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**DEVELOPMENT AND ADAPTATION OF
A CONTROL SYSTEM FOR OPTIMIZATION
OF
SINGLE AND MULTIPLE OPERATION MACHINING**

John S. Ramberg

JUNE 1974

FINAL REPORT

PREPARED BY

DAAF03-73-C-0110

INTERTECH CORPORATION

Iowa City, Iowa

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A system for determining optimal machining conditions based on actual production machining data is developed. This system is applicable to analysis and control of single-operation as well as multiple-operation (numerically-controlled) machining. The system incorporates a computer program which provides an evolutionary operation analysis and response surface, regression analysis of two responses, cost per piece and production rate. The output of this program provides production personnel with the information necessary for determining the optimal machining conditions for either minimum cost or maximum production.		

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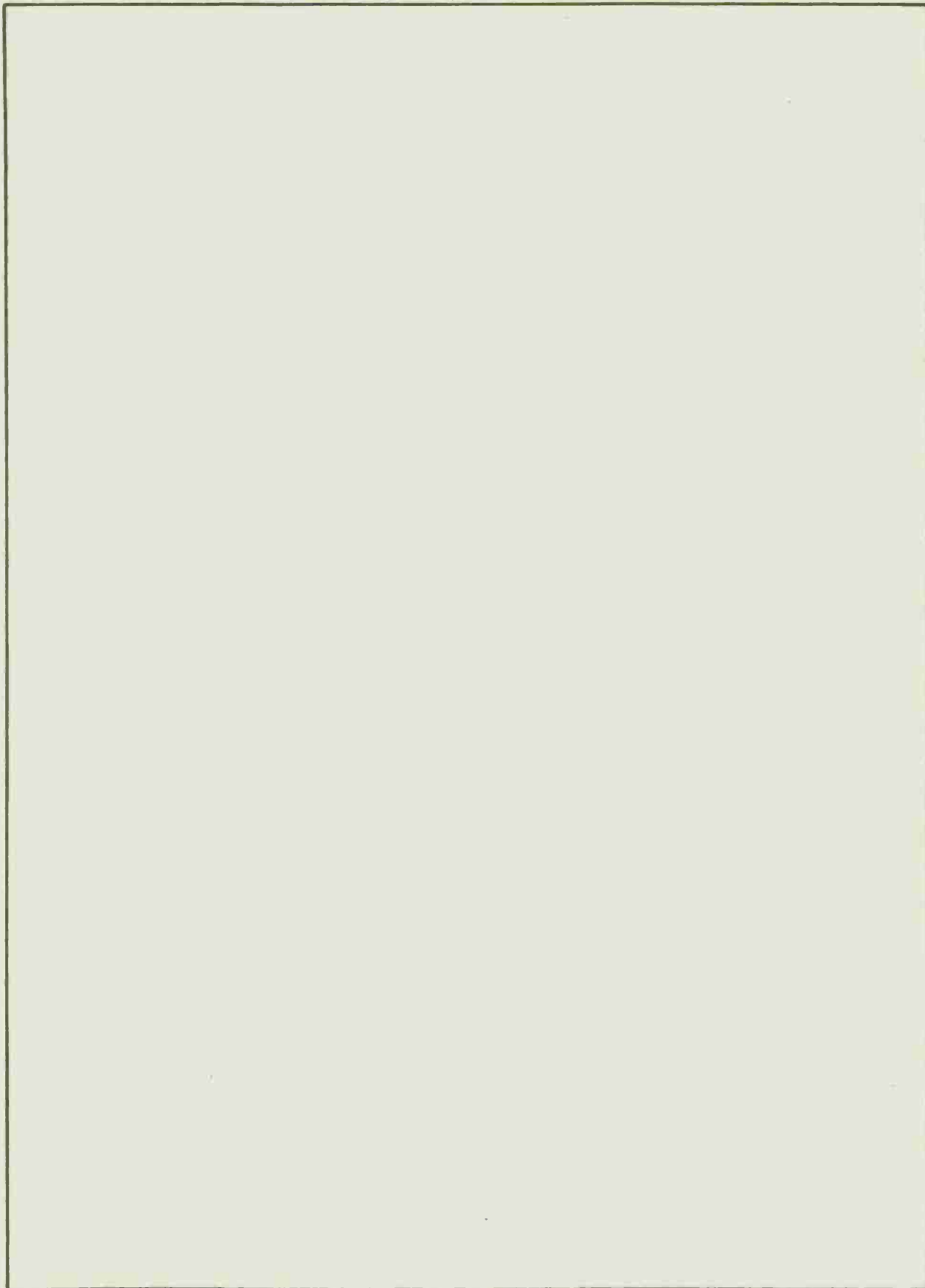
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FOREWORD

This report was prepared by John S. Ramberg, INTERTECH Corporation, Iowa City, Iowa, in compliance with Contract No. DAAF03-73-C-0110 under the direction of the Research Directorate, GEN Thomas J. Rodman Laboratory, with R. A. Kirschbaum as Project Engineer.

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1. Introduction

Nearly every machining operation has a potential for improvement in productivity. This potential arises from the fact that the optimum machining conditions vary with the job, the machine tool, the cutting tool, and the operator.

Machining conditions for a particular job are often selected by Taylor's tool life equation, through the use of handbooks such as the Machining Data Handbook [14], or on the basis of the engineer's or operator's experience. These methods in conjunction with trial runs allow the determination of machining conditions which apparently produce satisfactory results. ~~These machining conditions, however,~~ are often "ball park" estimates of the optimal conditions. They are in a sense similar to the estimates of the optimal operating conditions for a chemical facility obtained by pilot plant operations. A process of "tuning" still remains to be done. However, the production personnel may leave the process "untuned" in order to concentrate their efforts on more pressing problems.

The objective of this study is to develop and to implement a system for optimizing machining conditions for single-operation and multiple-operation (numerically controlled) machine tools. The measures of productivity considered are:

1. Production cost per piece, and
2. Production rate.

This system is designed to use data collected by production personnel and to provide feedback so that the machining parameters can be adjusted accordingly. This system is based on the concept that the machining process not only generates the configuration of a part, but also generates the necessary metal-cutting information on "how to machine the part." A primary consideration in the development of this system is that the process under study should not initially be drastically changed or upset. Thus changes in operating conditions should be minor rather than major. This is accomplished through a set of rules for normal operation, so that, without serious danger of loss through the manufacture of unsatisfactory parts, an evolutionary influence is at work which steadily and automatically moves the process toward its optimal operating conditions.

This planned program of perturbations of the process variables of a machining process differs from programs of planned statistical experimentation in the following two major ways [9]:

1. The program is conducted on the machining process during actual production of a product which is expected to be shipped to the customer. In a planned experiment, the testing is usually conducted in a laboratory or pilot plant during product development. Often a scaled-down version of the final product line is involved. Since actual production is being carried out, the amplitude of perturbations introduced during the program is generally small, and sometimes effects may only be determined statistically. In a standard experimental program, the amplitude of perturbations are often maximized to determine the effects resulting more expeditiously.
2. The program is frequently conducted over an extended time period rather than on a one-time basis as in the case of most standard experimental programs.

Certain process characteristics are favorable to this evolutionary manner of operation, while others are unfavorable. Table 1.1 gives a list of some of these characteristics. It is particularly important to note that low volume, non-repeating job shop orders are not suitable candidates for this type of optimization. These jobs are usually completed before sufficient information is gathered to suggest optimum operating conditions.

The optimization system includes computer programs which analyze the data. The computer output is then technically evaluated by a committee. The major task of this committee is to discuss the implications of current results and to suggest potential changes. This committee should be composed of production personnel, such as the foreman and an operator, as well as staff personnel, such as an industrial engineer and a tool engineer. This committee should meet on a regular basis to review the current operations and to suggest future studies.

The technical exchange which occurs in these meetings can be more important than the information provided by the computer programs. For example, the programs can suggest new speeds and feeds at which to operate and can be used to compare different tool materials and/or different types of tool inserts. However, they can not suggest a new tool material. These types of suggestions must come from personnel familiar with the particular problem. The programs, however, help to motivate these discussions, and the improvements are accomplished through the information exchange which takes place at these meetings. The programs can also be used to evaluate and to document the performance of different cutting tools. This documentation could serve as a justification to procure proven tools of particular brands at possibly higher costs for similar future applications.

Table 1.1

Process Characteristics Which are Favorable
or Unfavorable to the Use of EVOP[9]

<u>Characteristics Which Are Favorable</u>	<u>Characteristics Which Are Unfavorable</u>
1. The process involves high volume production over a reasonably extensive time period.	1. The process is a job shop with few or no repeats of units with identical specifications.
2. The potential benefits of process improvements are large (the process is an important one and is not already operating at optimum conditions).	2. The cost for process improvement exceeds the potential benefits.
3. The process variables can be perturbed readily.	3. The process variables cannot be perturbed readily.
4. The process stabilizes rapidly after a process change.	4. The process requires a long time to stabilize after a process change.
5. The process response can be obtained rapidly.	5. The process response is not obtained rapidly (for example, if the response variable is time until failure on a life test).

Two computer programs are given in this report for optimizing machining parameters, the Performance Index Method (PIM) program and the Machining Optimization (MACHOP) program.

The PIM program, referred to as the "on-hand" program in the contract, was available from AWC¹ as a computer listing. It was designed for optimizing machining conditions of single-operation machine tools. During the initial phase of this project, the PIM program was modified, debugged, and tested on simulated data. During this same period, production data was collected at the Rock Island Arsenal (RIA) Operations Division shops. Section 2 of this report contains a discussion of the problems encountered with the PIM program and the recommendations concerning its use.²

Because of the difficulty in collecting data for the PIM program and in using the program with shop data, the MACHOP program was developed. The latter program can be used to optimize single-operation machine tools as well as multiple operation (numerically controlled) machine tools.

The MACHOP approach is described in Section 3. Section 4 describes the use of MACHOP, including the data handling system. Section 5 contains the MACHOP analysis of the data collected at the RIA Operations Division shops.

Appendix A contains a sample output of a regression program which was used to verify the regression modules of the PIM and MACHOP optimization programs. Appendix B contains a simulation program listing and sample output. This program was developed for preliminary analysis of the logic in the PIM and the MACHOP programs. Appendix C contains the data collection forms for the MACHOP program. An analysis of the PIM design module is given in Appendix D. Appendix E contains sample output from the Carboloy Systems Computerized Machinability Program. A program listing for the MACHOP program is given in Appendix F. Program documentation necessary for the implementation and maintenance of the MACHOP program is included as Appendix G.

2. The Performance Index Method (PIM) Program

The first phase of this contract concerned the adaptation of the "on-hand" program (herein called the PIM program) for use with single-operation machine tools. This phase of the contract required approximately 3 months.

During this period, production operations in the Rock Island Arsenal (RIA) Operations Division shops were surveyed and data collection schemes were determined. Simultaneously the PIM program was converted from a

¹U.S. Army Weapons Command, now U.S. Army Armament Command.

²Section 2 can be bypassed without loss of continuity if the MACHOP program is of primary interest.

program listing to punch cards. The program logic was checked and corrected, and the program was tested on simulated data. The results of this testing indicated some additional programming errors. Following the correction of these errors, the program performed satisfactorily on the simulated data. Details are given in Sections 2.1 and 2.2.

Major problems were encountered in the collection and analysis of production data with the PIM program. A discussion of these problems is given in Section 2.4.

2.1 Recommendations on the Use of the PIM Program

The problems which may be encountered in using the PIM program restrict its applicability. On the basis of the experience obtained in using the PIM program on RIA data, the following recommendations are made:

1. The PIM program should be used only for those machining processes or operations where the production personnel are readily able to find nine feed-speed combinations (three levels of feed for each of three levels of speed), which can be run without disturbing the production process or risking the production of scrap parts.
2. The validity of the performance index prediction outside of the region where data has been taken is highly questionable. Hence the range of prediction, which is specified in the program by the usable speeds and feeds, should be restricted. In particular the usable feeds (speeds) should be limited to one feed (speed) level above and below the feeds (speeds) at which data are to be collected.
3. The data collection forms developed for the MACHOP program should be used for collection of data for the PIM program.
4. The PIM program can be used for multiple-operation tools (numerically controlled), replacing the speed and feed variables by increments of the speed and feed overrides, respectively.

2.2 Program Logic Check

The PIM program was available as a program listing. This was converted to punch cards and verified.

Although the PIM program had been previously "debugged," a few errors were noted. A list of the changes made in the program follows:

1. Definition of Performance Index (PI)

The PI was defined in the final Report DAAF01-70-C-106a [10] as:

$$PI = Q \cdot Pr + (1 - Q)/Cu.$$

In the computer program (subroutine PERIND) the following definition was used:

$$PI = (1 - Q) \cdot Pr + Q/Cu.$$

This was corrected to agree with the report.

2. Programming Errors in the PICK Subroutine

Following the determination of the optimum feed and speed based on a given set of experimental observations, the program selects the next set of feeds and speeds by one of two methods depending on whether the previous optimal point was on a boundary. If the previous optimal point was not on a boundary, Ham [10] indicates that nine points are to be picked around the previous optimal point, subject to the maximum feed, maximum speed, and maximum horsepower constraints and tests made for uniqueness. See Appendix D for an analysis of the design strategy.

The program (PICK subroutine), however, incorrectly selected at most eight points, one of which was the first point in the previously analyzed set. The other seven points (2-8) are shown in Figure 2.1.

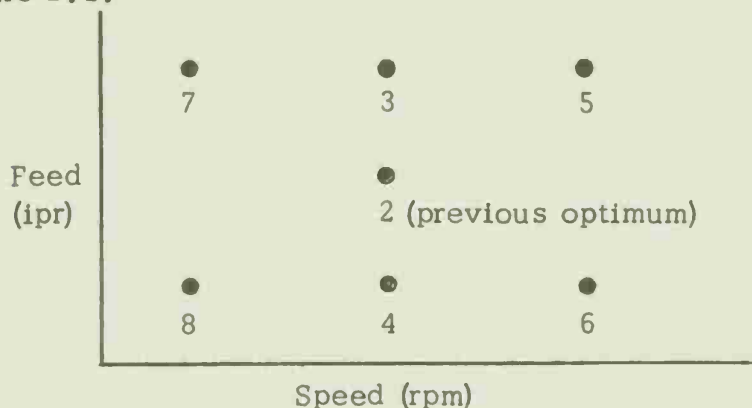


Figure 2.1 Points Selected by Design Module

To be consistent with the report and to achieve a reasonable design, line #15 of the program was changed to NPT=0 and line #25 was changed to IF(J.EQ.1) GO TO 75.

3. Format Statements

Some format statements in the program were changed to allow costs of over \$10 per piece to be printed out.

2.3 Program Testing with Simulated Data

Prior to obtaining plant data, a simulation model, which is discussed below, was constructed for testing the PIM program. Some of the logic errors reported in Section 2.1 were first noted when the data from these simulations were analyzed by the PIM program.

2.3.1 The Simulation Model

The simulation model was based on the turning operation on the Monarch lathe (RIA, ID #30303) for a recoil cylinder (part #10895646). This model was constructed for the preliminary evaluation of the PIM program. This simulation is different from that discussed by Ham [10]. He used Taylor's tool life equation to determine the tool life and thus the cost. Then a random error term was introduced into the cost function. In the simulation model given here, individual tool life data are generated.¹ On the basis of these tool lives, the number of pieces produced and the number of edges used during one shift of operation are determined. Thus, the data are in the same format as the production data.

The simulation model was developed according to the following assumptions:

1. The equation used for determining the tool life is

$$VT^{\alpha}F^{\beta} = C,$$

where α , β , and C are constants,

$$V = \frac{\pi DN}{12},$$

D = Diameter of work piece in inches,

N = spindle speed in rpm,

¹The tool life model does not include the possibility of tool breakage and the accompanying loss of unused edges.

F = feed in ipr, and

T = tool life in minutes.

If one takes logarithms, the above tool life equation can be written as

$$\ln T = \frac{1}{\alpha} [\ln C - \beta \ln F - \ln V].$$

A random error term, ϵ , is added to the above equation to introduce variability into the tool life. The error term, ϵ , is assumed to have a normal distribution with mean zero and standard deviation of

$$\frac{1}{\alpha} [\ln C - \beta \ln F - \ln V] \cdot \text{ERR},$$

where ERR is the percentage error appropriate for the process.

