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A NONLINEAR MODEL FOR EVALUATION OF COTTON PROCESSED BY MILLS FOR SPECIFIC
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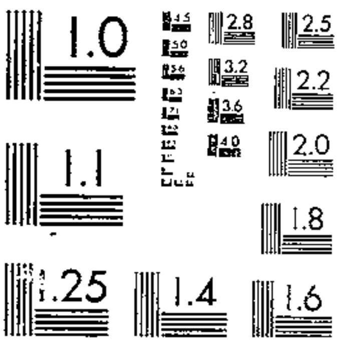

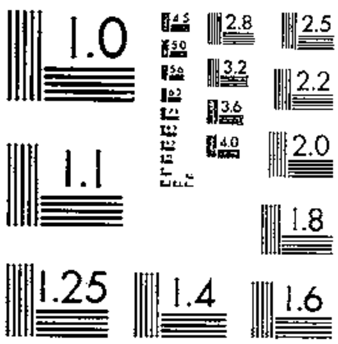

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Technical Bulletin No. 1401

A Nonlinear Model for Evaluation of Cotton Processed by Mills for Specific End Uses

U.S. DEPARTMENT OF AGRICULTURE
Economic Research Service

Preface

This bulletin describes one possible econometric model for evaluating different qualities of raw cotton used in the manufacturing of specified end use products. The model consists of a system of equations through which costs of processing and values of end product are considered in estimating relative use values of various cottons. The model allows for nonlinear relationships. Descriptions of applications to both firm and industry situations are included.

Simplified quantitative examples are included to demonstrate the quantification and solution of the firm and industry applications of the model. Brief notes on useful techniques for quantifying the model are also given.

The model, which can be extended to any stage of textile manufacturing, is intended as an aid to decisionmaking and to long-range planning by managers in the textile industry. Nonlinear applications can be made by managers using the model described in this bulletin. Further quantification work is underway that will supplement—rather than supplant—this model with simpler linear models.

Most of the work on which this report is based was conducted under contract by Mathematica, Princeton, N.J., and the Research Triangle Institute, Durham, N.C. Leaders of the work were M. L. Balinski and W. J. Baumol of Mathematica and Jack Coursey, Floyd M. Guess, and Philip S. McMullan of the Institute. Those who were particularly helpful with preparation and revisions of earlier drafts of the paper are James C. Barnes, The Kendall Company; C. Curtis Cable, Jr., formerly with ERS, now Agricultural Economist, Arizona Extension Service; William A. Faught, Chief, Fibers and Grains Branch, Marketing Economics Division, ERS; and James E. Martin, Dean of Agriculture, Virginia Polytechnic Institute.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 20 cents

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Washington D.C. 20250 January 1969

Summary

A theoretical model for evaluation of cottons is described and exemplified. The operations research approach in general and this specific evaluation model in particular promise valuable assistance in reaching solutions to firm and industry problems of cotton processing and marketing. Since quantification of the firm or industry model is tedious and may take years, the primary immediate advantage offered by this approach is a broad theoretical framework to give direction to firm and industry groups working to solve these problems. In the long run, this approach could furnish many new economies in cotton processing and marketing through greater control of forces affecting processing costs and market values of cotton products.

Simple hypothetical examples of firm and industry applications of the model demonstrate the quantification and solution of the model. Actual industrial applications of the model would be more complex than the examples shown.

A Nonlinear Model for Evaluation of Cotton Processed by Mills for Specific End Uses

By
Preston E. LaFerney
Marketing Economics Division
Fibers and Grains Branch

Introduction

Nature of the Study

This is a report on a major segment of a long-range, highly complex study of the textile manufacturing process in relation to producers of raw cotton, to individuals and groups who handle and modify cotton at various points in its marketing sequence, and to consumers of finished cotton products. The objective of the long-range task is to construct a system of mathematical relationships (a model) which can provide guidance to the various groups working with cotton—from those engaged in the development of new varieties to the manufacturers of consumer goods. This guidance would provide estimates of relative use values of different qualities of raw cotton when each is available in a given supply, processed in an optimum manner, and utilized where it can make its maximum contribution to satisfying consumer demand. The unique approach to studying textile manufacturing in the broad sense, the methodology employed, and the basic data developed are considered important to the industry at this time.

Among the important developments which will complete the research are the *forms* of mathematical relationships which best approximate the manufacturing processes at various stages. The approach proposed in this bulletin is limited to nonlinear relationships. This necessitates a great deal of complexity within the model and requires that nonlinear techniques be provided for solutions. There remains the possibility that simpler linear models can be used successively over narrow ranges of the relevant variables to adequately approximate the textile manufacturing processes. Current work on the long-range project includes the investigation of linear models.

The Problem

The processing of cotton from harvesting through the final product is complex. Technical aspects of the various processes are well known and easily specified. Yet many important analytic questions on the interrelationships among quality of fiber, stages of processing, and product quality remain unanswered. Relatively little is known about the technological and economic effects of variations in processing organization on the performance of fiber during succeeding stages of manufacture. Much more has to be learned, also, about the effects of raw cotton quality on processing efficiency, and the effects of fiber quality and processing organization, separately and in combination, upon the quality of the finished product.

The raw cottons which provide relatively low processing costs and final products of high quality, with economically optimum processing, are clearly the cottons which will be most valuable to the individual firm and to the industry. If use value can be measured and reflected in the market price of cotton, a powerful decision tool will have become available. This bulletin presents a method of evaluation which can accomplish this result.

The proposed method requires (1) fundamental quantitative information to specify the relationships between the physical characteristics of different raw cottons, the costs of each processing stage, and the value of the final product; and (2) a basic model to translate this information into the value figures needed by the firm or industry.

Increasing attention is being given to operations research techniques as a way of representing the complex interrelations in textile processing and obtaining meaningful answers. Answers can be obtained in terms of the relative values of alternative qualities of raw cotton in specified end uses, under processing conditions which approximate the optimum for the firm. This information, when combined with a knowledge of cotton prices, allows the manufacturer to determine the best cotton, or cotton blend, for producing each of his end products.

Although the techniques of operations research usually are applied to one firm, they can also apply to aggregate or industry problems. By extending the model to include many types of firms, a set of use values can be determined which reflect the relative usefulness of various qualities of cotton to processors and which result in the optimum allocation of resources under competitive conditions and given demand and supply situations. This application of the model also is discussed in the bulletin.

Objectives

The purpose of the bulletin is twofold: (1) to describe a model for establishing *relative* valuations for different qualities of raw cotton at the firm and industry levels, and (2) to describe and illustrate what is involved in obtaining data on raw cotton, processing, and final product and utilizing them in the model to estimate relative values of cottons.

