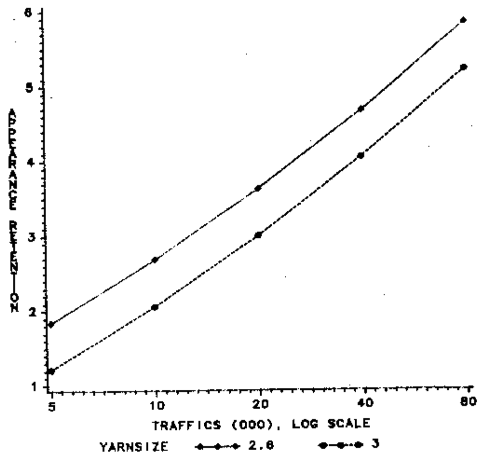

Figure 7.
CONSTRUCTION-TRAFFICS INTERACTION EFFECT

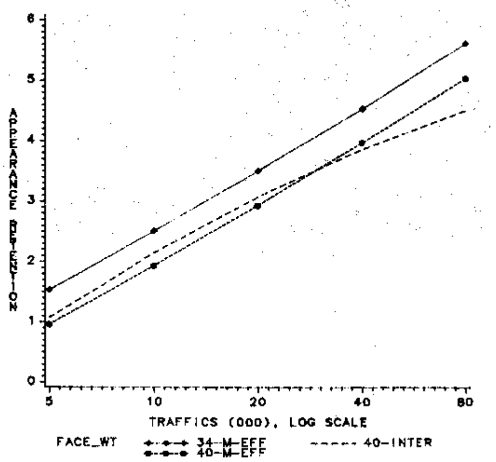

Figure 8.
MODELING FLOWCHART 1
VARIABLE SELECTION

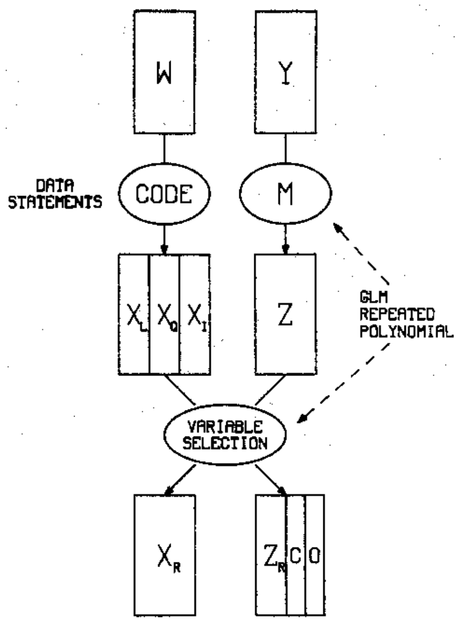

FIGURE 9.
MODELING FLOWCHART 2
PREDICTIONS AND RESIDUALS

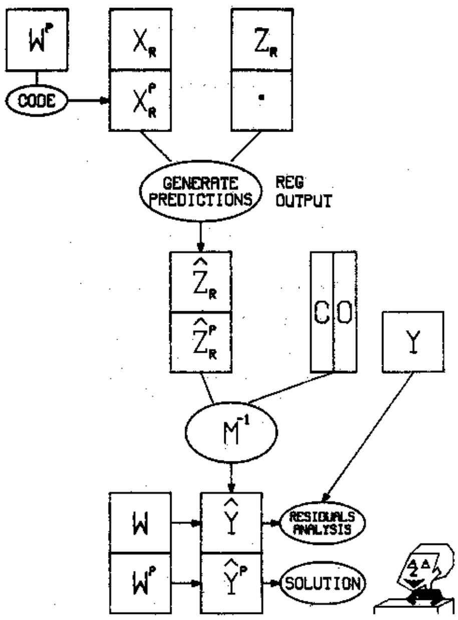

FIGURE 10.
SCATTERPLOT OF OBSERVED VS PREDICTED APPEARANCE RETENTION
5000 TRAFFICS R = .69

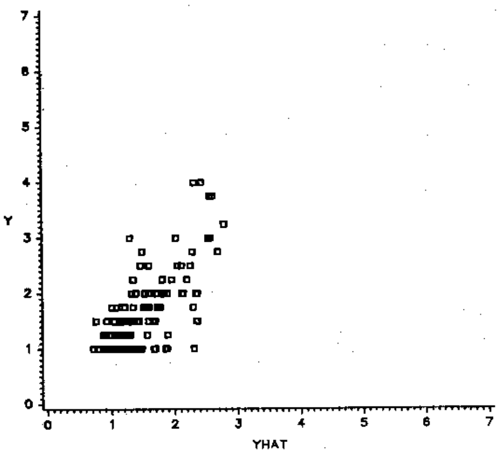

FIGURE 11.
SCATTERPLOT OF OBSERVED VS PREDICTED APPEARANCE RETENTION
20,000 TRAFFICS R = .76