2. An eight hour day, allowing for the operator's personal time, is assumed to consist of 420 minutes of production time.
3. If at the end of a shift, a part is over 75% finished, it is assumed to be completed.

A flow chart based on the above assumptions is given in Figure 2.2. The computer program, written in FORTRAN IV and a sample output are given in Appendix B.

2.3.2 Analysis of Simulation Data

The center of the initial set of points selected was $V = 220$ rpm and $F = 0.0187$ ipr. Although the PIM program will operate with as few as six design points, Ham's [10] recommendation of nine points in a geometric pattern of a 3^2 factorial design was followed. A large range of feeds and speeds were available on the Monarch lathe. However, the usable speed range was limited to 95 rpm - 330 rpm and the usable feed range was limited to 0.007 ipr - 0.0337 ipr.

The data generated by the simulation program for the first experiment are given in Table 2.1.

Based on these data, the on-hand program selected the optimal speed and feed as $V = 220$ rpm and $F = 0.0337$ ipr. Note that this is on the usable feed boundary. Hence, feed is no longer adjustable. The points suggested for the next experiment and the simulated production data for these points are given in Table 2.2.

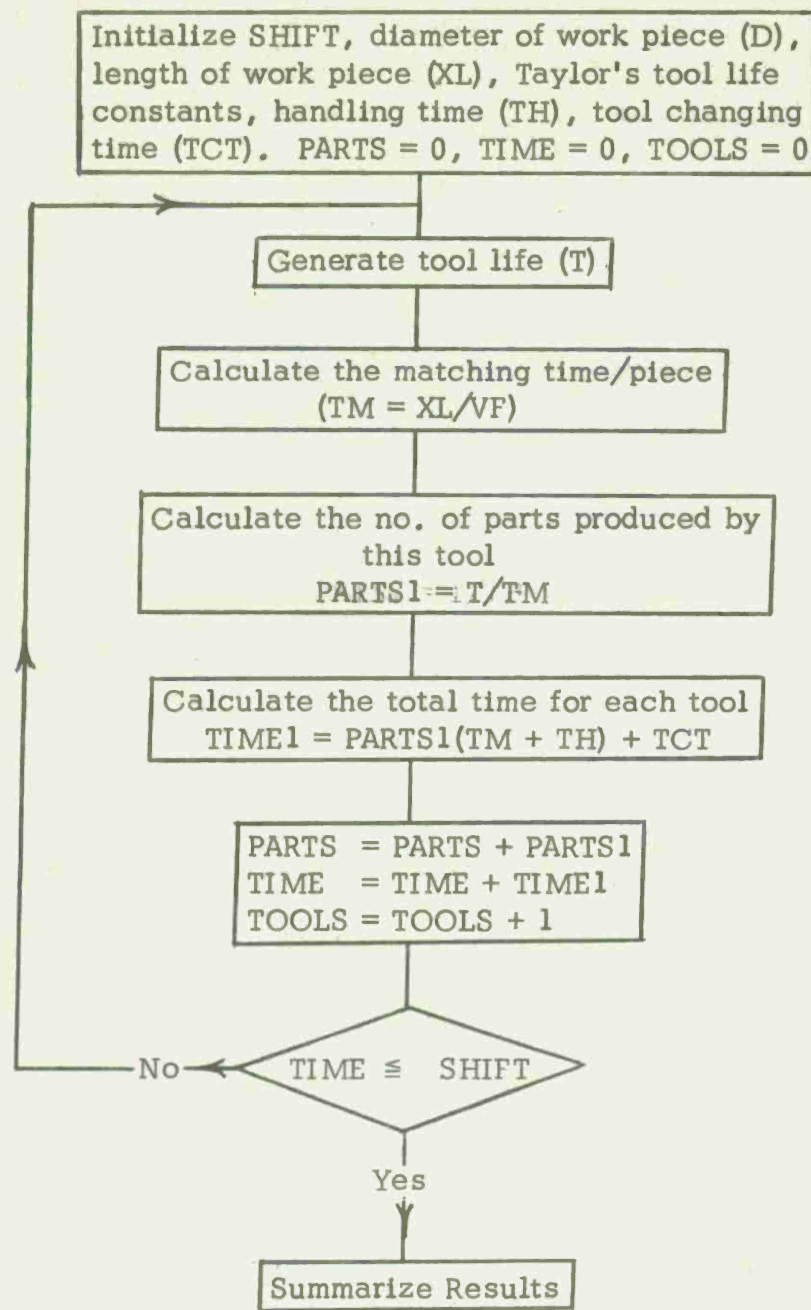


Figure 2.2 Simulation Flow Chart

Table 2.1 First Data Set

<u>Speed</u>	<u>Feed</u>	<u>No. of parts</u>	<u>Time</u>	<u>No. of edges</u>
192	0.0168	14.0	420.0	8.0
192	0.0187	14.0	420.0	11.0
192	0.0210	15.0	420.0	14.0
220	0.0168	14.0	420.0	16.0
220	0.0187	15.0	420.0	20.0
220	0.0210	16.0	420.0	21.0
255	0.0168	14.0	420.0	36.0
255	0.0187	15.0	420.0	32.0
255	0.0210	16.0	420.0	31.0

Table 2.2 Second Data Set

<u>Speed</u>	<u>Feed</u>	<u>No. of parts</u>	<u>Time</u>	<u>No. of edges</u>
166	0.0337	17.0	420.0	9.0
220	0.0337	19.0	420.0	17.0
290	0.0337	19.0	420.0	45.0
330	0.0337	18.0	420.0	64.0

Based on these data, the PIM program selected the optimal speed and feed as 220 rpm and 0.0337 ipr. Since the two previous optimal points were not identical, the PIM program selected a new set of five points on the feed boundary. The feed and speed settings and the simulated data for these 5 points are given in Table 2.3.

The point 220 rpm, 0.0337 ipr was again chosen as the optimal point. The analysis was terminated since the same point was chosen on two consecutive runs.

Table 2.3 Third Data Set

<u>Speed</u>	<u>Feed</u>	<u>No. of parts</u>	<u>Time</u>	<u>No. of edges</u>
126	0.0337	16	420.0	6.0
166	0.0337	18	420.0	2.0
220	0.0337	18	420.0	22.0
290	0.0337	19	420.0	46.0
330	0.0337	18	420.0	63.0

A graphical presentation of these results is given in Figures 2.3 and 2.4.

The PIM program required 18 observations to obtain the optimal feed and speed. Table 2.4 gives the cost per piece in dollars for some of the usable feeds and speeds for the case where ERR is 0.

Table 2.4 Cost/Piece (\$) as Given by Taylor's Equation

Speed (rpm)	145	166	192	220	255	290	330
Feed (ipr)							
0.0153	11.76	10.89	10.24	10.47	10.05	10.44	10.95
0.0168	10.78	10.05	10.24	9.72	9.38	9.74	10.22
0.0187	10.78	10.08	9.51	9.07	9.38	9.74	10.22
0.0210	9.95	9.36	8.88	9.10	8.79	9.14	9.58
0.0240	9.24	8.74	8.35	8.53	8.30	8.60	9.02
0.0337	8.11	7.71	7.42	7.58	7.41	7.67	8.47

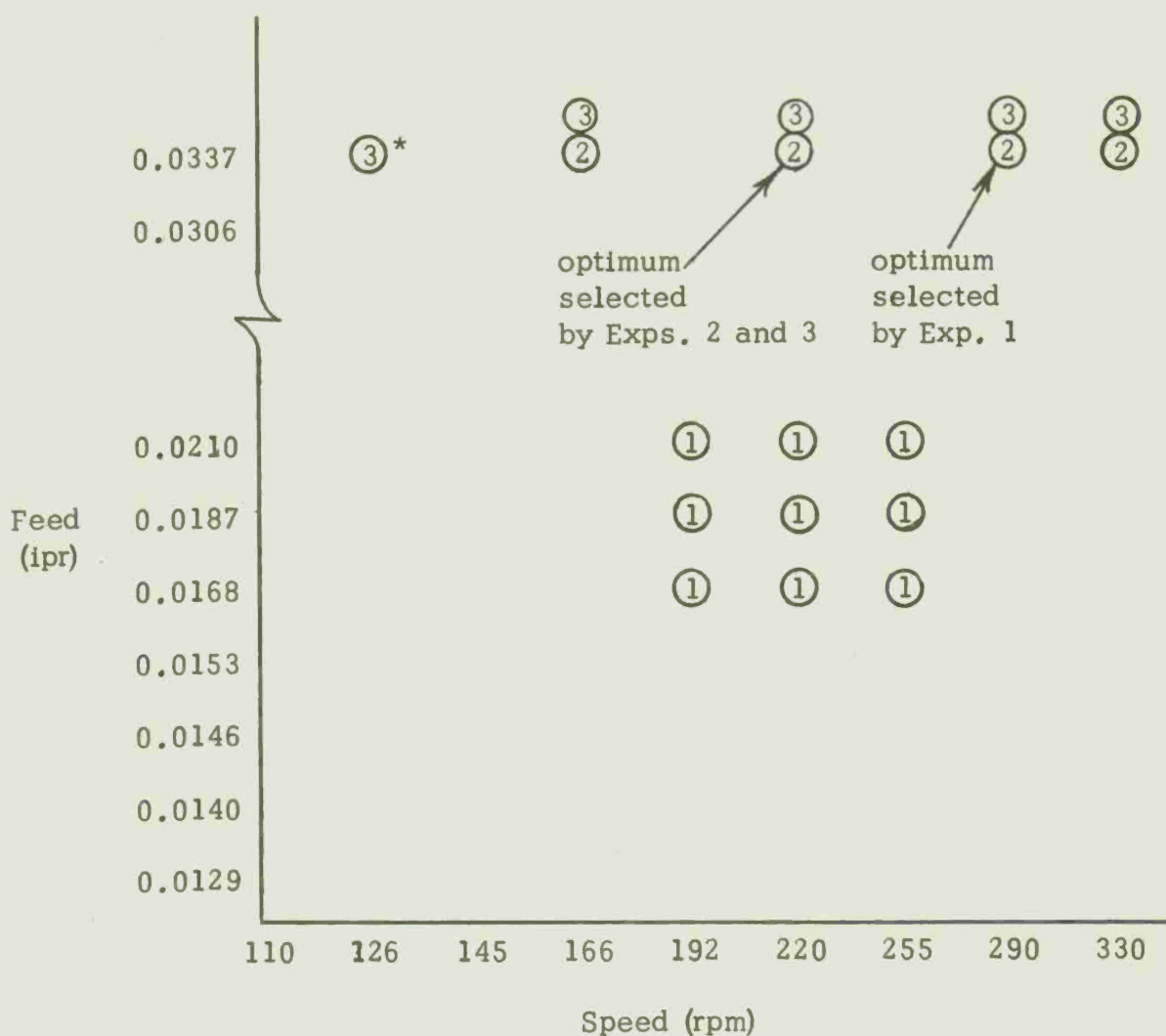


Figure 2.3 Design Points for the PIM Method

*the circled numbers indicate the experiment number,
i.e., i indicates that this point is in the i^{th} experiment.

			7.05 ³		7.51 ³		7.65 ³	8.47 ³
	0.0337	8.03 ³ *	7.63 ²		7.01 ²		7.63 ²	8.49 ²
Feed (lpr)	0.0210			8.97 ¹	8.43 ¹	8.69 ¹		
	0.0187			9.33 ¹	8.96 ¹	9.30 ¹		
	0.0168			9.24 ¹	9.48 ¹	10.08 ¹		
		126	166	192	220	255	290	330
		Speed (rpm)						

Figure 2.4 Cost/Piece Estimates (\$) at
Observed Feeds and Speeds

*The superscripts refer to the experiment number.

2.4 Program Testing with Rock Island Arsenal (RIA) Data

This phase of the study required a major portion of time and dollar expenditures of the research project. All previous experimentation using the PIM program was based on simulated data and/or a very limited amount of laboratory experimental data.

A turning operation on a recoil cylinder using the Monarch lathe was selected for the first study. Other information concerning this operation is given in the job description in Table 2.5.

Table 2.5 Job Description for First Study

Operation: - Turning

Part: - Variable recoil cylinder

Material: - Steel tube 4140.

Dimensions: 47.5" long, 8.5" dia., depth of cut 1/8"

Job order #: 0016011

Part #: 10895646

Cutting tool: - Titanium coated carbide insert, multi-edged

Tool cost/edge: - \$.42

Machine tool specifications: Monarch stepped lathe.
50 HP. RIA ID #30303

Available speeds (in rpm): 84, 95, 110, 126, 145, 166, 192, 220, 255, 290,
330, 380, 435

Available feeds (in ipr): .0032, .0035, .0037, .0038, .0042, .0047, .0013,
.0060, .0065, .0070, .0073, .0076, .0084, .0093,
.0105, .0120, .0129, .0140, .0146, .0153, .0168,
.0187, .0210, .0240, .0259, .0293, .0306, .0337,
.0374, .0421, .0451, .0518, .0561, .0585, .0612,
.0673, .0748, .0841, .0962, .1036, .1122, .1171,
.1224, .1346, .1496, .1683.

Labor and overhead rate: - \$18/hr.

A 3^2 factorial experiment¹ was conducted with $V = 220$ rpm and $F = 0.0187$ ipr as a center point. Each of the nine feed-speed combinations was used for one shift of operation. The same operator was used for all of the points. The data in Table 2.6 were recorded by the machine operator.

Based on the above production data, the cost per piece in dollars is calculated in each case and is given in the last column of Table 2.6. In this case the performance index is taken as $1/Cu$.² The PIM program fits a regression equation of the form $PI = b_0 + b_1V + b_2F + b_3V^2 + b_4F^2 + b_5V \cdot F$

to the data. (See Ham [10] for a more complete discussion.) The performance index is evaluated at all usable feed-speed combinations.

Table 2.6 Data Summary for Experiment 1
Results for Recoil Cylinder - First Study

Speed (rpm) V	Feed (ipr) F	No. of parts	Production time	No. of tool edges	Cu \$/piece
192	0.0168	14	434	17	9.51
192	0.0187	18	410	18	7.28
192	0.0210	14	377	18	8.63
220	0.0168	13	396	23	9.90
220	0.0187	15	393	15	8.28
220	0.0210	20	440	44	7.52
255	0.0168	10	217	17	7.22
255	0.0187	11	267	29	8.39
255	0.0210	14	357	31	8.58

The optimal feed-speed combination is selected as the point which maximizes the predicted performance index PI and thus minimizes the predicted cost, Cu.

¹An experiment conducted at 3 levels on each of 2 factors, resulting in a total of 9 experimental points.

²The reciprocal of Cu, the cost per piece, in \$/piece.

The feed-speed combination selected as optimal was $V = 95$ rpm and $F = 0.0187$ ipr. At this combination the performance index prediction is $PI = 0.212$ and hence the cost estimate is $C_u = \$4.72/\text{piece}$. However, a few calculations illustrate that the predicted cost cannot be achieved at this feed and speed.

The machining time per piece is $47.5/(95 \times .0240) = 20.8$ min/piece. Allowing nine min/piece handling and no time for tool change we arrive at a total time of 29.8 min/piece. Using the labor plus overhead rate of \$18/hr and neglecting the tool costs, we obtain a conservative estimate of cost per piece of \$9.00/piece. This is nearly double the cost predicted by the PIM program. It is also higher than the cost per piece for many of the original nine feed-speed combinations.

The cost estimates obtained by the PIM program for a number of feed-speed combinations are given in Table 2.7. (These are not printed by the PIM program but are easily obtained.)

The regression calculations in the PIM program were also verified by analyzing the data on a separate regression program. (See Appendix A.) No substantial differences were noted. The prediction equation explained 37.3% of the variability in the data.

Table 2.7 Cost/Piece Predictions (\$) Using the PIM Program

Speed (rpm) \ Feed (ipr)	95	145	166	192	220	255	290
0.0153		14.59	14.04	12.75	10.97	8.75	6.88
0.0168	8.67	9.81	9.90	9.66	9.01	7.87	6.61
0.0187	6.24	7.46	7.84	8.10	8.09	7.65	6.85
0.0210	5.10	6.49	7.08	7.76	8.32	8.59	8.19
0.0240	4.72 ¹	6.69	7.82	9.53	11.71	14.98	16.62

¹ Indicates the optimal point.