This model provides a theoretical framework which management of textile firms may use in solving the interrelated problems of procuring and processing cotton, and selling and distributing final products. More specifically, the model described can give guidance in use of available information and development of new information necessary to determine (1) relative use values of various qualities of cotton in relation to existing technology and new technological developments; (2) optimum combinations of cotton quality and machine settings for manufacturing specific products; (3) the economic sacrifice resulting from use of a less-than-optimum quality of cotton or processing organization; (4) possible trade-offs among various cotton qualities or between cotton quality and processing organization; (5) relationships among the various stages of processing that are critical to manufacturing cost or to product quality; and (6) the overall firm situation relative to the industry, along with indications of actions necessary to improve that situation.

The model ultimately can provide guidance for industry planning and policy formulation. Given "typical" or "average" firm models for the various cotton products manufactured, availabilities of various qualities of raw cotton, and demands for the cotton products, the model can be extended to represent the entire textile industry. Resulting relative use values of various raw cottons in the given industrial setting would provide both shortrun and longrun guidance to plant breeders, cotton producers, researchers, cotton processing machinery manufacturers, textile millers, government service agencies at all levels, and others interested in the textile industry.

Sources of Information

The theoretical model (*1*)[1] developed by Mathematica was simplified and condensed for presentation here. Initial steps have been taken, through work under contract with the Research Triangle Institute, Durham, N.C., and through cooperative work with the Agricultural Research Service Cotton Pilot Spinning Laboratory, Clemson, S.C., to quantify some phases of the model with actual mill or pilot laboratory data. A report on carding and another on spinning were used in preparation of the final section of the gper (*8, 12*). Various spinning studies conducted at the USDA Cotton Pilot Spinning Laboratory also are related to this problem and are cited summarily in the final section of the report and listed in the Bibliography (*18–27*).

[1] Italic numbers in parentheses refer to items in the Bibliography, p. 23.

A Model for Evaluating Cottons

Notation Used in the Model

PROCESSING STAGES.—In the model, each stage of processing must be identified mathematically so that it can be distinguished from other stages and so that essential quality and performance factors of cotton may be evaluated at each stage. The characteristics of the converted forms of cotton fiber at each stage of processing are a result not only of raw cotton quality, but also of the technology employed. For example, the twist put into roving, type of cleaning, draft distribution, etc., must affect subsequent forms and hence technologies encountered in the latter stages of the production process.

To identify each stage of processing, let S_0, S_1, S_2, . . . , S_n, respectively, represent the *set* of fiber characteristics in the field and at the first, second, and nth or final state of processing (fig. 1). Further, let S_1, cotton lint as it leaves the gin, be made up of a set of quality characteristics s_{11}, s_{12}, . . . , s_{1m}, where s_{11} might be fiber length distribution, s_{12} fiber strength, and s_{1m} fiber fineness of ginned lint. Thus, each set S is composed of m measurable fiber characteristics at a given stage of processing, and represents the *state* of the cotton as it leaves that processing stage.

TECHNOLOGIES USED.—Also important to the model are the technologies employed at each stage of processing to convert the cotton into another form. Let T_1, T_2, . . ., T_n represent the technology employed at processing stages 1, 2, through n. In general, then, $T_i \cdot (S_{i-1}) = S_i$. To take a specific set from figure 1, card sliver (S_4) is transformed into drawing sliver (S_5) by employing a certain technology (T_5) during the drawing process. Symbolically, this may be written as:

$$T_5 \cdot (S_4) = S_5$$

To make the above system of notation more clear, imagine a 1-pound lot of cotton as it leaves the cotton field. Suppose we restrict our attention to the weight (at a standard moisture content) of this lot as it goes through the processing stages. Let s_{01} denote the weight of the lot as it leaves the cotton field ($s_{01}=1$), s_{11} the weight of the lot as it leaves the gin, s_{21} the weight of the lot as it leaves the opening room, and so on. Then

$$1 = s_{01} \geq s_{11} \geq s_{21} \geq \ . \ . \ . \ s_{n1},$$

because the ginning process removes seed, trash, etc., the opening and picking process removes some short fiber, trash, etc. The various processing stages T_1, T_2, . . ., T_n transform the lot of cotton, changing its weight by removal of waste. In symbols we write

$$T_2 \cdot (s_{11}) = s_{21}, \ T_3 \cdot (s_{21}) = s_{31}, \ T_4 \cdot (s_{31}) = s_{41} \ . \ . \ .,$$

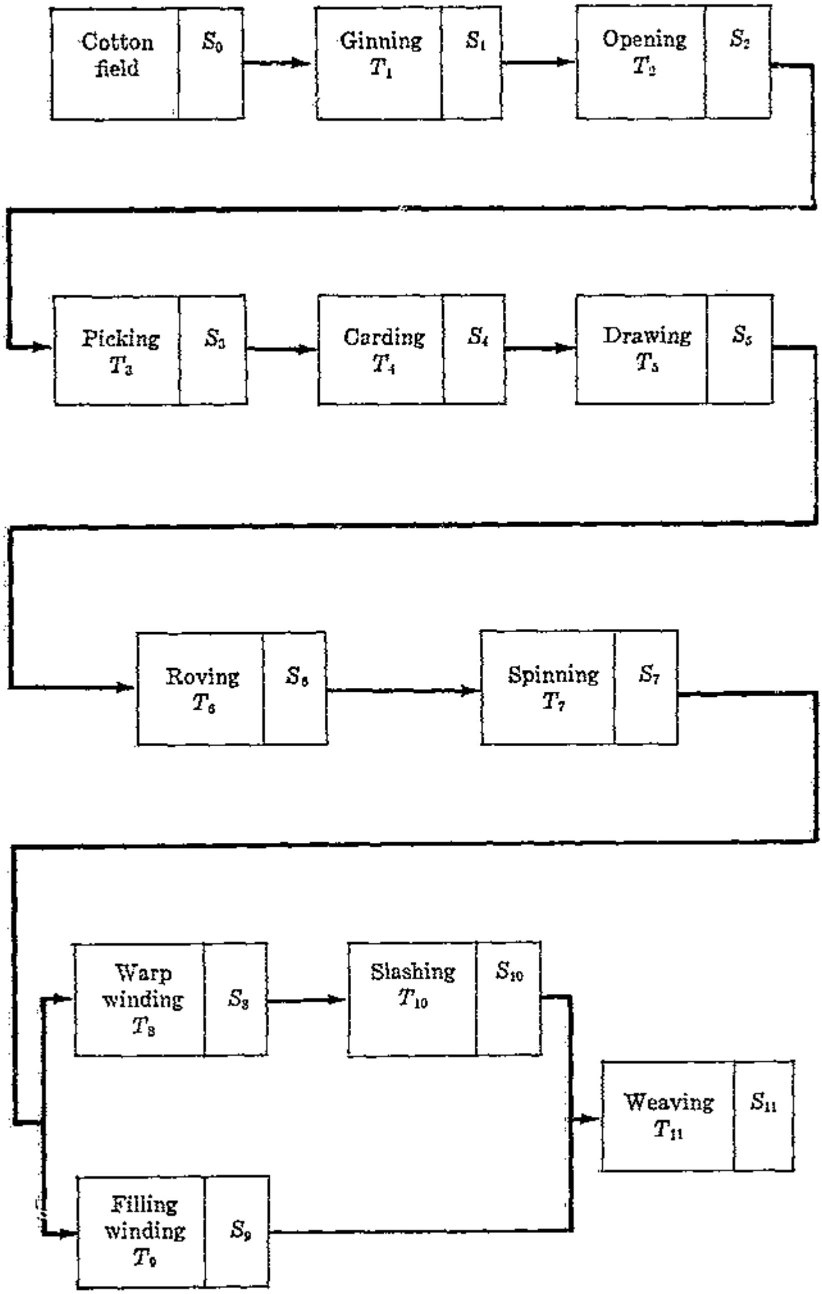

FIGURE 1.—Graphic model representing successive processing stages in the manufacturing of carded cotton products.