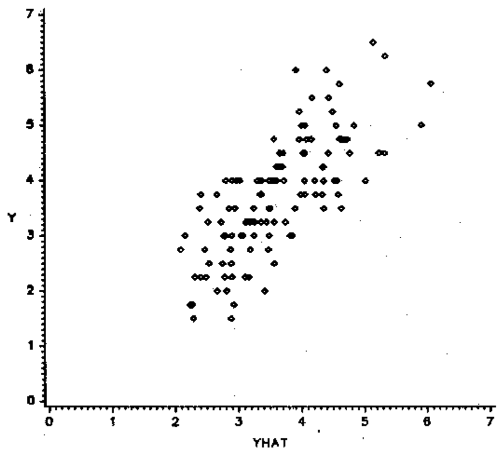

FIGURE 12.
SCATTERPLOT OF OBSERVED VS PREDICTED APPEARANCE RETENTION
80,000 TRAFFICS R = .70

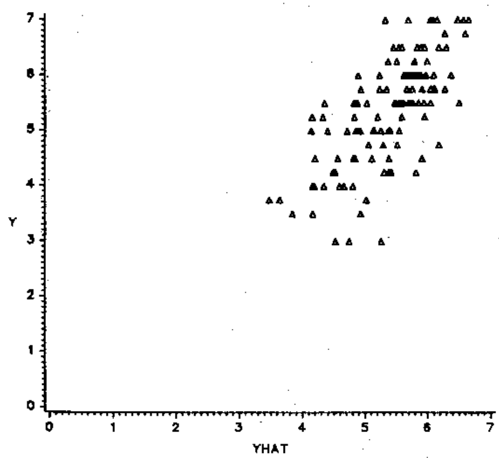

Figure 13.
EFFECT OF COTTON COUNT ON AR
OTHER VARIABLES CENTERED

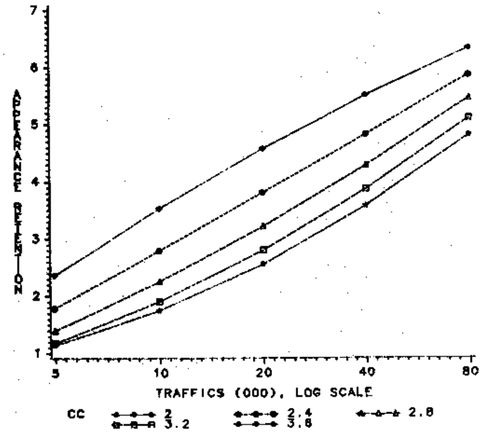

Figure 14.
EFFECT OF PLY TWIST MULTIPLE ON AR
OTHER VARIABLES CENTERED

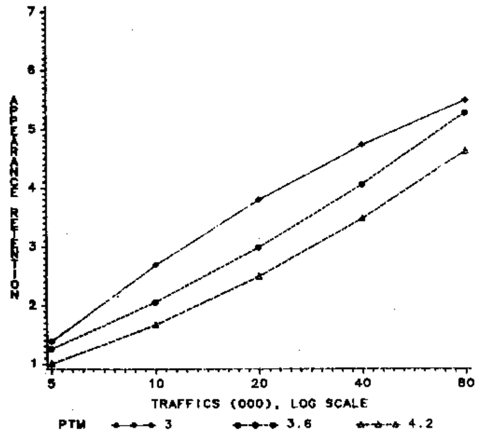

Figure 15.
EFFECT OF FACE WEIGHT ON AR
OTHER VARIABLES CENTERED

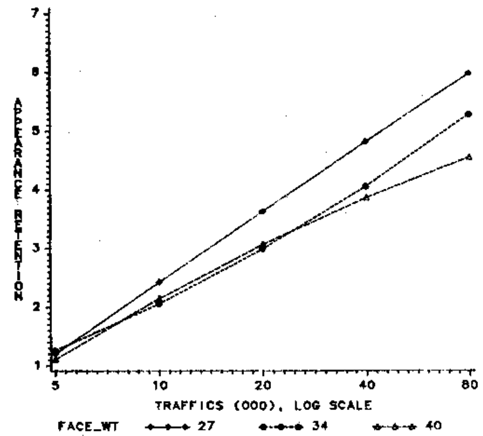

Figure 16.

REGION OF ACCEPTABLE YARN CONSTRUCTIONS