The major reason for this failure of the PIM program is the large amount of variability present in the data. Due to this high variability in the shop data, the prediction equation used in the PIM program was valid only over a small region of feed-speed combinations where the data were collected.

One method of reducing the variability of the prediction equation is to take data for at least two shifts at each feed-speed combination.¹ However, this would require data from eighteen shifts of operation. This does not appear to be a viable alternative because of the excessive length of time required to collect the data prior to feedback.

It should also be noted that the specification of constraints such as the horsepower constraint did not seem to be of any value. This is probably attributable to the fact that the mathematical expressions for the constraints are only approximations. Determination of feasible operating feed-speed combinations would be better left to shop personnel. These points can be determined on the basis of experience and trial runs.

Another problem was encountered in collecting shop data for the PIM program. The program requires a minimum of six feed-speed combinations. (Actually nine combinations are recommended in the users instructions.) On the operations observed in the RIA shop it was difficult to select three feeds and three speeds (yielding nine feed-speed combinations) without taking a high risk of producing scrap parts at one of these combinations.

Since the PIM program functioned satisfactorily with the simulated data, some commentary seems to be in order concerning the differences between the simulated data and the production data.

Whereas the simulation model assumed that the handling time and the total production time were constant, namely 15 min/part and 420 min/day, respectively, the quantities were highly variable in the actual production situation. The handling time varied from 9 min/part to 15.8 min/part, while the production time varied from 217 min/day to 440 min/day. The variation in the handling time leads to much higher variability in the estimates of the performance index. The production time variability illustrates the need for recording down time, rather than using the eight hour work shift as a time base. Another major difference between the simulation model and the real production situation is that the tool lives for the simulation model were determined by the tool life equation with a 20% random error term added. In the shop the variability was even higher due to tool breakage. Since "triangular throw away" inserts were being used, breakage of the tool could result in a loss of one to six edges at one time.

¹ The complete experiment should be performed using the same operator, if possible, so that an additional source of variability is not introduced. Data from long runs by multiple operators may be averaged.

3. The Machine Optimization (MACHOP) Program

The problems encountered in the collection of data and in the application of the PIM program indicate the importance of the following objectives for development of a usable optimization program:

1. A limited number of feeds and speeds should be attempted and analyzed initially in order to provide early feedback and to minimize disruption to the shop operation.
2. Since changes in feeds and speeds must be gradual, it is initially sufficient for the optimization program to determine the direction of the optimal operating conditions rather than selecting a particular feed-speed combination as optimal. This procedure will greatly reduce the chances of incorrectly determining the optimum feed-speed combination. This is particularly important because of the variability in shop data.
3. At most two variables should be varied simultaneously to facilitate the usage and understanding by production personnel.

The MACHOP program is designed to accomplish the above objectives in addition to those specified in the contract. No constraints other than the definitions of the speed and feed environment are considered in this process. Although certain constraints were directly incorporated into the PIM program, they were not incorporated into the MACHOP package. The data collected in this project indicates that the mathematical expressions for these constraints (i.e., the horsepower or the surface finish) were only crude approximations. Hence it seemed better to rely on the shop personnel's experience than to eliminate a particular operating point because of a constraint equation. In addition, these constraints are not as critical to the MACHOP program as they were to the PIM program, since the MACHOP program moves in small steps toward the optimum operating conditions.

To simplify the collection of data in the shop, observations are always taken in sets of four at two adjacent feeds and two adjacent speeds. For numerically-controlled multiple-operation machine tools the feeds and speeds are controlled by feed and speed overrides. This procedure avoids the cost of preparing new NC tapes for each run.

For each feed-speed combination, the following data are collected during one shift of operation:

1. the number of parts produced,
2. the number of tool edges used for each tool type, and

3. the production time.¹

These results are submitted to the MACHOP program.

On the basis of these data the MACHOP program calculates two performance indices:

1. the cost/piece (Cu) in dollars/piece, and
2. the production rate (Pr) in pieces/minute.

The MACHOP program then performs two types of analyses for each of the responses or performance indices:

1. an evolutionary operation analysis, and
2. a response surface, regression analysis.

The evolutionary operation analysis is based on the work of Box and Draper [3]. An automatic feedback provision for systematic optimization is given in this portion of the program. The program recommends a set of four feed-speed combinations for the next phase or cycle of operation. (This set of feed-speed combinations may be the same as the set just completed.) The evolutionary operation analysis makes no assumptions concerning the form or shape of the response surfaces. Its purpose is to evaluate the differences in the observed responses at the four feed-speed combinations as compared to the variability of the process and to suggest the direction of movement toward the optimal machining conditions.

The response surface, regression analysis uses the same data as the evolutionary operation analysis. The parameters of two regression equations are estimated, and these equations are used to predict the responses at the feed-speed combinations in the region in which data have been collected. When sufficient data are available, second order equations are fitted to the natural logarithms of the feeds and speeds. Each of these second order equations requires the estimation of six parameters, and hence, at least six different feed-speed combinations are necessary to estimate all the parameters.

When data has been collected at fewer than six feed-speed combinations, lower order equations are used. For example, for the initial set of four feed-speed combinations, first order models are fitted to the data, and used to make the predictions. In addition to the predictions, analysis of variance tables are also provided.² An understanding of regression analysis is not necessary for program use. Production personnel will generally be interested only in the predictions.

¹Actual cutting, work piece handling and tool changing time.

²A complete discussion of regression and analysis of variance tables is given in references [4] and [5].

The output of these two portions of the program serves as the basis for the MACHOP committee's discussion concerning the next phase or cycle of experimentation. In general, the committee should follow the MACHOP suggestions, unless their collective experience indicates otherwise. The prediction output gives them an indication of both the unit costs and the production rates at adjacent feeds and speeds.

On the basis of this information the committee can also make decisions such as the following:

1. try a new cutting tool,
2. try a different machining process, or
3. prepare a new tape for an N/C job.

A new cutting tool might be suggested upon collaboration by the tool engineer and the operator. It might be determined that a more expensive cutting tool is warranted by a corresponding increase in production rate and/or reduction in total cost. A different machining process might be proposed in order to decrease high machining costs for particular parts. The suggestion to prepare a new tape might result from the fact that the MACHOP program suggests that an override be increased by 5%, although the upper limit has already been attained. Under these circumstances it may be economical to prepare a new tape. This situation could also occur if the program suggested increasing an override, but the operator felt that this change would have a negative effect on one or more of the machining operations. In this case a new tape could be prepared which would change the feeds and/or speeds of a particular set of operations relative to the feeds and/or speeds of the other operations. Following any of these changes, the usual data should be collected and submitted to the program in order to investigate and to document the effect of the change.

The technical aspects of the MACHOP program are discussed in the subsequent sections. Section 3.1 gives information on the performance index calculations. The details of the evolutionary operation portion of the program are given in Section 3.2, and the response surface-regression analysis portion of the program is discussed in Section 3.3.

3.1 Computation of Performance Indices

The two performance indices used in the MACHOP program are

C_u = Cost per piece (\$/piece), and

P_r = Production rate (pieces/minute).

These quantities are calculated for each of the test points.

For a given test point the following data are collected:

N_p = Number of parts produced,

N_{ti} = Number of tool edges of tool i used, and¹

T = Time period of test (in minutes).

The test will usually consist of running at a given feed and speed for one shift. Forms for collecting these data are provided in Appendix C. Note that the length of the test will usually be less than the shift time because of interruptions for other activities such as safety meetings and personal time.

The production rate computation for single-operation, multiple-operation, and/or numerically controlled processes is

$$Pr = N_p / T.$$

For a single-operation machining process the cost per piece is

$$C_u = [(RLO)T + (TLC)N_t] / N_p$$

where

RLO = Labor and overhead rate in dollars per minute, and

TLC = Tool cost in dollars per edge.

If the objective is to minimize tool cost per piece then RLO is set equal to zero. Alternatively, the overhead may be removed from the problem by setting RLO equal to the labor rate.

For a multiple-operation machining process the cost per piece is

$$C_u = [(RLO)T + \sum_{i=1}^n (TLC_i)N_{ti}] / N$$

where

n = Number of different tools, and

TLC_i = Cost of tool i in dollars per edge.

¹ N_{t1} is shortened to N_t .

3.2 Evolutionary Operation (EVOP)

Evolutionary operation (EVOP) is a method of process improvement that:

1. is readily conducted under actual processing conditions by production personnel,
2. operates despite the presence of large experimental error,
3. provides an efficient basis for scientific or technological feedback, and
4. does not assume knowledge of the functional form of the response surface or any explicit knowledge of the response function except that it is smooth.

EVOP computations and procedures for analyzing the results of the 2^2 factorial experiment are based on the work of Box and Draper [3]¹. In this analysis, the two performance indices, Cu and Pr, are examined as a function of the feed and speed of the machining operation. The effect that each of these factors exerts on the performance indices is evaluated and two (possibly identical) sets of operating conditions are suggested for future operation.

3.2.1 EVOP Calculations

A cycle is a set of four observations in a rectangular pattern at two adjacent feeds and two adjacent speeds. This set of four observations allows the determination of the effect of

1. feed,
2. speed, and
3. feed-speed interaction

on both the production rate and the cost per piece.

¹Box and Draper also consider a 2^2 factorial design with an additional reference condition. This approach, if used here, would require taking data at three feed and speed levels. Experience with the machining operations at the RIA shops indicated that this was too wide a range and could lead to production of scrap. Hence, the 2^2 factorial design without reference condition was chosen.

A phase consists of repetitions of the same cycle. In other words, phase indicates which set of four points is being observed and cycle indicates the number of observations which has been taken at each feed-speed combination during this phase. Cycles are repeated within a phase until sufficient information is gathered on the effects of feed, speed and their interaction to suggest a new set of feed-speed combinations, i.e., a new phase of operation. The new phase begins when observations are taken at a new set of feed-speed combinations. The concepts of phase and cycle are important in understanding the EVOP analysis. A minimum of two cycles of observations are required in Phase 1 to estimate the variability of the data. Prior estimates of the variability can also be used as will be discussed later. The estimate of variability is necessary to determine the significance of the effects of feed and speed on the responses. Moving to a new phase constitutes the movement across the response surface. Taking another cycle means additional information is being gathered to determine the direction of movement.

The EVOP computations of Box and Draper [3] have been modified to accomodate machining data and to facilitate computerization. The computational procedure is summarized in Figure 3.1. A complete discussion of these calculations is given for phase M and cycle n.

The first step in the EVOP analysis is the calculation of the phase averages and phase ranges. These computations are the same for each of the performance indices. The performance index will be denoted by y in the following discussion. Each of the performance indices are calculated for each feed-speed combination, for which data are available, according to the equations given in Section 3.1. For cycle n the new observations at each of the four feed-speed combinations are denoted by y_{in} ($i=1,2,3,4$). The previous cycle sum (PCS_i) at each of these four points is given by

$$PCS_i = \sum_{j=1}^{n-1} y_{ij}.$$

Thus, the previous cycle average is

$$\bar{y}_i' = PCS_i / (n-1).$$

The four differences (d_i) are calculated by subtracting the new observations from the previous cycle averages, i.e.,

$$d_i = \bar{y}_i' - y_{in}.$$

These differences are used to estimate the variability of the data. The new sums (NS_i) are computed as the sum of the previous cycle sums and the new observations

$$NS_i = PCS_i + y_{in}.$$

Finally the new averages are calculated as

$$\bar{y}_i = NS_i/n$$

for each of the four feed-speed combinations.

The new averages are the values used to determine the effects of the factors on the performance index. The new cycle sums and the new cycle averages become the previous cycle sums and previous cycle averages for the next cycle (i.e., cycle $n + 1$), if the current phase is continued.

For the first cycle of any phase, the previous cycle sums and the previous cycle averages are zero by definition. The new sums and new averages (NS_i and $\bar{y}_i$) are just the new observations. The range is not meaningful and hence is not calculated for this cycle. If this is the first phase, there is no measure of error with which to compare the effects of the factors. This is the reason that a minimum of two cycles in the first phase is required to produce an initial estimate of the standard deviation of the error of the response. In later phases, the estimate obtained from previous phases is used.

The effects of the factors, feed and speed, are calculated using the new averages $\bar{y}_i$. Consider the 2^2 factorial design configuration as in Figure 3.1. Each $\bar{y}_i$ is associated with a point i in Figure 3.1. Speed increases from left to right as depicted by the arrow. The effect of speed is given by

$$\text{SPEED EFFECT} = \frac{1}{2} ((\bar{y}_2 + \bar{y}_3) - (\bar{y}_1 + \bar{y}_4)) = \frac{1}{2} (\bar{y}_2 + \bar{y}_3 - \bar{y}_1 - \bar{y}_4).$$

Feed increases as indicated by the labeled arrow and the effect of feed is given by

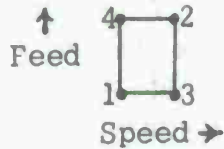
$$\text{FEED EFFECT} = \frac{1}{2} ((\bar{y}_2 + \bar{y}_4) - (\bar{y}_1 + \bar{y}_3)) = \frac{1}{2} (\bar{y}_2 + \bar{y}_4 - \bar{y}_1 - \bar{y}_3).$$

The effect of the interaction of speed and feed is given by

$$\text{SPEED-FEED (INTERACTION) EFFECT} =$$

$$\frac{1}{2} ((\bar{y}_1 + \bar{y}_2) - (\bar{y}_3 + \bar{y}_4)) = \frac{1}{2} (\bar{y}_1 + \bar{y}_2 - \bar{y}_3 - \bar{y}_4).$$

(2² Factorial)



PHASE =

CYCLE(n) =

Calculation of Averages					Calculation of Standard Deviation					
Operating conditions	(1)	(2)	(3)	(4)						
(i)Previous cycle sum	PCS ₁	PCS ₂	PCS ₃	PCS ₄						
(ii)Previous cycle average	$\bar{y}'_1$	$\bar{y}'_2$	$\bar{y}'_3$	$\bar{y}'_4$	Previous average S =					
(iii)New observations	y _{1n}	y _{2n}	y _{3n}	y _{4n}	New S = range × f _{4,n} =					
(iv)Differences (ii) less (iii)	d ₁	d ₂	d ₃	d ₄	Range=MAX[d _i]-MIN[d _i]= 1 1					
(v)New sums	NS ₁	NS ₂	NS ₃	NS ₄	New sum S=S'+New S =					
(vi)New averages: $\bar{y}_1$	$\bar{y}_1$	$\bar{y}_2$	$\bar{y}_3$	$\bar{y}_4$	New average S = New sum S/2 =					
Calculation of Effects					Calculation of 2 S.E. Limits					
SPEED effect = $\frac{1}{2} (\bar{y}_2 + \bar{y}_3 - \bar{y}_1 - \bar{y}_4) =$										
FEED effect = $\frac{1}{2} (\bar{y}_2 + \bar{y}_4 - \bar{y}_1 - \bar{y}_3) =$					For new effects:					
SPEED-FEED effect = $\frac{1}{2} (\bar{y}_1 + \bar{y}_2 - \bar{y}_3 - \bar{y}_4) =$					$\pm \frac{2}{\sqrt{n}} S =$					
n	1	2	3	4	5	6	7	8	9	10
f _{4,n}	0	0.34	0.40	0.42	0.43	0.44	0.45	0.45	0.46	0.46

Figure 3.1 Evolutionary Operation

The variability of the data is measured by the standard deviation (S) of the observation errors, and the computational procedure to obtain it for phase M cycle n is described subsequently. The new S for cycle n is computed as the range multiplied by the factor $f_{4,n}$ (given in Figure 3.1) as follows:¹

$$\text{New } S = \text{Range} * f_{4,n},$$

where $\text{Range} = [\text{MAX}(d_i) - \text{MIN}(d_i)]$. The new sum S is then computed as

$$\text{New sum } S = (S' + S),$$

where S' is the previous sum S . The new average S ($\bar{S}$) is equal to the new sum S divided by 2:

$$\bar{S} = (\text{New Sum } S)/2.$$

As indicated, the standard deviation is a weighted average of the standard deviations of all previous cycles.