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and similarly for any measurable fiber characteristic which is transformed at the successive stages of processing.

Still another quantity is needed relative to the processing technologies in the firm or industry; namely, the r_{ij}, the number of units of output or end-product j produced per unit of raw cotton i.

DEMAND FOR PRODUCT.—A price-demand function is assumed to be known for each end product in any time period, so that market values may be established. If Q_j units (perhaps yards) of end-product j are produced by an entire industry, it is assumed that the price per unit is known, or closely approximated, as a function of Q_j and other relevant demand factors. We call this the unit price, $P_j(Q_j)$. If a firm sells competitively, and most of them do, $P_j(Q_j)$ is not affected by the firm's output. But if the firm enjoys any monopoly of the market, $P_j(Q_j)$ decreases as firm output is increased. In the industry model, $P_j(Q_j)$ decreases as industry output is increased.

Other symbols will be used as needed to complete the firm model or the industry model. The symbols above are used in both industry and firm models.

Firms' Use of the Model

It is assumed, for the purposes of developing the theory below, that cottons (or cotton blends), their converted forms, and end products are meaningfully defined by the sets of factors, S_i (each of these sets of factors is composed of specified quality values relevant to the ith converted form). In particular, end products are uniquely defined by S_n, which represents the last stage of processing (taken to be S_{11}=woven goods in fig. 1), whose components are the variables which define the product in the marketplace.

Furthermore, it is assumed that processing cost functions for each stage of processing technology may be determined as functions of the sets of relevant variables (S_i) which define the types of cottons used and the end products produced.[2] That is, it is assumed that the cost of each stage of processing a particular cotton (or cotton blend) into each particular product may be determined. Finally, it is assumed that a price-demand function is known, relating the unit price of each end product to the total quantity of this product on the market.

Suppose that a specific cotton (or cotton blend) $S_1{}^h$ is to be processed into an end-product j, which is described by a set of measured properties, S_n (n being the last stage of production). Usually, there are many possible technologies which can be used to transform $S_1{}^h$ into S_n or end-product j (e.g., amount and types of cleaning equipment, spinning frame settings, etc.); and the total costs for these different processing technologies may well be different.

[2] In reality, estimation of these cost functions is undoubtedly one of the most difficult obstacles to quantifying the theoretical model.

It seems reasonable to suppose that the individual processor is able (by evolutionary operation or other techniques) to discover the best (in the sense of least-cost) technology for each processing stage (*5, 6, 15*). Thus, it is assumed that the best processing organization is used for each distinct quality of raw cotton and each type of product, although discovery of the best organization is a challenging problem within itself.[3] This means that there is only one possible set of transformations, $T_1, T_2, \ldots, T_n$, and therefore we can express all sets S_i, $i=1, \ldots, m$, in terms of S_1^h (in terms of ginned lint, the raw stock of manufacturing processes);

$$S_2 = T_2 \cdot (S_1^h),\ S_3 = T_3 \cdot (S_2) = T_3 \cdot T_2 \cdot (S_1^h),\ S_4 = T_4 \cdot T_3 \cdot T_2 \cdot (S_1^h), \text{ etc.}$$

We can then find and express the costs per unit of raw cotton input at each stage of processing as functions of the cotton S_1^h and the end-product j. Call these $C_{1j}(S_1^h)$, $C_{2j}(S_1^h)$, ... $C_{nj}(S_1^h)$, where $C_{ij}(S_1^h)$ represents the costs per unit of raw cotton input of the ith processing stage when cotton (S_1^h) is to be converted into end-product j. Here, $C_{1j}(S_1^h)$ might represent the cost of opening, $C_{2j}(S_1^h)$ the cost of picking, $C_{3j}(S_1^h)$ the cost of carding, etc., all per unit of cotton S_1^h, the input to the first processing stage. Thus, if 1 pound of S_1^h is processed, $C_{3j}(S_1^h)$ represents the cost of carding what is left of that pound after removal of waste in the previous stages.

Comparisons of the performance of any two different grades of cotton (or blends) characterized by S_1^h and S_1^i now can be made when both go into end-project j. To obtain the comparison, let $W_j(S_1^h)$ and $W_j(S_1^i)$ represent the gross return to the manufacturer minus processing costs of S_1^h and S_1^i. These are the present discounted use values of the two cottons in the production of end-product j.

Given the estimated quantities discussed above, and assuming the same series of processing stages, comparisons of the use values of the two cottons can be made algebraically as follows:[4]

[3] In fact, determination of the best processing organization is part of the problem of determining the optimum (most profitable) operation. The processing phases which are likely to be critical in determining product quality or overall cost of production should be made a part of the model by providing alternative processing organizations for each raw cotton-end product combination.

To the extent that quality of product is related to processing costs, the alternative processing organizations must be included in the model. Since there is no assurance that a series of least-cost transformations will produce the same quality product as some other series, what is really needed in the model is a joint production process $T(T_4, T_3, T_2)$ which will produce the final product at greatest profit.

Here, to keep concepts clear and notation simple, we assume that there is only one possible set of transformations.

[4] All prices and costs are discounted by standard methods to allow for differences in time of purchase, sale, etc. Also, differences in *value* of waste material are ignored in the model and should be considered as "adjustment factors" to the solutions obtained.

$$W_j(S_1^h)=r_{hj}\cdot P_j(Q_j)-C_{1j}(S_1^h)- \ldots -C_{nj}(S_1^h) \quad (1)$$

$$W_j(S_1^t)=r_{tj}\cdot P_j(Q_j)-C_{1j}(S_1^t)- \ldots -C_{nj}(S_1^t) \quad (2)$$

Therefore,

$$W_j(S_1^h)-W_j(S_1^t)=P_j(Q_j)\cdot[r_{hj}-r_{tj}]-[C_{1j}(S_1^h)-C_{1j}(S_1^t)] - \cdots -[C_{nj}(S_1^h)-C_{nj}(S_1^t)] \quad (3)$$

is the difference between the end-use values to the firm of the two cottons, S_1^h and S_1^t, relative to end-product j. If $W_j(S_1^h)$ is greater than $W_j(S_1^t)$, this means that the value to the manufacturer of a unit of cotton S_1^h is greater than the value of the cotton S_1^t. If $r_{hj}=r_{tj}$, this difference is entirely accounted for by differences in processing costs. Since in equation (3) only *differences* in costs need be computed, fixed costs can be ignored. This is a particularly attractive feature, since computing "true costs" is very difficult.