When a prior estimate of the standard deviation of the response variable is known, it can be used as a substitute for the computed standard deviation during the initial phase. Having reached the second cycle in any phase, however, the prior estimate of the standard deviation is disregarded, and the computed standard deviation is used.

For any cycle ($n > 1$), the standard deviation is recomputed as indicated. For the first cycle of a new phase (i.e., $n = 1$), the standard deviation from the last phase is used. For $n > 1$ the standard deviation is updated as above.

The standard error (SE) is calculated as follows:

$$SE = \bar{S}/\sqrt{n},$$

where n is the cycle number, and $\bar{S}$ is the estimate of the standard deviation.

3.2.2 Direction of Movement on the Response Surface

Based on the results of the EVOP calculations, the MACHOP routine selects a set of operating conditions. This may be another cycle in the current phase (i.e., new observations at the same four feed-speed combinations) or a new phase may be initiated (i.e., observations at a different set of four feed-speed combinations). In either case, MACHOP recommends the four points (i.e., two adjacent feeds and two adjacent speeds) where new observations should be taken.

¹The factor $f_{4,n}$ is used to convert a range to an estimate of the standard deviation.

The recommendations are derived by comparing the calculated effects with two standard errors of the effect:

1. If the absolute value of an effect is greater than or equal to the two standard errors, the effect is judged significant, i.e.,

$$\text{If } |\text{EFFECT}| \geq 2\text{SE}$$

then the EFFECT is judged significant.

2. If the absolute value of an effect is less than two standard errors, the effect is judged not significant, i.e.,

$$\text{If } |\text{EFFECT}| < 2\text{SE},$$

then the EFFECT is judged not significant.

When one or more effects are judged significant, a new set of operating conditions is recommended by the program (i.e., a new phase) in accordance with a decision table. The decision table for minimizing C_u is given in Table 3.1. To maximize the production rate (Pr), the negative of Pr is minimized. Hence the same table is used by the program with the production rates replaced by their negatives.

3.3 Response Surface and Regression Analysis

Regression analysis is a technique for estimating the parameters of an equation relating a response variable to a set of independent variables. The resulting equation is called a regression equation. In the MACHOP program two response variables, the cost per piece and the production rate, are considered and regression equations are developed for each. The two independent variables are the feed (F) and the cutting speed (V).

The regression equation is used to predict the response (y) for the feeds and speeds in the region where the data were collected. Five different forms of the prediction equation are considered:

$$(3.1) \quad y = b_0 + b_1 \ln V + b_2 \ln F$$

$$(3.2) \quad y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F$$

$$(3.3) \quad y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln V)^2$$

$$(3.4) \quad y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln F)^2$$

$$(3.5) \quad y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln V)^2 + b_5 (\ln F)^2$$

Table 3.1 Decision Table for Minimization of Cost*

Significance and Direction of Effects			Action				
Speed(V)	Feed(F)	Interaction (V×F)	Reobserve same settings	Inc. Speed	Decr. Speed	Inc. Feed	Decr. Feed
0	0	0	*				
P	0	0			*		
N	0	0		*			
0	P	0					*
0	N	0				*	
P	P	0			*		*
N	P	0		*			*
P	N	0			*	*	
N	N	0		*		*	
0	0	P	If $\bar{y}_1$ is min., decr. speed and feed; if $\bar{y}_2$ is min., incr. speed and feed; if $\bar{y}_3$ is min., incr. speed and decr. feed; if $\bar{y}_4$ is min., decr. speed and incr. feed.				
0	0	N					
P	0	P			*	*	
P	0	N			*		*
N	0	P		*			*
N	0	N		*		*	
0	P	P		*			*
0	P	N				*	*
0	N	P			*	*	
0	N	N		*		*	
P	P	P			*		*
P	P	N			*		*
P	N	P			*	*	
P	N	N			*	*	
N	P	P		*			*
N	P	N		*			*
N	N	P		*		*	
N	N	N		*		*	

*P(N) indicates a significant positive (negative) effect; A 0 indicates the effect is not significant.

The natural logarithmic transformation of feed and speed was deemed appropriate on the basis of the work of Ermer and Wu [8] and the experience gained in analyzing RIA shop data. The program can be easily modified to use other transformations. One of the equations 3.1 - 3.5 is selected depending on the number of data points available and the number of levels of the feeds and speeds through the logic depicted in Figure 3.2.

The general methodology of the regression program is briefly explained in Section 3.3.1 for m independent variables and n observations. An understanding of this section is not necessary for use of the program. Section 3.3.2 contains a discussion of the regression calculations for phase 1, cycle 1.

3.3.1 General Methodology

A multiple regression equation may be expressed in the following form:

$$y - \bar{y} = \beta_1 (x_1 - \bar{x}_1) + \beta_2 (x_2 - \bar{x}_2) + \dots + \beta_m (x_m - \bar{x}_m) + e,$$

where $\bar{y}$ and $\bar{x}$ are sample averages.

Given the set of observations:

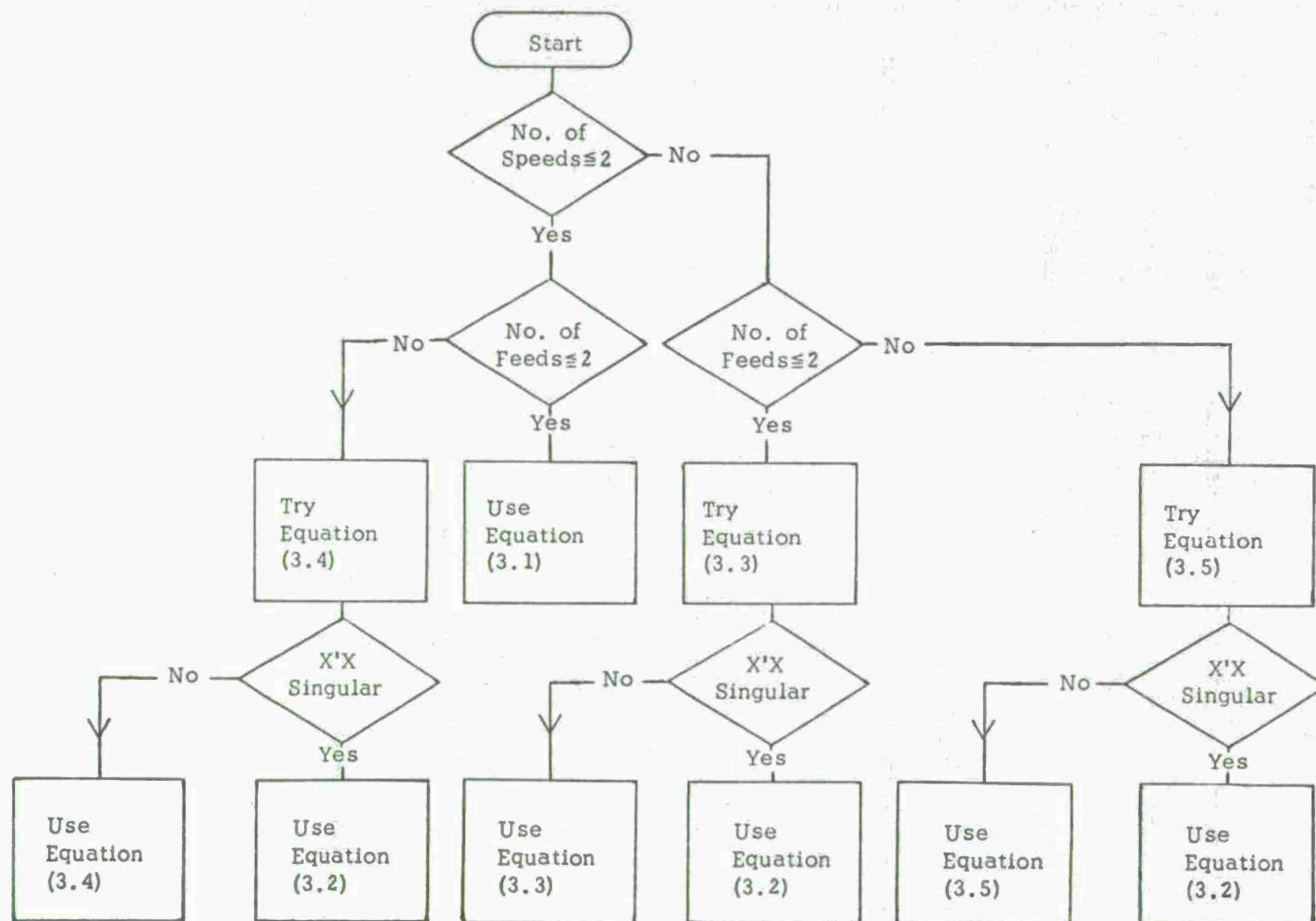
$$\begin{array}{cccc} x_{11} & x_{21} \dots x_{m1} & y_1 \\ x_{12} & x_{22} \dots x_{m2} & y_2 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ x_{1n} & x_{2n} \dots x_{mn} & y_n \end{array}$$

the X matrix is defined as

$$X = \begin{bmatrix} (x_{11} - \bar{x}_1) & (x_{21} - \bar{x}_2) \dots (x_{m1} - \bar{x}_m) \\ (x_{12} - \bar{x}_1) & (x_{22} - \bar{x}_2) \dots (x_{m2} - \bar{x}_m) \\ \cdot & \cdot \\ \cdot & \cdot \\ (x_{1n} - \bar{x}_1) & (x_{2n} - \bar{x}_2) \dots (x_{mn} - \bar{x}_m) \end{bmatrix}$$

where

$$\bar{x}_i = \sum_{j=1}^n x_{ij} / n.$$



Selection of the Regression Equation

Figure 3.2

The $\underline{b}$ vector contains the unknown coefficients

$$\underline{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

and the $\underline{y}$ vector is calculated from the dependent variable observations by

$$\underline{y} = \begin{bmatrix} (y_1 - \bar{y}) \\ (y_2 - \bar{y}) \\ \vdots \\ (y_n - \bar{y}) \end{bmatrix}$$

where

$$\bar{y} = \sum_{j=1}^n y_j / n.$$

The least squares estimates of the unknown coefficients are

$$\underline{b} = (X'X)^{-1}X'\underline{y},$$

and the resulting prediction equation is

$$y = \bar{y} + b_1(x_1 - \bar{x}_1) + \dots + b_m(x_m - \bar{x}_m).$$

The analysis of variance table is given in Table 3.2.

Table 3.2 Analysis of Variance (ANOVA)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Total	$n - 1$	$\underline{y}'\underline{y}$		
Regression	m	$\underline{b}'(X'\underline{y})$	$\frac{\underline{b}'(X'\underline{y})}{m}$	$\frac{\underline{b}'(X'\underline{y})(n-1-m)}{m[\underline{y}'\underline{y}-\underline{b}'(X'\underline{y})]}$
Residual	$n - 1 - m$	$\underline{y}'\underline{y}-\underline{b}'(X'\underline{y})$	$\frac{\underline{y}'\underline{y}-\underline{b}'(X'\underline{y})}{n - 1 - m}$	

The significance of the resultant regression may be tested by an F test. Draper and Smith [5] state that the equation should not be considered a satisfactory predictor unless the F value is at least 4 times greater than the test statistic $F_{(m, n-1-m, 1-\alpha)}$, where α is the significance level for the test.

The ratio (regression sum of squares)/(total sum of squares), denoted R^2 , is a measure of the "goodness" of fit of the regression equation. An $R^2 = 1$ indicates a perfect fit of the data to the function, while $R^2 = 0$ indicates $b_1 = b_2 = \dots = b_m = 0$. The variance, σ^2 , is estimated by the mean square of the residuals.

3.3.2 Illustration of Regression Calculations for Phase 1, Cycle 1

To illustrate the regression methodology we consider the cost per piece prediction for phase 1, cycle 1. For phase 1, cycle 1, the following information is available ($m = 2$, $n = 4$):

V_1	F_1	NPT_1	NTC_1	NT_1
V_2	F_2	NPT_2	NTC_2	NT_2
V_3	F_3	NPT_3	NTC_3	NT_3
V_4	F_4	NPT_4	NTC_4	NT_4

where

- V = speed (rpm),
- F = feed (ipr),
- NPT = no. of parts produced,
- NTC = no. of tool changes, and
- NT = total production time in minutes.

The logarithm of the feed ($\ln F$) and of the speed ($\ln V$) are the independent variables. The X matrix is

$$X = \begin{bmatrix} (\ln V_1 - \overline{\ln V}) & (\ln F_1 - \overline{\ln F}) \\ \vdots & \vdots \\ (\ln V_4 - \overline{\ln V}) & (\ln F_4 - \overline{\ln F}) \end{bmatrix},$$

where $\overline{\ln}$ denotes the averages of the logarithms.

The $\underline{b}$ vector is

$$\underline{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} .$$

The $\underline{y}$ vector is determined from the equations in Section 3.1 by

$$\underline{y} = \begin{bmatrix} y_1 - \bar{y} \\ y_2 - \bar{y} \\ y_3 - \bar{y} \\ y_4 - \bar{y} \end{bmatrix} .$$

The $\underline{b}$ vector is given by

$$\underline{b} = (X'X)^{-1} X'\underline{y} .$$

The prediction equation is given in the form

$$y = \bar{y} + b_1 (\ln V - \bar{\ln V}) + b_2 (\ln F - \bar{\ln F}) .$$

The ANOVA table is calculated according to Table 3.2 using the expressions given above.

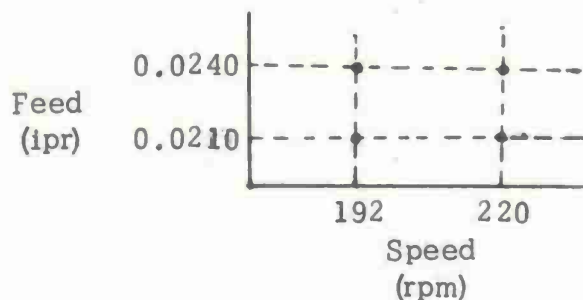
The MACHOP output contains an analysis of variance (ANOVA) table, the coefficient of multiple regression (R^2), the regression coefficients, their t values and the standard deviations for both the cost per piece and the production rate. Predictions of the cost per piece and the production rate are made for all feeds and speeds within one level of the extremes of the feeds and speeds where observations have been taken.

4. Use of MACHOP

The MACHOP program incorporates evolutionary operation and response surface-regression analysis to determine the optimal machining conditions for single-operation and multiple-operation (numerically controlled) processes. It is intended for use by managers or foremen directly concerned with the operation of individual machining processes.

4.1 Collecting Data for MACHOP

To simplify the collection of data in the shop, observations are always taken in cycles--a set of four observations at two adjacent feeds and two adjacent speeds. For example, if the feeds and speeds selected are (0.0210 ipr, 0.0240 ipr) and (192 rpm, 220 rpm), respectively, then data is collected at the following feed-speed combinations:



The MACHOP committee, composed of the foreman, the appropriate technical personnel and the machine operator, selects an initial set of operating conditions (two adjacent speeds and two adjacent feeds) for the machining operation under study. Before collecting data for the MACHOP program, trial runs should be made at each of the four feed-speed combinations to insure machinability under these conditions. If problems are encountered during trial runs at any of these four feed-speed combinations, a new set of four points should be selected, omitting the feed-speed combinations where problems were encountered. Trial runs should be made at these feed-speed combinations. This process is continued until four feed-speed combinations (at two adjacent feeds and two adjacent speeds) have been selected. Each feed-speed combination is then run for one shift of operation, and the following information is collected:

1. the number of parts produced,
2. the number of tool edges used for each tool type, and
3. the production time.¹

¹Actual machining, work piece handling and tool handling time.

The quality of the parts being machined should always be observed, and if at any time the operator feels the produced parts are in danger of not meeting standards, he should stop taking data at this feed and speed combination.

If data collection is discontinued at any feed-speed combination during a production run, a decision must be made concerning the use of the data already collected at this point. If the number of parts machined is sufficient to give accurate measures of the performance indices, the results can be used for input to the MACHOP program, even though a full shift of data has not been collected. If problems of workpiece accuracy are encountered or if it becomes apparent that scrap or tool breakage costs will exceed other potential gains during a production run prior to obtaining a sufficient number of parts, a new set of four feed-speed combinations should be selected. After collecting data at each of the four combinations and recording this information on the forms provided, the data is summarized and submitted to the MACHOP program. (Sample data collection forms are given in Appendix C, and a sample summary form is given in Figure G.1 of Appendix G.)

4.2 Analysis of the MACHOP Output

Sample MACHOP outputs appear in Figures 5.1 - 5.3. Each output gives the following information on separate pages:

- a. Input information such as feed-speed limits, labor and overhead rates, tool costs, and prior estimates of standard deviations of the response variables (if any).
- b. The specified feed-speed environment represented "graphically."
- c. The cumulative input data and the computed responses (cost per piece and production rate).
- d. A table of the computed responses for this phase and cycle.
- e. Evolutionary operation calculations for both the cost per piece and production rate responses.
- f. A recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the cost per piece analysis.
- g. A graphical representation of the operating conditions recommended in f.
- h. The recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the production rate analysis.

- i. A graphical representation of the operating conditions recommended in h.
- j. The results of the regression analysis and the accompanying analysis of variance table for the cost per piece analysis.
- k. The results of the regression analysis and the accompanying analysis of variance table for the production rate analysis.
- l. The predicted response surfaces for cost/piece and production rate calculated from the respective prediction equations.

The output information in a, b, c and d should be reviewed for detection of any input errors. If any recording and/or transcription errors are noted, the input should be corrected and resubmitted to the MACHOP program. If it is determined that any of the data were collected under abnormal operating conditions, new data should be collected at these points. The results should then be resubmitted to the MACHOP program.

If the output information in a, b, c and d appears acceptable, the remainder of the output e-l should be examined. Parts f, g, h, i, and l are of particular interest to production personnel. Analysis of these results should allow a decision to be made concerning operating conditions for the next set of observations. (The other parts (e, j, and k) give additional details concerning the computations.) If the results and recommendations seem to be reasonable, the data should be collected at the set of points suggested by the MACHOP program. After the data have been collected, the above procedure is again followed. This process continues until MACHOP committee decides that sufficient data have been collected in order to determine optimal operating conditions.

The MACHOP recommendations should be treated as possible courses of action. The final decision rests with the MACHOP committee. If the committee decides to collect additional data, the following rules must be observed. The new set of observations must be taken either at the same four points (another cycle in the current phase) or at another rectangular pattern of adjacent points (a new phase). (A more complete discussion of phases and cycles was given in Section 3.2.1.) We suggest the movement be restricted to feed-speed combinations immediately adjacent to the previous feed-speed combinations. Either speed or feed or both may be varied at one time.

4.3 Scope of Application

The MACHOP routines can be used for single operation as well as multiple-operation (numerically controlled) processes.

For multiple-operation (non-numerically controlled) machine tools, data must be collected on all the cutting tools. In addition, one operation of the machine must be selected for the initial study, since only one set of feeds and speeds can be varied at a time. The selection of this particular operation is important. In general, it should be the operation which has the greatest potential for improvement. This will often be the operation requiring the longest time. After this operation has been optimized, another operation can be selected for study. Sample data collection forms are given in Appendix C.

For numerically controlled processes a different problem is encountered. In this case the feeds and speeds for the operations are pre-programmed. However, the feeds and speeds can be adjusted by overrides. The optimization program is conducted through the use of these overrides in order to avoid reprogramming. Again a rectangular pattern is used, now in terms of percentage feed and speed overrides. Increments of five percent seem reasonable. If analysis of the data collected indicates that either the speed or feed increment should be adjusted beyond its presently programmed limits, consideration should be given to reprogramming the tape. At this point the relationship of the various speeds and feeds should also be discussed. Whenever the tape is changed, the MACHOP program must be restarted. That is, all previous data should be removed, and Phase 1 should begin again. The only information which can be used from the previous output are the estimates of the standard deviations and the costs. The estimates of the standard deviations from the last output should be submitted as prior estimates of the standard deviations. For numerically controlled processes, data is recorded on the same form as for multiple-operation processes. However instead of recording only feeds and speeds, the feed and speed overrides are also recorded.

4.4 Data Handling System

During the initial set-up of the problem (phase 1, cycle 1), the necessary data such as speed and feed environments must be recorded. Once this is accomplished, all succeeding cycles use the same input with the addition of a new set of observations and punched output from the previous cycle.

Once the initial information is given, less than five minutes per cycle will be required for data recording and preparation. Consequently, no elaborate data handling system is considered necessary for this process. A volume of four new cards per cycle is not sufficient to justify elaborate equipment. The most effective method for accomplishing this is for the individual directly interested with the process (ultimately the machinist) to be responsible for preparing the data sheets for forwarding to the data processing unit for key punching.

5. MACHOP Analysis of RIA Data

In this section the results of the MACHOP analysis of the turning operation (recoil cylinder, Part No. 10895646) on a Monarch lathe are given. The details of this particular operation are given in Table 2.5. A summary of the data collected is given in Table 5.1. For this machining operation the response variables (cost per piece and production rate) are calculated from the production data as explained in Section 3.1. In addition to the input information required by the MACHOP program, a prior estimate of the standard deviation of the cost per piece of 0.60 dollars was specified, based on observations made during the initial phases of the study.¹ No estimate was made of the standard deviation of the production rate.

The data and output information for phase 1, cycle 1 are given in Figures 5.1a - 5.1l. The cost analysis (Figure 5.1f) indicates that the factor feed was significant. Since no prior estimate of the production rate standard deviation was supplied, the EVOP analysis indicates none of the factors was significant. The response surface-regression analysis (Figure 5.1l) was in general agreement with the EVOP analysis, so phase 2 was initiated. The feeds and speeds recommended by the EVOP cost per piece analysis (Figure 5.1f) were used for phase 2, cycle 1.

The MACHOP output for phase 2, cycle 1 is given in Figures 5.2a - 5.2l. Based on the new data, a three variable regression equation was fitted. (See Section 3.3 for details.) Neither of the resulting EVOP analyses (Figures 5.2f and 5.2h) indicated that any factor was significant. Consequently, another cycle of data was taken for phase 2.

The MACHOP output for phase 2, cycle 2 appears in Figures 5.3a - 5.3l. The EVOP analysis of the cost per piece and production rate results (Figures 5.3f and 5.3h) again indicates that none of the effects are significant. However, the predictions of cost per piece and production rate in response surface-regression (Figure 5.3l) indicate the same direction toward the optimum. On the basis of these results, we could take another cycle of data for phase 2 or begin phase 3. We recommend beginning phase 3 of the study at either of the following sets of feed-speed combinations:

<u>Speed</u>	<u>Feed</u>		<u>Speed</u>	<u>Feed</u>
166	0.0210		166	0.0240
166	0.0240	or	166	0.0270
192	0.0210		192	0.0240
192	0.0240		192	0.0270

However, before beginning this phase, a trial run should be made at each of the new combinations to insure acceptable machining results.

Comparison of the predicted costs in Figure 5.3l gives an indication of the potential for cost reduction through optional selection of feeds and speeds.

¹Note that an estimate of the standard deviation is not required.

Table 5.1 Summary of RIA Data

	<u>Date</u>	<u>Speed</u>	<u>Feed</u>	<u>No. of Parts</u>	<u>Time</u>	<u>No. of Tool Edges</u>	<u>Comments</u>
	1) 6/12/73	192	0.0187	18	410	18	None
	2) 6/13/73	220	0.0210	20	440	44	Inserts break in half or chip. The out of round condition seems to contribute to insert breakage as I ran 2 pieces on one insert because they were fairly straight and had trouble running one piece with 2 inserts when the piece was extremely out of round.
	3) 6/27/73	255	0.0187	11	267	29	None
	4) 6/28/73	192	0.0210	14	377	18	Chips are still too tight. Tips of inserts are chipping at times depending on out of round condition of piece.
	5) 6/29/73	220	0.0189	15	393	15	Good chips. Finish real good considering the condition of the pieces.
	6) 7/5/73	192	0.0168	14	434	17	None
	7) 7/10/73	220	0.0168	13	396	23	Tips of inserts are chipping easily on irregular pieces. Finish is poor as insert breaks down at about 3/4 of the way down the piece. Chips are small and tight.
	8) 7/17/73	255	0.0168	10	217	17	None
	9) 7/18/73	255	0.0210	14	357	31	Inserts break down about 1/4 way across cut. Finish is horrible.
	10) 8/3/73	192	0.0187	14	374	16	None
	11) 8/6/73	220	0.0187	15	394	17	Inserts break down 1/3 of the way through cut. Finish is very rough. (1 insert broke on end of piece so was able to use replaced edge on next piece.)
	12) 8/7/73	220	0.0187	9	228	15	None
	13) 8/16/73	192	0.0187	8	214	16	None
	14) 8/17/73	220	0.0187	13	381	20	Finish was real good even for first time pieces done with one insert edge, but on third piece, insert had a tendency to break down 1/3 of the way across.

M A C H O P

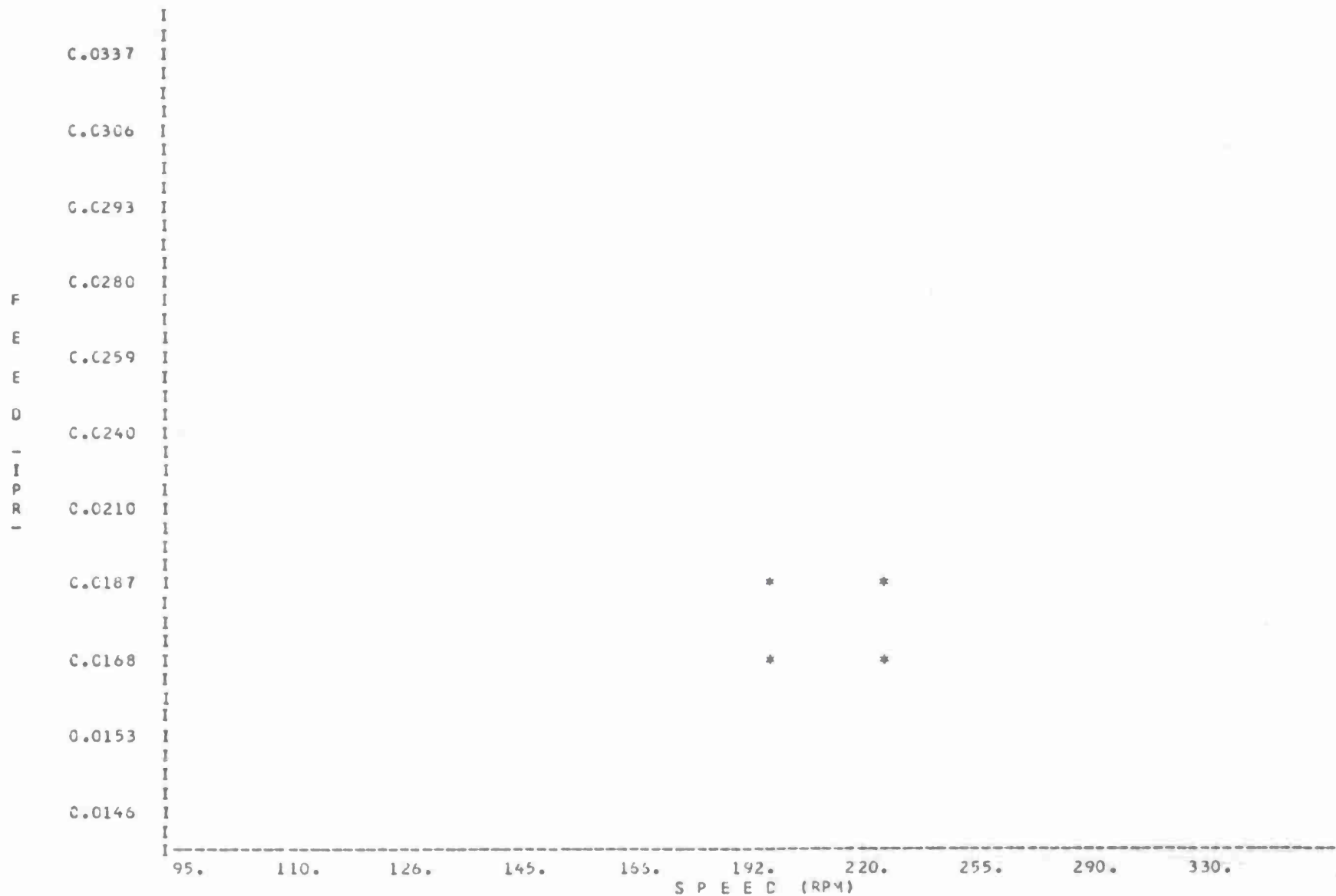
TURNING OPERATION ON A MONARCH LATHE-- RECOIL CYLINDER, PART NO. 10895646

PHASE IS 1
CYCLE IS 1
TYPE OF PROCESS IS 1 SINGLE
SPEED-FEED LIMITS NOT SPECIFIED
LABOR-OVERHEAD (\$/MIN) 0.3000
COST STD. DEV. EST. IS 0.6000
P.R. STD. DEV. EST. IS NOT SPECIFIED
NUMBER OF TOOLS IS 1
SPECIFIED TOOL COST/EDGE 0.4200
NUMBER OF SPEEDS IS 10
NUMBER OF FEEDS IS 11

a.

Figure 5.1 MACHOP Output for Phase 1, Cycle 1

SPECIFIED ENVIRONMENT



b.

Figure 5.1 (continued)

INPUT VALUES AND COMPUTED RESPONSES

SPEED	FEED	PARTS	TIME	TOOL-EDGES																COST (\$/PIECE)	PROD RATE (PIECES/MIN)
				(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)								
				(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)								
192.	0.0168	14.	434.	17.																9.81	0.0323
220.	0.0187	15.	393.	15.																8.28	0.0382
220.	0.0168	13.	396.	23.																9.88	0.0328
192.	0.0187	18.	410.	18.																7.25	0.0439

C.

Figure 5.1 (continued)

TABLE OF RESPONSES

FEED (IPR)							
0.0187	COST	=	7.25	COST	=	8.28	
	PROD. RT.	=	0.0439	PROD. FT.	=	0.0382	
0.0168	COST	=	9.81	COST	=	9.88	
	PROD. RT.	=	0.0323	PROD. RT.	=	0.0328	
			192.			220.	
				S P E E D (RPM)			

d.

Figure 5.1 (continued)

EVOLUTIONARY OPERATION ANALYSIS
PHASE 1 CYCLE 1

CALCULATION OF AVERAGES

OPERATING CONDITIONS	COST				PRODUCTION RATE			
	SPEED (RPM)	220.	220.	192.	192.	220.	220.	192.
FEED (IPR)	0.0168	0.0187	0.0168	0.0187	0.0168	0.0187	0.0168	0.0187
PREVIOUS CYCLE SUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PREVIOUS CYCLE AVERAGE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NEW OBSERVATIONS	9.81	8.28	9.88	7.25	0.0323	0.0382	0.0328	0.0439
DIFFERENCES	-9.81	-8.28	-9.88	-7.25	-0.0323	-0.0382	-0.0328	-0.0439
NEW SUMS	9.81	8.28	9.88	7.25	0.0323	0.0382	0.0328	0.0439
NEW AVERAGES: Y(1)	9.81	8.28	9.88	7.25	0.0323	0.0382	0.0328	0.0439

CALCULATION OF STANDARD DEVIATIONS

PREVIOUS AVERAGE S	0.6000	0.0
NEW S = RANGE * F _{4,N}	0.0	0.0
RANGE	2.6282	0.0116
NEW SUM S	0.0	0.0
NEW AVERAGE S = NEW SUM S/2	0.0	0.0

CALCULATION OF 2 S.E. LIMITS:

FOR NEW EFFECTS	1.2000	0.0
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e.

Figure 5.1 (continued)

COST ANALYSIS

THE EFFECT OF SPEED IS 0.5491 --- NOT SIGNIFICANT ---

THE EFFECT OF FEED IS -2.0791 *** -- SIGNIFICANT -- ***

THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS 0.4776 --- NOT SIGNIFICANT ---

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

4) SPEED = 192.
FEED = 0.0210

2) SPEED = 220.
FEED = 0.0210

1) SPEED = 192.
FEED = 0.0187

3) SPEED = 220.
FEED = 0.0187

f.