If the two cottons S_1^h and S_1^t require a different series of processing stages, however, it is necessary to compute the "true costs" for each, and equations (1) and (2) must be computed separately; they cannot be combined to derive equation (3).

This model provides the basic logic by which a manufacturer can decide upon the relative values of the available cottons for his operation in producing various end products. It permits him to choose that cotton (or blend) which has the greatest present net value with respect to processing costs and subsequent value of end product.

Extension of the Model to Meet Industry Problems

The above model provides a uniform decision rule for every individual cotton processor. Suppose, now, that all processors were, in fact, to use this decision rule; many may use some form of the rule at present. It may be expected that, with a given supply and demand, the dynamics of the raw cotton market should settle down or at least fluctuate about some equilibrium set of prices. These prices would depend on the technological costs facing the entire processing industry and on the markets for finished products. The crucial question, of course, is: What is this dependency and how can it be determined to find a set of "equilibrium" prices or implicit (use) values for cottons?

The proposed theoretical model will prove useful also in obtaining these equilibrium prices. This section is designed to show how to use the model to determine a set of prices or values which reflect the true values of the cottons to the processors and which will result in an optimum allocation of resources.

DETERMINING LEAST COST.—The model will determine the quantities of the various cottons available (call them i, $i=1, 2, \ldots, m$) which should be used by the entire processing industry to produce the most profitable (or least cost) levels of all end products. Each cotton,

i, is different at the raw cotton or ginned lint stage, based on the characteristics described above. Thus, S_1, described earlier, differs in quality among these cottons. Simultaneously, a set of imputed or marginal values or prices for the various cottons will be determined which will represent the best prices that growers can expect to obtain from an efficiently operating processing industry.

Let A_{ij} ($i=1, \ldots, m$ and $j=1, \ldots, n$) be estimates of the average processing costs per unit of cotton i used in making end-product j (substitute A_{ij} for the C_{ij} which were used in the firm model). Further, let R_i be the total number of units of cotton i available for purchase by manufacturers (including surpluses, if appropriate). The structure of the problem is summarized in figure 2.

In figure 2, availability (R_i) of any raw cotton i must not be exceeded by the total inputs of that cotton. The inputs of any raw cotton i are free to enter production of any product j so long as its processing costs (A_{ij}) and yields (r_{ij}) are favorable in relation to those of other raw cottons. Total products (Q_j) are determined through the market demand functions by their relative prices $P_j(Q_j)$, subject to raw cotton availabilities and processing costs. Given a perfect market, through which final consumers can make their wants known through prices paid, each raw cotton will find its optimum use (highest return) while the optimum (most profitable) levels of all products j are being produced.

The total manufacturing industry problem can then be thought of as that of purchasing cottons to minimize the value of total costs minus total returns.[5] Let x_{ij} be the number of units of cotton i used by the entire industry for the production of end-product j; let A_{ij} be the average unit cost of transforming cotton i into end-product j; and let R_i be the total supply of cotton of type i which is currently available to the industry.

The industry's objective may be stated as the minimization of

$$f(x)=\sum_{i,j}A_{ij}\cdot x_{ij}-\sum_{j}P_j(Q_j)\cdot Q_j, \tag{4}$$

subject to the condition that

$$\sum_{j}x_{ij}\leq R_i, \text{ for all } i, \text{ that} \tag{5}$$

$$\sum_{i}r_{ij}\cdot x_{ij}=Q_j, \text{ for all } j, \text{ and that} \tag{6}$$

$$x_{ij}\geq 0, \text{ for all } i, j, \text{ and} \tag{7}$$

$$Q_j\geq 0, \text{ for all } j. \tag{8}$$

[5] This is usually reversed in discussions of economic theory. However, it is discussed in the above manner to set the stage for a minimization problem to be solved with digital programming.

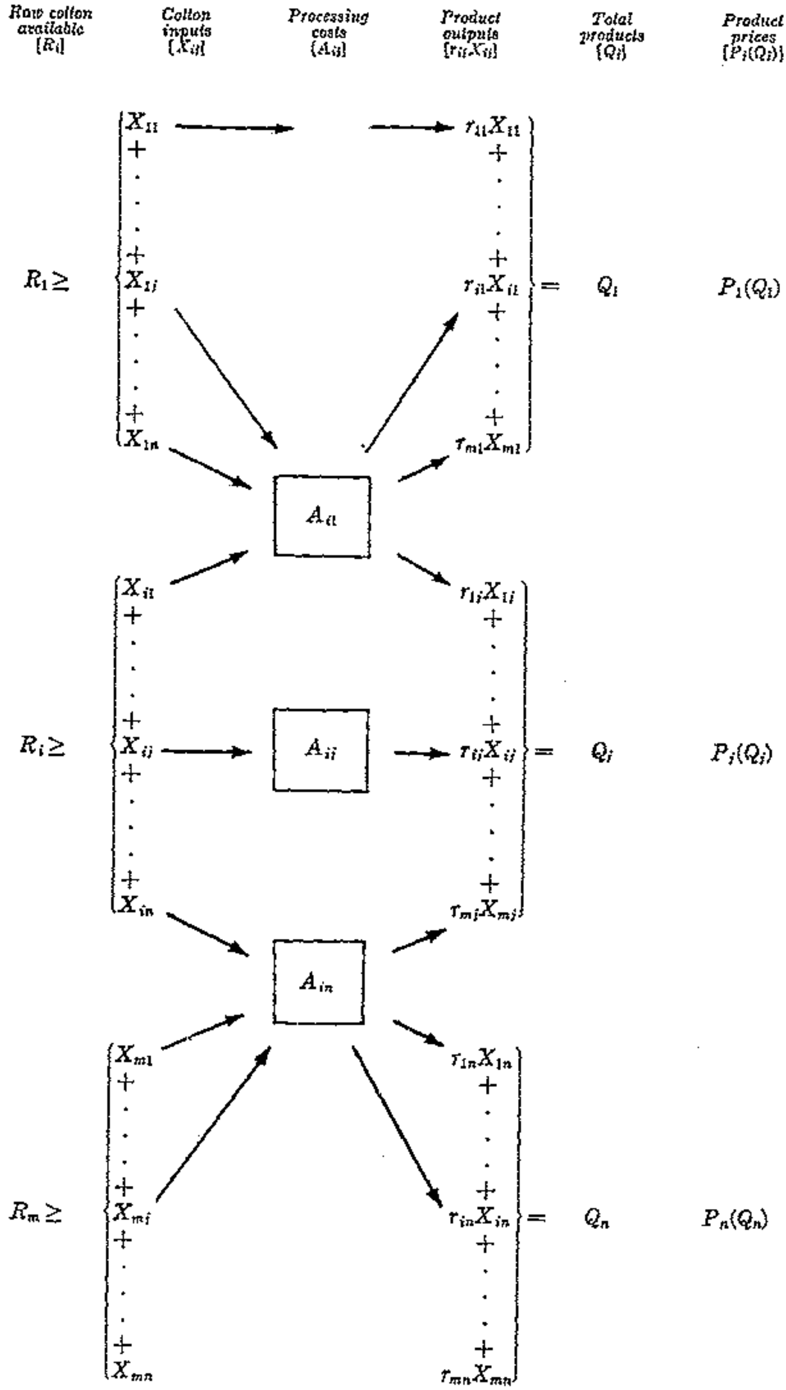


FIGURE 2.—Summary statement of the theoretical model as used on the industry level.