Figure 5.1 (continued)

NEW COST ENVIRONMENT

46

F
E
E
C
-
I
P
R
-

C.C337

C.0306

C.C293

C.0280

C.0259

0.0240

C.C210

C.C187

C.C168

C.C153

C.C146

95. 110. 126. 145. 166. 192. 220. 255. 290. 330.
S P E E D (RPM)

g.

Figure 5.1 (continued)

PRODUCTION RATE ANALYSIS

NO PARAMETERS ARE SIGNIFICANT

THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

4) SPEED = 192.
FEED = 0.0187

2) SPEED = 220.
FEED = 0.0187

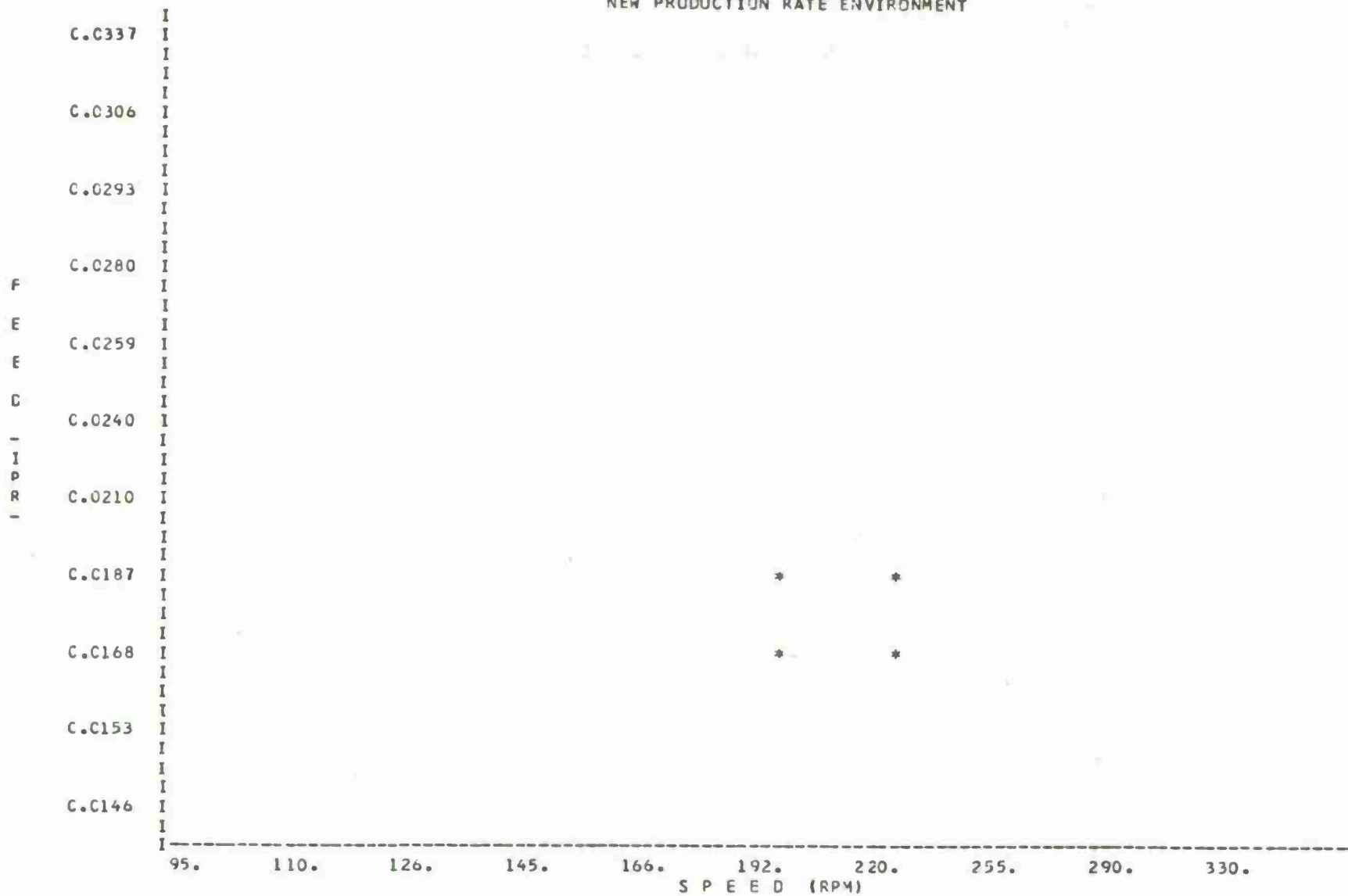
1) SPEED = 192.
FEED = 0.0168

3) SPEED = 220.
FEED = 0.0168

h.

Figure 5.1 (continued)

NEW PRODUCTION RATE ENVIRONMENT



i.
Figure 5.1 (continued)

MULTIPLE REGRESSION ON 2 VARIABLES WITH 4 OBSERVATIONS

COST EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	3	0.48522396E 01		
REGRESSION	2	0.46241693E 01	0.23120842E 01	0.10127596E 02
RESIDUAL	1	0.22807026E 00	0.22807026E 00	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.95299685E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUBC = -0.90930115E 02		
BHAT(1) = 0.403359604E 01	T(1) = 0.11497908E 01	SD(1) = 0.35081120E 01
BHAT(2) = -0.194046631E 02	T(2) = -0.43535252E 01	SD(2) = 0.44572296E 01

THE PREDICTION EQUATION IS

$$PI = -90.9301 + 4.0336 * \ln(\text{SPEED}) + -19.4047 * \ln(\text{FEED})$$

j.

Figure 5.1 (continued)

MULTIPLE REGRESSION ON 2 VARIABLES WITH 4 OBSERVATIONS

PRODUCTION RATE EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	3	0.88719112E-04		
REGRESSION	2	0.78781697E-04	0.39390841E-04	0.39638910E 01
RESIDUAL	1	0.99374156E-05	0.99374156E-05	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.88799012E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUBC = 0.45743413E 00		
BHAT(1)=-0.189676855E-01	T(1)=-0.81911176E 00	SD(1)= 0.23156650E-01
BHAT(2)= 0.792576671E-01	T(2)= 0.26938515E 01	SD(2)= 0.29421683E-01

THE PREDICTION EQUATION IS

$$PI = 0.4574 + -0.0193 \cdot \ln(\text{SPEED}) + 0.0793 \cdot \ln(\text{FEED})$$

k.

Figure 5.1 (continued)

PREDICTED COSTS
(PREDICTED PRODUCTION RATES)

FEED (IPR)

O.C210	I				
	I	4.65	5.24	5.79	6.39
	I	(0.0543)	(0.0515)	(0.0489)	(0.0461)
O.C187	I				
	I	6.91	7.49	8.04	8.64
	I	(0.0451)	(0.0423)	(0.0397)	(0.0369)
O.C168	I				
	I	8.98	9.57	10.12	10.72
	I	(0.0366)	(0.0338)	(0.0313)	(0.0285)
O.C153	I				
	I	10.80	11.39	11.94	12.53
	I	(0.0292)	(0.0264)	(0.0238)	(0.0210)

166. 192. 220. 255.

S P E E D (RPM)

l.

Figure 5.1 (continued)

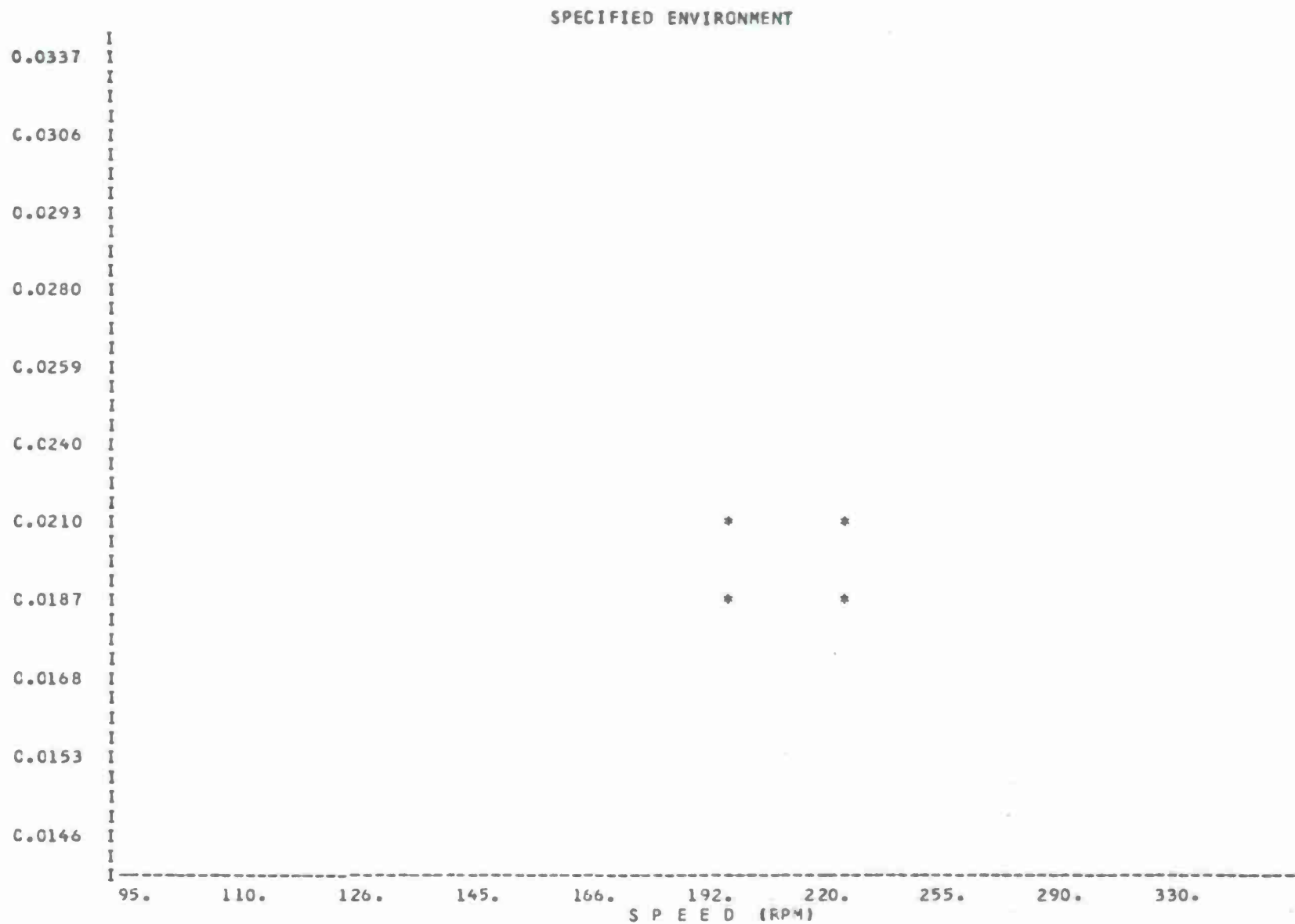
M A C H O P

TURNING OPERATION ON A MONARCH LATHE-- RECOIL CYLINDER, PART NO. 10895646

PHASE IS 2
CYCLE IS 1
TYPE OF PROCESS IS 1 SINGLE
SPEED-FEED LIMITS NOT SPECIFIED
LABOR-OVERHEAD (\$/MIN) 0.3000
COST STD. DEV. EST. IS 0.6000
P.R. STD. DEV. EST. IS NOT SPECIFIED
NUMBER OF TOOLS IS 1
SPECIFIED TOOL COST/EDGE 0.4200
NUMBER OF SPEEDS IS 10
NUMBER OF FEEDS IS 11

a.

Figure 5.2 MACHOP Output for Phase 2, Cycle 1



b.

Figure 5.2 (continued)

INPUT VALUES AND COMPUTED RESPONSES

54

SPEED	FEED	PARTS	TIME	TOOL-EDGES																COST (\$/PIECE)	PROD RATE (PIECES/MIN)
				(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)								
				(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)								
192.	C.0168	14.	434.	17.																9.81	0.0323
192.	C.0187	18.	410.	18.																7.25	0.0439
220.	0.0168	13.	396.	23.																9.88	0.0328
220.	C.C187	15.	393.	15.																8.23	0.0382
192.	C.0187	8.	214.	16.																8.86	0.0374
220.	0.0210	20.	440.	44.																7.52	0.0455
220.	C.0187	15.	394.	17.																8.36	0.0381
192.	0.0210	14.	377.	18.																8.52	0.0371

c.

Figure 5.2 (continued)

TABLE OF RESPONSES

FEED (IPR)							
0.0210	COST	=	8.62	COST	=	7.52	
	PROD. RT.	=	0.0371	PROD. RT.	=	0.0455	
0.0187	COST	=	8.86	COST	=	8.36	
	PROD. RT.	=	0.0374	PROD. RT.	=	0.0381	
			192.			220.	
				S P E E D (RPM)			

d.

Figure 5.2 (continued)

EVOLUTIONARY OPERATION ANALYSIS
PHASE 2 CYCLE 1

CALCULATION OF AVERAGES

OPERATING CONDITIONS	COST				PRODUCTION RATE			
	192.	220.	220.	192.	192.	220.	220.	192.
SPEED (RPM)	192.	220.	220.	192.	192.	220.	220.	192.
FEED (IPR)	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210
PREVIOUS CYCLE SUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PREVIOUS CYCLE AVERAGE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NEW OBSERVATIONS	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
DIFFERENCES	-8.86	-7.52	-8.36	-8.62	-0.0374	-0.0455	-0.0381	-0.0371
NEW SUMS	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
NEW AVERAGES: Y(I)	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371

CALCULATION OF STANDARD DEVIATIONS

PREVIOUS AVERAGE S	0.6000	0.0
NEW S = RANGE * F4,N	0.0	0.0
RANGE	1.3410	0.0083
NEW SUM S	0.0	0.0
NEW AVERAGE S = NEW SUM S/2	0.0	0.0

CALCULATION OF 2 S.E. LIMITS:

FOR NEW EFFECTS	1.2000	0.0
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e.

Figure 5.2 (continued)

57

57

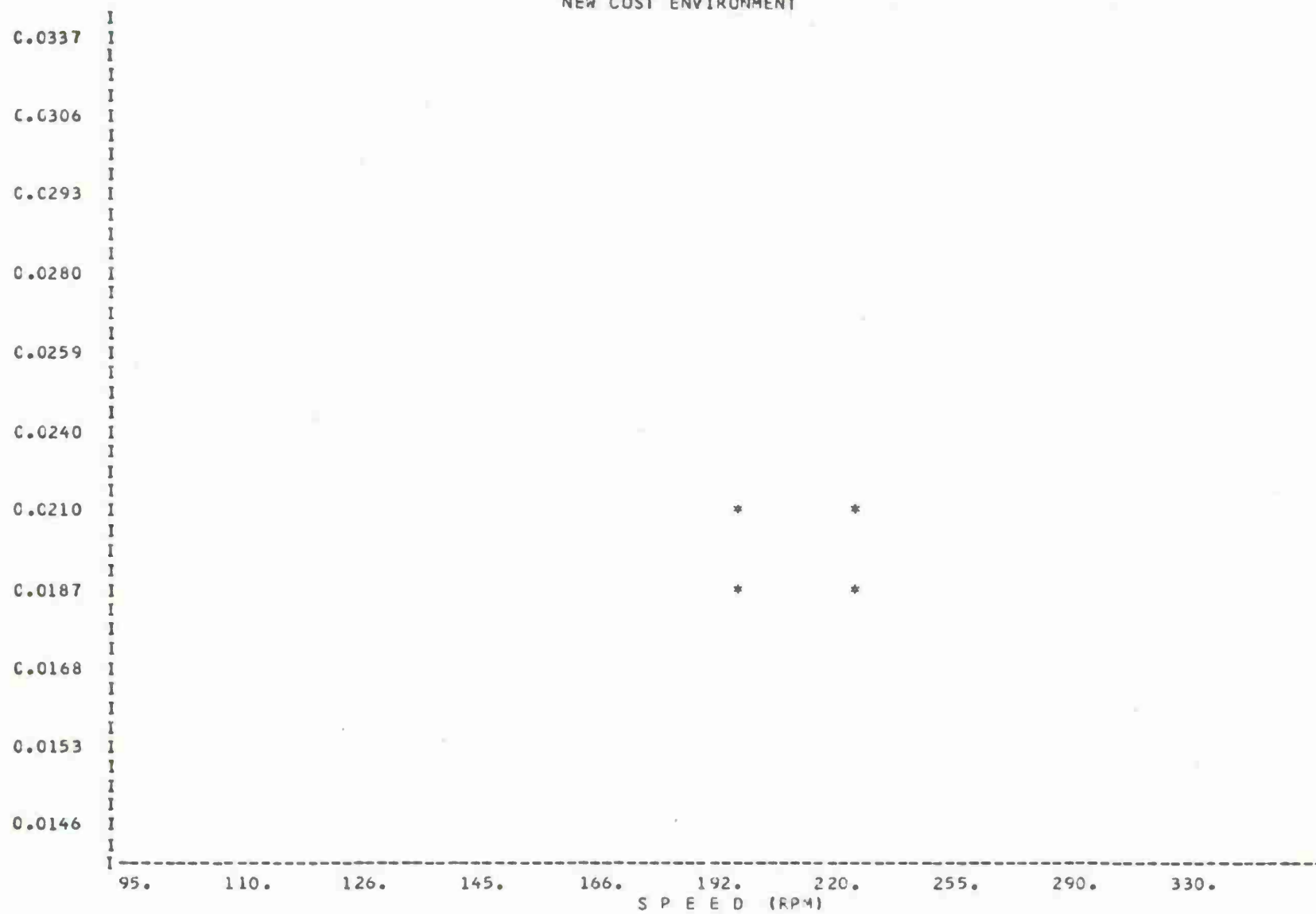
57

57

57

57

NEW COST ENVIRONMENT



g.
Figure 5.2 (continued)

PRODUCTION RATE ANALYSIS

NO PARAMETERS ARE SIGNIFICANT

THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

4) SPEED = 192.
FEED = 0.0210

2) SPEED = 220.
FEED = 0.0210

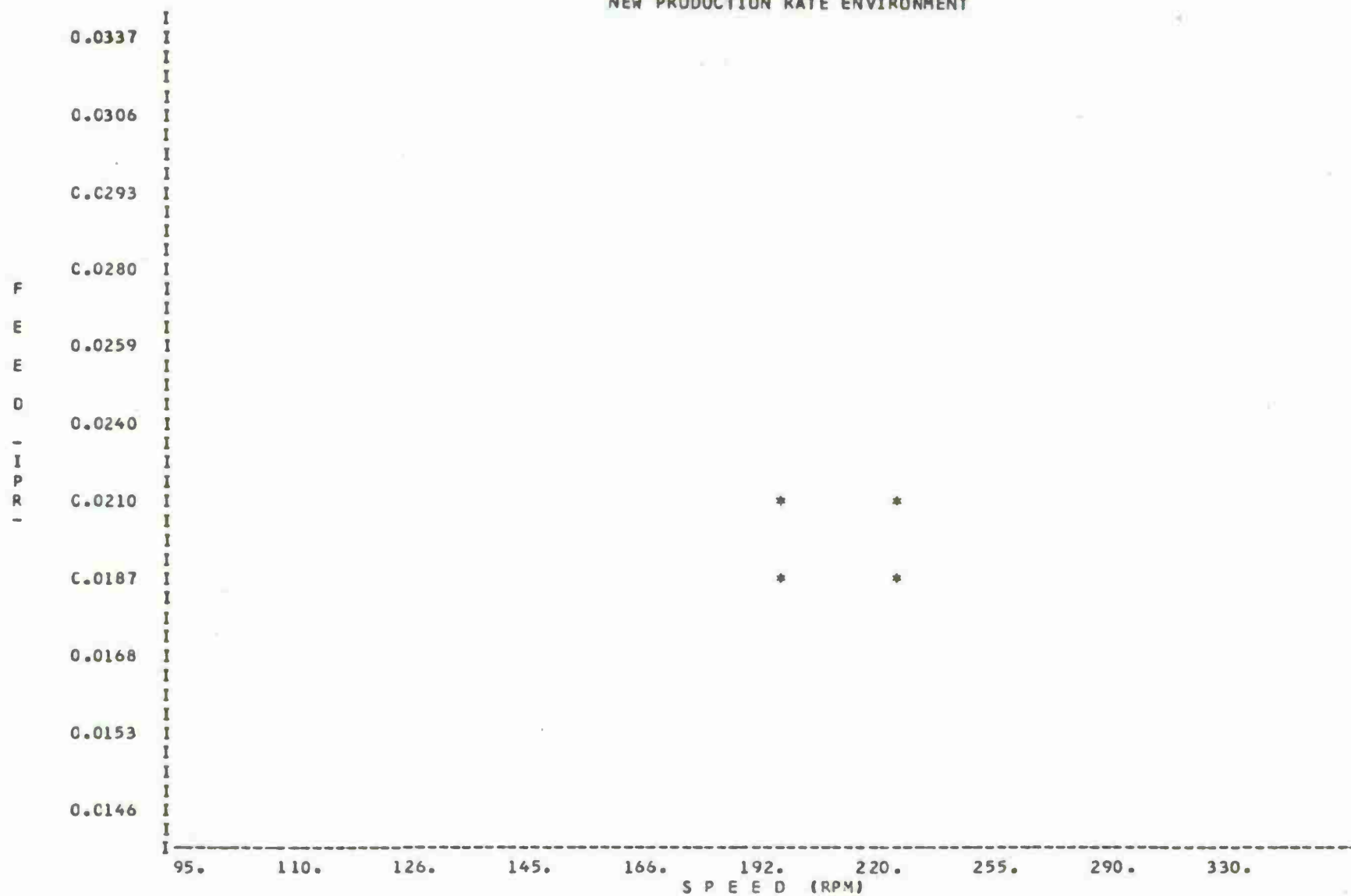
1) SPEED = 192.
FEED = 0.0187

3) SPEED = 220.
FEED = 0.0187

h.

Figure 5.2 (continued)

NEW PRODUCTION RATE ENVIRONMENT



1.
Figure 5.2 (continued)

MULTIPLE REGRESSION ON 3 VARIABLES WITH 8 OBSERVATIONS

COST EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	7	0.63046255E 01		
REGRESSION	3	0.30963936E 01	0.10321312E 01	0.12868528E 01
RESIDUAL	4	0.32082319E 01	0.80205798E 00	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.49113041E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUB0 = 0.13522401E 02		
BHAT(1)=-0.678432846E 01	T(1)=-0.12261572E 01	SD(1)= 0.55330000E 01
BHAT(2)= 0.164294243E-02	T(2)= 0.54037174E 00	SD(2)= 0.25656072E-02
BHAT(3)=-0.14725323E 01	T(3)=-0.19548788E 01	SD(3)= 0.75326025E 00

THE PREDICTION EQUATION IS

$$PI = 13.5224 + -6.7843*LN(SPEED) + 0.0016*LN(FEED) + -1.4725*LN(SPEED)*LN(FEED)$$

j.

Figure 5.2 (continued)

MULTIPLE REGRESSION ON 3 VARIABLES WITH 8 OBSERVATIONS

PRODUCTION RATE EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	7	0.15110668E-03		
REGRESSION	3	0.77535209E-04	0.25845060E-04	0.14051676E 01
RESIDUAL	4	0.73571471E-04	0.18392864E-04	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.51311564E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUB0 = 0.52310526E-03		
BHAT(1)= 0.361627676E-01	T(1)= 0.13648310E 01	SD(1)= 0.26496135E-01
BHAT(2)=-0.111279078E-04	T(2)=-0.90573573E 00	SD(2)= 0.12286042E-04
BHAT(3)= 0.731847808E-02	T(3)= 0.20288677E 01	SD(3)= 0.36071721E-02

THE PREDICTION EQUATION IS

$$PI = 0.0005 + 0.0362 * \ln(\text{SPEED}) + -0.0000 * \ln(\text{FEED}) + 0.0073 * \ln(\text{SPEED}) * \ln(\text{FEED})$$

k.

Figure 5.2 (continued)

PREDICTED COSTS
(PREDICTED PRODUCTION RATES)

FEED (IPR)

0.C240	I				
	I	6.91	6.72	6.55	6.36
	I	(0.0459)	(0.0472)	(0.0484)	(0.0497)
0.C210	I	7.92	7.76	7.61	7.45
	I	(0.0409)	(0.0420)	(0.0431)	(0.0443)
0.C187	I	8.79	8.65	8.53	8.39
	I	(0.0366)	(0.0376)	(0.0385)	(0.0396)
0.C168	I	9.59	9.48	9.38	9.27
	I	(0.0326)	(0.0335)	(0.0343)	(0.0352)
0.C153	I	10.30	10.21	10.12	10.03
	I	(0.0291)	(0.0299)	(0.0306)	(0.0314)

166. 192. 220. 255.

S P E E D (RPM)

2.

Figure 5.2 (continued)

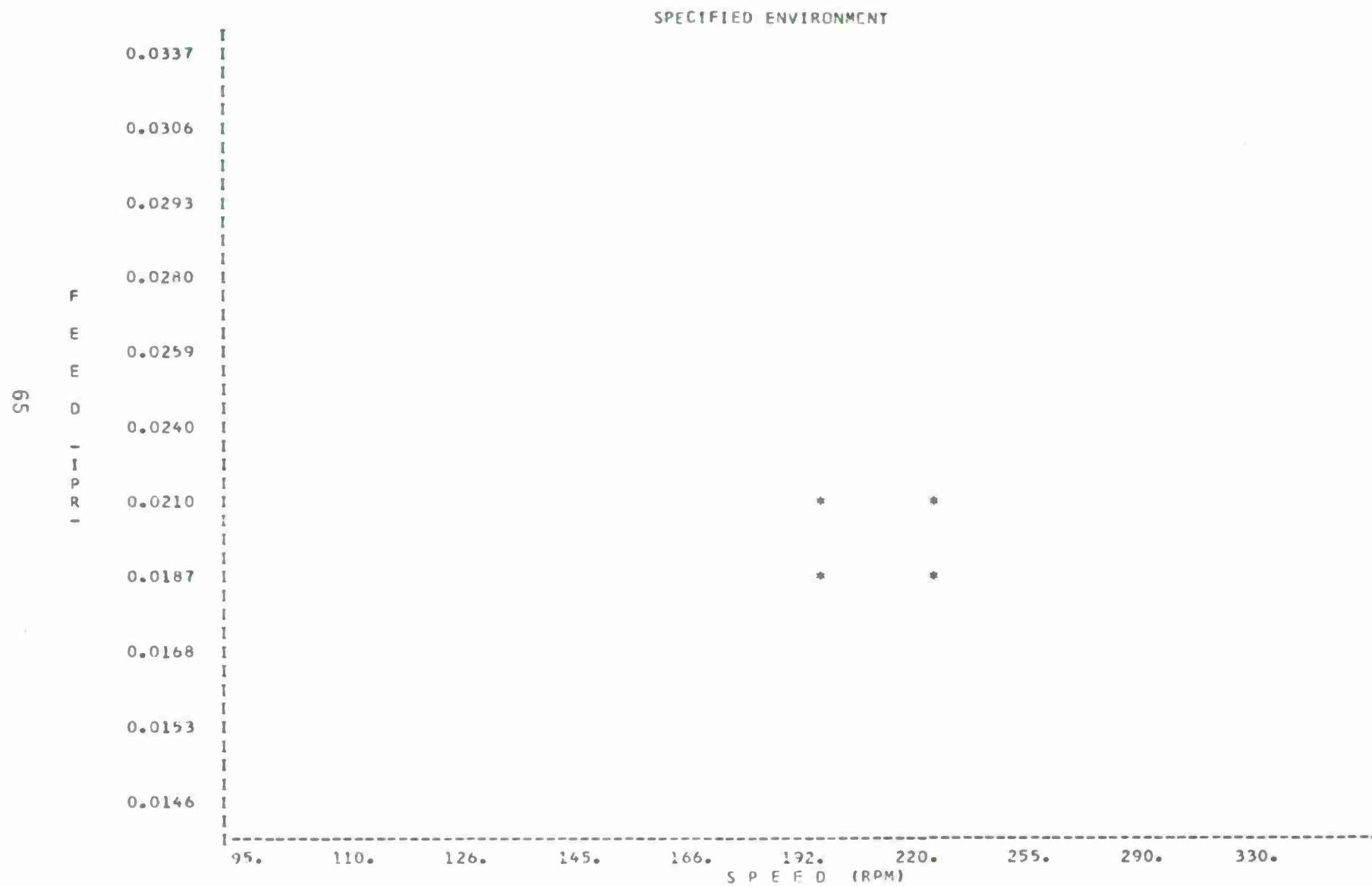
M A C H O P

TURNING OPERATION ON A MONARCH LATHE-- RECOIL CYLINDER, PART NO. 10895646

PHASE IS 2
CYCLE IS 2
TYPE OF PROCESS IS 1 SINGLE
SPEED-FEED LIMITS NOT SPECIFIED
LABOR-OVERHEAD (\$/MIN) 0.3000
COST STD. DEV. EST. IS 0.6000
P.R. STD. DEV. EST. IS NOT SPECIFIED
NUMBER OF TOOLS IS 1
SPECIFIED TOOL COST/EDGE 0.4200
NUMBER OF SPEEDS IS 10
NUMBER OF FEEDS IS 11

a.

Figure 5.3 MACHOP Output for Phase 2, Cycle 2



b.
Figure 5.3 (continued)

INPUT VALUES AND COMPUTED RESPONSES

96

SPEED	FEED	PARTS	TIME	TOOL-EDGES										COST (\$/PIECE)	PROD RATE (PIECES/MIN)
				(1) (11)	(2) (12)	(3) (13)	(4) (14)	(5) (15)	(6) (16)	(7) (17)	(8) (18)	(9) (19)	(10) (20)		
192.	0.0168	14.	434.	17.										9.91	0.0323
192.	0.0187	18.	410.	18.										7.25	0.0439
220.	0.0168	13.	396.	23.										9.88	0.0328
220.	0.0187	15.	393.	15.										8.28	0.0382
220.	0.0210	20.	440.	44.										7.52	0.0455
192.	0.0187	8.	214.	16.										8.86	0.0374
220.	0.0187	15.	394.	17.										8.36	0.0381
192.	0.0210	14.	377.	18.										8.62	0.0371
192.	0.0187	14.	374.	14.										8.43	0.0374
220.	0.0210	6.	173.	47.										11.94	0.0347
220.	0.0187	13.	381.	20.										9.44	0.0341
192.	0.0210	6.	149.	18.										8.71	0.0403

C.

Figure 5.3 (continued)

TABLE OF RESPONSES

FEED (IPR)							
0.0210	COST	=	8.71	COST	=	11.94	
	PROD. RT.	=	0.0403	PROD. RT.	=	0.0347	
0.0187	COST	=	8.43	COST	=	9.44	
	PROD. RT.	=	0.0374	PROD. RT.	=	0.0341	
				192.			
					220.		
S P E E D (RPM)							

d.

Figure 5.3 (continued)

EVOLUTIONARY OPERATION ANALYSIS
PHASE 2 CYCLE 2

CALCULATION OF AVERAGES

OPERATING CONDITIONS	COST				PRODUCTION RATE			
	192.	220.	220.	192.	192.	220.	220.	192.
SPEED (RPM)	192.	220.	220.	192.	192.	220.	220.	192.
FEED (IPR)	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210
PREVIOUS CYCLE SUM	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
PREVIOUS CYCLE AVERAGE	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
NEW OBSERVATIONS	8.43	11.94	9.44	8.71	0.0374	0.0347	0.0341	0.0403
DIFFERENCES	0.43	-4.42	-1.08	-0.09	-0.0000	0.0108	0.0040	-0.0031
NEW SUMS	17.30	19.46	17.79	17.33	0.0748	0.0801	0.0722	0.0774
NEW AVERAGES: Y(I)	8.65	9.73	8.90	8.66	0.0374	0.0401	0.0361	0.0387

CALCULATION OF STANDARD DEVIATIONS

PREVIOUS AVERAGE S	0.0	0.0
NEW S = RANGE * F _{4,N}	1.6479	0.0047
RANGE	4.8467	0.0139
NEW SUM S	3.2958	0.0095
NEW AVERAGE S = NEW SUM S/2	1.6479	0.0047

CALCULATION OF 2 S.E. LIMITS:

FOR NEW EFFECTS	2.3305	0.0067
-----------------	--------	--------

e.