This is a typical mathematical programming problem. Once it is quantified, it is soluble for x_{ij} and Q_j. Various computer programs are available for such problems. The solution would give the quantity x_{ij} of each type of cotton i going into each end-product j to maximize total returns minus total costs for the industry.

DETERMINING USE VALUES.—Use values of the cottons $i=1, 2, \ldots, m$ remain to be computed. This is accomplished through application of a duality theory of convex mathematical programming. This technique is essentially another programming problem of the same form as that above, which may be stated as

$$\text{Maximize } g(u, x)=\sum_{i,j} Q_j \cdot \frac{\partial P_j(Q_j)}{\partial x_{ij}} \cdot x_{ij}-\sum_i R_i \cdot u_i, \tag{9}$$

where the u_i are to be determined, subject to the conditions that

$$u_i \geq \frac{\partial}{\partial x_{ij}}[P_j(Q_j) \cdot Q_j]-A_{ij}, \text{ all } i, j, \tag{10}$$

and

$$\sum_i r_{ij} \cdot x_{ij}=Q_j,\ x_{ij} \geq 0,\ u_i \geq 0, \text{ all } i, j. \tag{11}$$

Although it is somewhat difficult to give a complete economic interpretation to the objective function (9) of the dual problem, given a solution to the primal problem (equation 4) all that remains to be done is to find u_i which maximize $-\sum_i R_i \cdot u_i$ since the rest of the terms in (9) have been determined. The object is to minimize

$$\sum_i R_i \cdot u_i \tag{12}$$

constrained by

$$u_i \geq 0 \tag{13}$$

and

$$u_i \geq \frac{\partial}{\partial x_{ij}} \cdot [P_j(Q_j) \cdot Q_j]_{x_{ij}=x_{ij}^0}-A_{ij}, \text{ all } ij \tag{14}$$

where x_{ij}^0 is from the solution to the model $f(x)$ above. That is, the u_i must be positive and at least as large as the gross marginal revenue of the j^{th} product using the i^{th} input.

The u_i then, may be interpreted as the marginal prices or imputed values of the cottons i. For an economic interpretation, the problem of (12) to (14) is that of finding a set of prices u_i for cotton i which minimizes the total imputed price or value of all cottons $\Sigma R_i u_i$ subject to the condition that the price of each cotton must be at least as large as the greatest value of net marginal revenue produced by that cotton (i.e., among its alternative uses).

Therefore, the prices u_i assigned to cotton i are certainly "fair" to cotton growers: they are the greatest net marginal revenues produced by the cottons, given raw cotton availabilities and market demands for products. On the other hand, the prices u_i are also "fair" to the manufacturers, since they correspond to the most efficient production schedule and cheapest total cost of cottons. They are the prices toward which the market will move (in equilibrium) as long as the same processing cost structure, cotton availabilities, and product demands prevail.

Special Techniques Useful in Quantifying the Model

This brief discussion of techniques is designed to give some direction as to how one proceeds to give quantitative meaning to the theoretical model described above. Many firms which manufacture raw cotton may have data available with which to quantify at least a portion of the general model. The descriptions presented here are general, and intended only as pertinent suggestions concerning techniques which should be useful in obtaining relevant information and in using the information in the model. Specific detail as to analytical procedures is available in the references cited in the bibliography.

UTILIZATION OF AVAILABLE DATA.—A few well-known techniques for analyzing data should prove useful to firms which have access to records of their past operations, in terms of cotton quality, processing performance, and end-product quality. Some of the more promising analytical techniques and considerations in using them are:

(1) Multiple regression and correlation;
(2) Use of information concerning uncontrolled variables in controlled experiments; and
(3) Examination of interrelationship among the responses in controlled and semicontrolled experiments, and in data recorded from ongoing production processes.

There is a tendency to analyze experiments so that a response is measured in terms of one variable at a time rather than as a joint function of all independent variables. This can be very misleading and costly. Consider the following example, in which spinning end breakage Y is expressed as a function of fiber fineness X or fiber length uniformity Z or both:

Ends down (Y)	*Fineness* (X)	*Uniformity ratio* (Z)
45	3.3	42.0
43	3.7	41.7
38	4.2	43.3
61	4.4	41.7
32	5.0	46.0
29	5.4	46.0

Ignoring the Z column and expressing Y as a function of X yields the formula

$$Y=73-7.35X, \text{ with } r^2=0.25.$$

On the other hand, expressing Y as a function of Z while ignoring X yields the equation

$$Y=240-4.58Z, \text{ with } r^2=0.68.$$

Neither of these equations, however, is even close to the true relation. Multiple regression analysis considers the effects of X and Z on Y simultaneously, yielding the equation

$$Y=345+10.78X-8.07Z, \text{ with } R^2=0.83.$$

which is a completely different relation from either of the two above.

Initial differences in cotton inputs often affect a measured response as much or more than does the treatment. As an example, suppose the effects of two types of ginning procedures on percentage of short fibers are to be examined. For this purpose, two loads of cotton are ginned by each procedure and the following table of percentages of short fiber are obtained:

Ginning method 1	*Percent*	*Ginning method 2*	*Percent*
Load 1	11.5	Load 3	7.5
Load 2	10.0	Load 4	6.0

Apparently, ginning method 2 is better than method 1, since method 2 yielded the lower short fiber content. But the following information is also available concerning moisture content during ginning, which the experimenter was unable to control:

	Percent		*Percent*
Load 1	3.8	Load 3	5.0
Load 2	4.0	Load 4	6.5

Since there is also a good relationship between the moisture content and percentage of short fibers, moisture would also have to be considered when evaluating the effects of the two ginning methods. This example is typical of many problems which arise in controlled experiments. One must be reasonably certain that all relevant variables are, in fact, controlled, or at least measured.

Checking for interrelations among different responses to a treatment often reveals useful information. As an example, suppose that a controlled experiment using four ginning procedures is run and that a load of cotton is split equally among the four processes. After processing, both the percentage of short fibers and fiber strength are measured:

Ginning method	*Percent of short fiber*	*Strength*
1	10.0	22.4
2	9.0	24.9
3	8.0	25.3
4	10.5	21.4

Methods 2 and 3 would be considered best, since they yielded higher strength and lower short fiber content. Examine, however, the product of percentage of short fiber and fiber strength, and compute the table:

Method	*Product*	*Method*	*Product*
1	224	3	202
2	224	4	225

Note that method 3 has a product that differs markedly from the others. This raises some questions. Are the measurements on method 3 in error? Does this procedure alter the strength of the fiber without changing the distribution of fiber lengths? Or, does the difference reflect variation within the original source of cotton? This technique gives an indication that there is something different about either the measurements or the effects in method 3. Another, and perhaps more common, use of such response interrelations is in techniques of filling in missing data from an experiment. Again, use of interrelations among data may prove to be very fruitful in studying cotton processing data.

In addition to the techniques discussed, thorough examination of available data is a necessity. This amounts to analyzing data in many different ways to discover clues concerning possible effects or lack of effects. Many such techniques are discussed in two papers by Tukey (*13, 14*).

EXPERIMENTATION TO DETERMINE CHARACTERISTICS OF COTTON PROCESSING.—Cotton processing is a multistage operation and experiments can be conducted on one stage at a time, or on the cotton going in initially compared with the finished end product, or on some combination of these. The primary interest is in relating finished product to properties of raw cotton and cost of processing. It would seem that the most efficient procedure for determining such relations is a combination of semicontrolled production experiments, controlled pilot-plant experiments, and detailed experiments at various stages of processing.

The type of strategy that appears most reasonable to adopt is as follows: To determine effects of differences in raw cotton quality either on the final output or on the output of certain stages of production, it would seem reasonable to conduct controlled experiments in a pilot plant. One type of experiment that seems desirable at this stage is a fractionated design that will test for the main effects of from two to many factors at a time. Responses observed should include those connected with intermediate processing stages as well as those connected with the final product. When any effect is found to be isolated to one stage of processing then that stage can be studied in more detail. The controlled experiments can be supplemented with multiple regression analyses of mill production data.

Second, semicontrolled experiments should be carried out in ongoing production processes or in pilot plants with certain characteristics of the inputs and processing operations being changed by small amounts that may change the outputs by correspondingly small amounts. In this manner, the established relationships can be refined. Evolutionary operation is typical of this kind of experiment. This is an attempt to study a process during actual production without drastically altering or disturbing the outputs. Whitwell states that this procedure is an attempt to circumvent the "noise problem," that is, to overcome the purely random variations in the production process (*15*). The method generally requires considerable replication.

A principal concern is to use experimental results of each processing stage in analyzing the next stage. The nature of cotton manufacturing makes it impossible to limit attention to examination of final output alone. Efficient experimentation necessarily requires analysis of intermediate products and processing stages.

Some Specifics on Variables of the Theoretical Model

A brief statement of types of variables in the evaluation model and of possible ways to estimate each might be useful at this point. The input-output coefficients, r_{ij}, for each quality of cotton can easily be estimated by firms with records of past production. Most mill managers could probably produce fairly close estimates of r_{ij} for the raw cottons i and end-products j with which they are concerned.

Estimates of unit cost, C_{ij} (S_i^h), normally are much more difficult to obtain. Perhaps by reexamination of all available data, hypotheses can be developed which would indicate properties of cotton which account for differences in processing costs at the various processing stages. These hypotheses would need to be tested by experimentation along the lines discussed above. In any case, it appears that numerous experiments will have to be performed where the set of cotton quality factors (S_i^h) at each processing stage of each product is systematically varied. It would be desirable to obtain several observations on C_{ij} (S_i^h) for each i, j, S_i^h combination and then use the average of each combination as the cost estimate.

For the individual firm it is assumed that price $P_j(Q_j)$ is reasonably independent of firm output in most cases. But the price which the firm may expect for end-product j is usually unknown in advance of production. There is a large amount of literature on the problems involved in the estimation of demand functions. Most mills may be able to obtain fairly good estimates of end-product price based on recent experience and knowledge of factors likely to change price in the short run.

These estimates of r_{ij}, $C_{ij}(S_i^h)$, and $P_j(Q_j)$ are obviously more easily obtained for use by one firm than for use in setting industry policies. Problems of aggregation complicate the determination of estimates for industrywide use. Perhaps, as suggested in the introduction, "typical" or "average" firm estimates can be used as satisfactory approximations of industry aggregates.

Simplifying Examples of Quantified Models

Firm Model

For those who are not accustomed to thinking in algebraic terms, the following example is offered to illustrate and perhaps clarify use of the firm model. Although the data are purely hypothetical, they appear to be reasonably typical of those actually existing in an individual processing firm.

To keep the example simple, a few assumptions are necessary. Two cottons of different quality are used to make one product j, 40/1 carded knitting yarn. Each cotton produces yarn which meets specifications. Only five quality factors are observed at each stage of processing (fiber length, length uniformity, strength, grade, and fineness). Also, only five processing stages are used by the hypothetical firm (opening and picking, carding, drawing, roving, and spinning). The scope of this abbreviated example, although purposely brief, is sufficient to demonstrate how the model would be used by an individual firm to estimate relative use values of two or more raw cottons. The firm's operation is shown graphically in figure 3. Although the setup in figure 3 appears to be fairly simple, two important factors would force an actual mill problem to be more difficult: (1) the cost, price, and input-output coefficients are, in fact, difficult to obtain, and (2) actual problems typically involve a greater number of different raw cottons, processing stages, and cotton quality factors at each stage of processing.

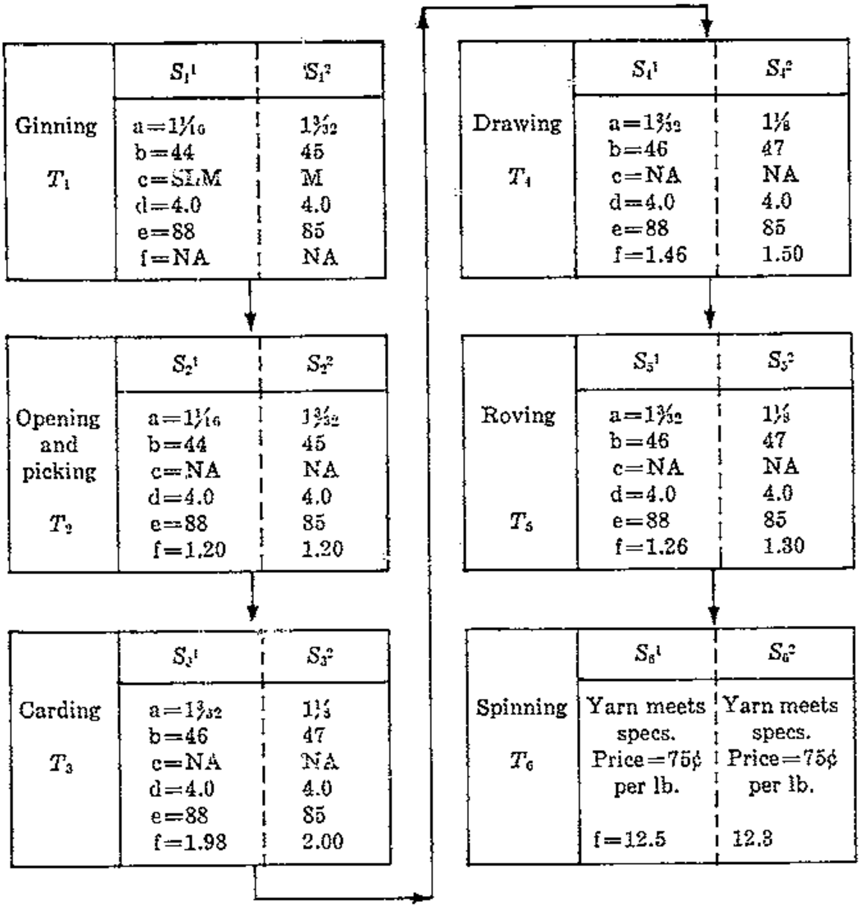
Based on the hypothetical data of figure 3, the equations of the model (equations (1)–(3)) are:

$$W_j(S_1^1) = r_{1j} \cdot P_j(Q_j) - C_{2j}(S_1^1) - \ . \ . \ . \ - C_{6j}(S_1^1) \qquad (1a)$$
$$= .815(75) - 1.20 - 1.98 - 1.46 - 1.26 - 12.5$$
$$= 61.12 - 18.40 = 42.72 \text{ cents/lb. raw cotton}$$
$$W_j(S_1^2) = r_{2j} \cdot P_j(Q_j) - C_{2j}(S_1^2) - \ . \ . \ . \ - C_{6j}(S_1^2) \qquad (2a)$$
$$= .85(75) - 1.20 - 2.00 - 1.50 - 1.30 - 12.3$$
$$= 63.75 - 18.30 = 45.45 \text{ cents/lb. raw cotton}$$
$$W_j(S_1^2) - W_j(S_1^1) = 45.45 - 42.72 = 2.73 \text{ cents/lb.} \qquad (3a)$$

Therefore, cotton 1 has an end-use value in this mill which is 2.73 cents lower than that of cotton 2. The mill would use cotton 2 to make 40/1 knitting yarn so long as the price differential is anything less than 2.73 cents per pound of raw cotton.

Industry Model

The following is a very simple hypothetical example which demonstrates how the theoretical model of an industry is used to estimate



a=Staple
b=Uniformity
c=Grade index
d=Micronaire reading
e=Strength (Pressley "O", 1,000 p.s.i.)
f=Cost of processing $C_{ij}(S_i^h)$, h=1,2
NA=Not Appropriate

r_{1j}=pounds Yarn/1 pound raw cotton 1=0.815
r_{2j}=pounds Yarn/1 pound raw cotton 2=0.850

FIGURE 3.—Graphic summary of the simplified firm model quantified with hypothetical data.

relative use values of cottons under specified supply, demand, and cost conditions. An actual case would be much more complex in terms of the number of firms, the number of different cottons, and the number of end products involved. However, the principles involved in this simple hypothetical example are sufficient to handle any actual case, when extended to include the larger number of firms, cottons, and end products.

For simplicity, assume an industry composed of two firms which produce two distinct end products from two different raw cotton inputs. They are supposed to be "typical" or represent the industry "average" firm. The following essential data, in terms already defined, are assumed to exist in the industry:

Raw cotton available:

$$R_1 = 300{,}000 \text{ bales} = 150 \text{ million pounds}$$
$$R_2 = 200{,}000 \text{ bales} = 100 \text{ million pounds}$$

Unit output per unit of input:

$$r_{11} = .815$$
$$r_{21} = .850$$
$$r_{12} = .800$$
$$r_{22} = .830$$

Average total processing cost per pound:

$$A_{11} = .184$$
$$A_{21} = .183$$
$$A_{12} = .196$$
$$A_{22} = .194$$

Market demand:

$$P_1(Q_1) = 0.80 - 0.000000005\ Q_1$$
$$P_2(Q_2) = 0.90 - 0.000000003\ Q_2$$

To determine the combination of raw cotton inputs and final product output which maximizes returns to the industry, it is necessary to find the minimum of the following function through quadratic programming:

$$\begin{aligned} f(x) &= A_{11}x_{11} + A_{21}x_{21} + A_{12}x_{12} + A_{22}x_{22} - P_1(Q_1)\cdot Q_1 - P_2(Q_2)\cdot Q_2 \\ &= A_{11}x_{11} + A_{21}x_{21} + A_{12}x_{12} + A_{22}x_{22} - 0.80Q_1 + 0.0000000005Q_1^2 - 0.90Q_2 \\ &\qquad + 0.000000003Q_2^2 \end{aligned}$$

Subject to:

$$x_{11}+x_{12}\leq 150 \text{ million}$$
$$x_{21}+x_{22}\leq 100 \text{ million}$$
$$.815x_{11}+0.850x_{21}=Q_1$$
$$.800x_{12}+0.830x_{22}=Q_2$$
$$x_{ij}\geq 0$$
$$Q_i\geq 0$$

The solution in pounds is:

$x_{11}=120$ million $X_{14}=19$ million

$x_{12}=30$ million $Q_1=166{,}650{,}000$

$X_{13}=81$ million $Q_2=39{,}770{,}000$

Maximum return=$104 million

To determine the relative end use value (theoretical price) of each cotton in each end use, the following function is maximized (u_1 and u_2 are the desired prices):

$$g(u,x)=Q_1\frac{\partial P_1(Q_1)}{\partial x_{11}}x_{11}+Q_1\frac{\partial P_1(Q_1)}{\partial x_{21}}x_{21}+Q_2\frac{\partial P_2(Q_2)}{\partial x_{12}}x_{12}+$$
$$Q_2\frac{\partial P_2(Q_2)}{\partial x_{22}}x_{22}-R_1u_1-R_2u_2$$

Subject to:

$$u_1\geq\frac{\partial}{\partial x_{11}}[P_1(Q_1)\cdot Q_1]-A_{11}$$
$$u_1\geq\frac{\partial}{\partial x_{12}}[P_2(Q_2)\cdot Q_2]-A_{12}$$
$$u_2\geq\frac{\partial}{\partial x_{21}}[P_1(Q_1)\cdot Q_1]-A_{21}$$
$$u_2\geq\frac{\partial}{\partial x_{22}}[P_2(Q_2)\cdot Q_2]-A_{22}$$
$$r_{11}x_{11}+r_{21}x_{21}=Q_1$$
$$r_{12}x_{12}+r_{22}x_{22}=Q_2$$
$$x_{11},\ x_{21},\ x_{12},\ x_{22}\ \geq 0$$
$$u_1,\ u_2\geq 0.$$

The solution to this problem (the dual) reveals that the cottons, when used in the optimum manner, would be priced in accordance with their marginal productivities as follows:

Cotton 1: $u_1=33.3$ cents per pound
Cotton 2: $u_2=35.5$ cents per pound

Initial Efforts To Quantify the Model

The preceding discussion has related only to theory and to highly simplified examples of its application. Application of the model to one firm or to the industry involves many practical problems of specifying and measuring relevant variables and establishing interrelationships among these variables. Thus, in initial phases of quantifying a firm or industry model, some segmenting or dividing of processes is almost essential. Ultimately all phases of processing would need to be considered simultaneously. However, studying isolated processing phases would reveal ways to suboptimize processing within one phase and would furnish data necessary to quantify the complete model at a later time.

Two studies of isolated cotton processing stages have been made within the theoretical framework described above. One involves the carding process, the other involves spinning. Both were made under contract with the Research Triangle Institute, Durham, N.C. (*8*, *12*). In addition to these studies, numerous controlled studies have been conducted at the Cotton Pilot Spinning Laboratory, Clemson, S.C., which relate to processing stages through spinning.

Carding Study

The primary objective of this study was to derive measures of the interrelationships among quality and cost variables in cotton carding. Secondary objectives were to develop a technique for measuring the relationship between physical and monetary variables in carding and to develop a detailed descriptive model of the carding process.

To accomplish the primary objective, data were obtained from J. F. Bogdan, School of Textiles, North Carolina State University at Raleigh. The data were derived from experiments on picker lap obtained from six mills and were analyzed by multiple linear regression. Experiments involved the following types and qualities of cottons:

Mill submitting cotton	Territory	Staple length (inches)	Grade	Number of tests
A	Carolina	1	LM	41
B	Unknown	15/16	LM	28
C	Miss. Delta	1 1/16	SM	34
D	Miss. Delta	1 1/16	SM	34
E	Eastern (50%) & Arizona (50%)	1 1/32	SLM	31
F	Unknown	1	M	30

The following seven measurements of material were made and used as dependent variables in the analyses:

- Count-strength product [6]
- Cylinder waste
- Doffer waste
- Flat strip waste
- Fly waste
- Scavenger waste
- Total waste

[6] This is a yarn characteristic, so may appear to be out of place in the list of waste materials. It was included in the test since it was subject to change due to carding variables.

Twenty-four separate carding variables (various speeds, distances, and settings) were related to the dependent variables.

Valuable knowledge was gained relative to the effect of carding variables upon card waste, which for the most part confirmed and extended findings of previous work. The numerous equations showing the significant relationships are not included in this report. General significant results are summarized briefly below.

In most cases, the results of these analyses confirmed earlier published reports by Bogdan and others. There was one instance where the present results conflicted with those presented by Bogdan. There were several instances of effects found that had not been covered in the carding literature. Finally, in two cases, results which had been expected were not found.

REVERSALS.—In one case, findings contradicted those expected:

a. Decreasing the distance from the front knife plate top edge to the cylinder significantly increased fly waste, but had no significant effect on flat strip waste.

EFFECTS DETECTED NOT PREVIOUSLY REPORTED IN THE CARDING LITERATURE.—In six cases, some new effects of carding variables upon waste were found:

a. Increasing the distance from cylinder to cylinder screen, middle setting, was found to increase scavenger waste.
b. Increasing the distance from the bottom front knife plate to the cylinder was found to increase both fly waste and total waste. This variable had been virtually ignored in the carding literature as a cause of fly waste.
c. Increasing the distance between the back knife plate, bottom edge setting to the cylinder was found to increase flat strip waste.
d. Increasing the distance from the feed plate to the top mote knife was found to increase flat strip and scavenger waste.
e. Increasing the length of the licker-in screen was found to decrease doffer, scavenger, and total waste, and to increase cylinder waste.
f. Increasing the number of wires on the licker-in was found to increase cylinder and fly waste, and to decrease doffer, flat strip, and scavenger waste.

REPORTED ON IN CARDING LITERATURE, BUT NOT DETECTED.—In two cases, significant effects had been expected as they have been reliably reported in the carding literature, but they were not found in this analysis:

a. The back plate, top edge distance from the flats did not affect scavenger waste.
b. The distance from the front knife plate top edge to the flats did not affect waste.

Although valuable knowledge was gained in the carding study, this knowledge requires further development and expansion. For future study, statistically designed experiments were suggested by the contractor as the most efficient route to a better understanding of cotton carding. It was suggested that the following concepts should be incorporated in future experiments with carding:

1. The number of variables should be kept to a strict minimum.
2. The design should allow for nonlinear effects.
3. Provision should be made to estimate the effects of carding production rate.
4. Cotton fineness and strength should be added to the cotton quality variables.

Spinning Study

The purposes of the spinning study were (1) to determine the feasibility of utilizing historical fiber quality, processing, and product quality data from a firm's commercial operation to establish interrelationships among measured fiber properties and subsequent spinning performance and quality of yarn, (2) to establish quantitatively as many of these relationships as possible from available data, and (3) to obtain and relate detailed spinning cost data to variations in raw cotton quality. The study constituted a joint effort involving one mill of a textile corporation, the Operations Research and Economics Division of the Research Triangle Institute, and the Economic Research Service.

Data on cotton properties and mill operations covering 152 weeks of operation of one plant were collected and compiled for statistical analyses. Detailed cost data for the spinning department were collected or estimated by the firm's personnel. Multiple regression analysis was used to estimate the relationships between cotton properties and operational performance. The results of the multiple regression analyses were used with plant cost data to perform a preliminary economic evaluation of cotton properties.

Although some relationships were established and some preliminary evaluations of cotton properties were made, the detailed results of the study are not available for publication, since only one firm was involved.

The results of the study did indicate that there are serious limitations to use of data from a commercial operation. The more serious limitations of using commercial data to establish the desired relationships are:

1. Most "independent" variables were highly interrelated.
2. The time lag between opening of the bale and spinning of the cotton is difficult to establish and may not be constant within a plant.
3. Relevant variables often are not measured for a representative quantity of cotton studied.
4. Changes in processing organization usually are not recorded.
5. Missing data.
6. Week-to-week variations were very small relative to variation possible in the relevant variables.

Recommendations for further study of spinning involved use of results from this study and others to decide upon the more important independent variables, use of controlled experiments on a pilot plant scale, and use of fractional experimental designs.

Pilot Laboratory Studies

Several studies of the processing of cotton through spinning have been conducted at the pilot spinning laboratory, Clemson, S.C. These were largely spinning studies in which relationships of fiber properties to processing performance and product quality were estimated. Additionally, some study of the effects of alternative processing organizations (machinery settings) has been made. Estimation of these relationships is a part of the continuing work of the laboratory and the resulting estimates complement the quantification of models such as the one presented in this paper.

Sufficient studies have been conducted in the pilot laboratory to establish the *direction* of the effects of the more important independent variables on the various dependent factors. Also, progress has been made in establishing the functional forms of relationships and the *extent* of independent effects. However, a considerable amount of work remains to be done in these areas before sufficient quantitative knowledge is available to completely quantify a complex firm or industry model.

Results of the pilot laboratory studies are available in various published sources. The ones which relate to quantification of models are listed in the bibliography (*18–27*).

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U.S. GOVERNMENT PRINTING OFFICE: 1969

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