Figure 5.3 (continued)

COST ANALYSIS

THE EFFECT OF SPEED IS 0.6576 --- NOT SIGNIFICANT ---
THE EFFECT OF FEED IS 0.4247 --- NOT SIGNIFICANT ---
THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS 0.4101 --- NOT SIGNIFICANT ---
NO PARAMETERS ARE SIGNIFICANT
THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

4) SPEED = 192.
FEED = 0.0210

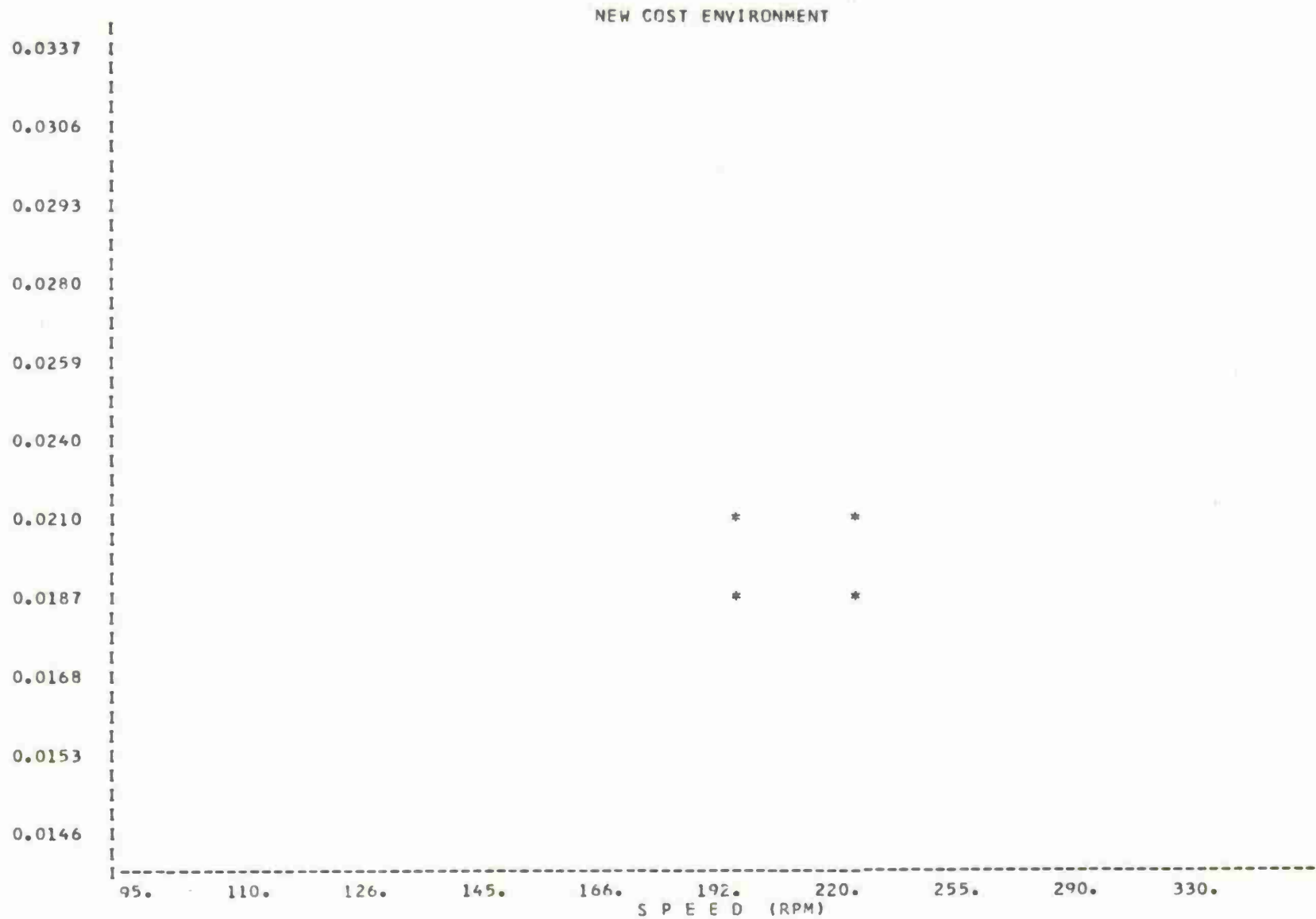
2) SPEED = 220.
FEED = 0.0210

1) SPEED = 192.
FEED = 0.0187

3) SPEED = 220.
FEED = 0.0187

f.

Figure 5.3 (continued)

F
E
E
D
-
I
P
R
-

g.
Figure 5.3 (continued)

PRODUCTION RATE ANALYSIS

THE EFFECT OF SPEED IS -0.0000 --- NOT SIGNIFICANT ---
THE EFFECT OF FEED IS -0.0026 --- NOT SIGNIFICANT ---
THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS -0.0013 --- NOT SIGNIFICANT ---
NO PARAMETERS ARE SIGNIFICANT
THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

4) SPEED = 192.	2) SPEED = 220.
FEED = 0.0210	FEED = 0.0210
1) SPEED = 192.	3) SPEED = 220.
FEED = 0.0187	FEED = 0.0187

h.

Figure 5.3 (continued)

NEW PRODUCTION RATE ENVIRONMENT

72

F
E
E
D
I
P
R

0.0337

0.0306

0.0293

0.0280

0.0259

0.0240

0.0210

0.0187

0.0168

0.0153

0.0146

95.

110.

126.

145.

166.

192.

220.

255.

290.

330.

S P E E D (RPM)

1.

Figure 5.3 (continued)

MULTIPLE REGRESSION ON 3 VARIABLES WITH 12 OBSERVATIONS

COST EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	11	0.16933578E 02		
REGRESSION	3	0.15972290E 01	0.53240967E 00	0.27772433E 00
RESIDUAL	8	0.15336349E 02	0.19170437E 01	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.94323158E-01

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUB0 = -0.72270166E 03		
BHAT(1) = 0.136644745E 03	T(1) = 0.45348996E 00	SD(1) = 0.30131812E 03
BHAT(2) = -0.178687088E 03	T(2) = -0.44082719E 00	SD(2) = 0.40534497E 03
BHAT(3) = 0.333668671E 02	T(3) = 0.43842232E 00	SD(3) = 0.76106674E 02

THE PREDICTION EQUATION IS

$$PI = -722.7017 + 136.6447 \cdot \ln(\text{SPEED}) + -178.6871 \cdot \ln(\text{FEED}) + 33.3669 \cdot \ln(\text{SPEED}) \cdot \ln(\text{FEED})$$

j.

Figure 5.3 (continued)

MULTIPLE REGRESSION ON 3 VARIABLES WITH 12 OBSERVATIONS

PRODUCTION RATE EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	11	0.18127424E-03		
REGRESSION	3	0.54460019E-04	0.18153340E-04	0.11451931E 01
RESIDUAL	8	0.12681422E-03	0.15851765E-04	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.30042887E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUB0 = -0.13912010E 01		
BHAT(1) = 0.28804028E 00	T(1) = 0.33243382E 00	SD(1) = 0.86645901E 00
BHAT(2) = -0.369292736E 00	T(2) = -0.31682760E 00	SD(2) = 0.11655951E 01
BHAT(3) = 0.743305087E-01	T(3) = 0.33964205E 00	SD(3) = 0.21884954E 00

THE PREDICTION EQUATION IS

$$PI = -1.3912 + 0.2880 \cdot \ln(\text{SPEED}) + -0.3693 \cdot \ln(\text{FEED}) + 0.0743 \cdot \ln(\text{SPEED}) \cdot \ln(\text{FEED})$$

k.

Figure 5.3 (continued)

PREDICTED COSTS
(PREDICTED PRODUCTION RATES)

FEED (IPR)

0.0240	I				
	I	6.09	7.87	9.53	11.33
	I	(0.0414)	(0.0430)	(0.0445)	(0.0460)
0.0210	I				
	I	7.18	8.30	9.36	10.50
	I	(0.0400)	(0.0401)	(0.0402)	(0.0404)
0.0187	I				
	I	8.12	8.68	9.21	9.78
	I	(0.0387)	(0.0376)	(0.0366)	(0.0354)
0.0168	I				
	I	8.99	9.03	9.07	9.12
	I	(0.0376)	(0.0353)	(0.0332)	(0.0309)
0.0153	I				
	I	9.75	9.34	8.95	8.54
	I	(0.0366)	(0.0333)	(0.0302)	(0.0269)

166. 192. 220. 255.

S P E E D (RPM)

2.

Figure 5.3 (continued)

6. Summary

Optimization of machining parameters, such as cutting speed and feed, is possible, in relation to time and costs, by use of this developed system and production machining data. This system, MACHOP (Machine Optimization Program), is applicable to analysis and control of single-operation as well as multiple-operation (numerically-controlled) machining. Simple formats are used to gather data from, and return computerized results to, production personnel. In application, two variables of the machining parameters may be adjusted independently or simultaneously, either manually by the machinist or by the numerical-control programmer, using small-step increments within the limits of the machine tool or the workpiece tolerances. Computation of results from data collected at the original adjusted machining parameters provides print-outs of four-point performance indices. These print-outs not only show time and cost performance at the machining parameters from which the data for computation has just been taken, but also give production settings which could improve performance. Subsequently, machining at adjoining machining parameters is tested and analyzed until the print-outs repeatedly indicate that the optimal conditions have been reached. Notably, the data system and computer program are simple, and general, enough to readily allow optimization of other machining parameters such as cutting fluids, work material selection, and tool material and geometry, as well as speeds and feeds.

The development of this system and related computer program has advanced the state-of-the-art of optimization in machining. In the past, optimization was restricted to optimizing an expanded Taylor Tool-Life equation, not optimization of the actual production machining operation itself, or required more adjustments of variables than were practicable in production operation.

7. Recommendations

It is recommended that this system and computer program be applied to analyze and control all major machining, and similar process, operations in which a large number of parts are produced in a single run or repetitive runs. It is also recommended that it be used to augment or replace time-study methods presently used to establish production standards; and, in particular, that it be applied to all new, major machining operations, and operations where new parameters, such as work material, cutting fluid, or tool material and geometry are introduced. Furthermore, it is strongly recommended that it be used to provide computerized print-outs of cutting tool-life and costs per workpiece for procurement and use of quality tools according to tool performance instead of merely tool price. Finally, it is recommended that this optimization procedure be used on other processes in which operations parameters may be adjusted to improve control of time and costs.

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Appendix A. Verification of Regression Modules of
the PIM and MACHOP Programs

This appendix contains an output from a stepwise regression program, which was used to check the accuracy of the regression portion of the PIM program. A similar check was performed on the MACHOP program.

STEP NUMBER 5
VARIABLE ENTERED 1

MULTIPLE R 0.6104
STD. ERROR OF EST. 0.0172

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	0.001	0.000	0.356
RESIDUAL	3	0.001	0.000	

VARIABLES IN EQUATION				VARIABLES NOT IN EQUATION			
VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE	VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER
(CONSTANT	-0.90118)						
SPEED 1	0.08087	0.60953	0.0176 (2)				
FEED 2	0.96511	1.09571	0.7758 (2)				
SPEDSQ 4	0.03636	0.12451	0.0853 (2)				
FEEDSQ 5	-0.17757	0.27903	0.4050 (9)				
SPEDFD 6	-0.12478	0.12969	0.9257 (2)				

F-LEVEL OR TOLERANCE INSUFFICIENT FOR FURTHER COMPUTATION

SUMMARY TABLE

STEP NUMBER	VARIABLE ENTERED	REMOVED	MULTIPLE R	RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	FEEDSQ	5	0.1995	0.0400	0.0400	0.2913	1
2	FEED	2	0.3584	0.1284	0.0885	0.6091	2
3	SPEDSQ	4	0.4038	0.1630	0.0346	0.2067	3
4	SPEDFD	6	0.6074	0.3689	0.2059	1.3048	4
5	SPEED	1	0.6104	0.3726	0.0037	0.0176	5

A.1 Sample Stepwise Regression Output

Appendix B. Simulation Program

This appendix contains a listing of the simulation program and a typical output. The instructions for using the program are given in the program as comments. This simulation program was developed for preliminary analysis of the PIM and MACHOP programs.

FORTRAN IV G LEVEL 21

MAIN

DATE = 73361

17/31/11

```

0001      IMPLICIT REAL*8 (A-H,O-Z)
0002      DIMENSION P(30),T(30),TP(30)
0003      DIMENSION F(30), V(30),PR(30),CU(30),PI(30)
0004      COMMON INT
      C
      C      NPT - IS THE NUMBER OF POINTS AT WHICH THE DATA IS TO BE GENERATED
      C
      C      Q - IS THE PERFORMANCE INDEX COEFFICIENT
      C
      C      INT - IS THE RANDOM SEED, A SEVEN DIGIT INTEGER
      C
0005      READ (5,12) NPT,Q,INT
0006      12  FORMAT (110,F10.2,110)
      C
      C      RLO - IS THE LABOR AND OVERHEAD IN $/MIN
      C
      C      TLC - IS THE TOOL COST IN $/EDGE
      C
0007      READ (5,20) RLO,TLC
0008      20  FORMAT (2F10.4)
0009      WRITE (6,30) RLO,TLC
0010      30  FORMAT (30X,'SIMULATION OF PRODUCTION DATA'///25X,'LABOR & OVERHEAD
      COST = $',F5.2,' /MIN'///30X,'TOOL COST = $',F5.2,' /EDGE'///)
0011      READ (5,10) ((V(I),F(I)),I=1,NPT)
0012      10  FORMAT (2F10.4)
0013      DO 15 J = 1,NPT
0014          CALL SIM(J,F,V,NCT,KPT,TPD)
0015          P(J) = KPT
0016          T(J) = TPD
0017          TP(J) = NCT
0018      15  CONTINUE
0019          CALL PERIND(P,T,TP,CU,PR,PI,J,RLO,TLC,NPT)
0020          WRITE (6,24)
0021      24  FORMAT ('1',10X,' SPEED ', ' FEED ', ' PARTS ', ' TOOL
      1 ', ' TIME ', ' COST/ ', ' PROD. ', ' PI- ' /
      213X,'(RP1)',5X,'(IPR)',17X,'CHANGES',14X,'PIECE',6X,'RATE',7X,'IND
      3EX'//)
0022          WRITE (6,25) ((V(I),F(I),P(I),TP(I),T(I),CU(I),PR(I),PI(I)),I=1,
      INPT)
0023      25  FORMAT (10X,F10.1,F10.4,F10.1,F10.1,F10.1,F10.1,F10.2,2F12.4/)
0024      RETURN
0025      END

```

FORTTRAN IV G LEVEL 21

RAND

DATE = 73361

17/31/11

```

00C1      SUBROUTINE RAND(INT,IREAL)
00C2      REAL*8 DREAL, DINT, DKEEP
           C      ARGUMENT NO 2 IN LIST IS A REAL IN THE CALL STATEMENT, BUT AN INTEGER
           C      IN THE SUBROUTINE
00C3      DINT = INT
00C4      DREAL = DINT * 16RC7.
00C5      KEEP = DREAL / 2147483647.
00C6      DKEEP = KEEP
00C7      INT = DREAL - DKEEP * 2147483647.
00C8      IREAL = (INT/129) * 1073741E24
00C9      RETURN
0010      END

```

FORTTRAN IV G LEVEL 21

UNINOM

DATE = 73361

17/31/11

```

00C1      FUNCTION UNINOM(ERR,SIGMA)
00C2      IMPLICIT REAL*8 (A-H,O-Z)
00C3      COMMON INT
00C4      CALL RAND(INT,REAL)
00C5      XNORM = (REAL**0.19269651DO - (1-REAL)**0.19269651DO)/0.1306456DO
00C6      UNINOM = ERR*SIGMA*XNORM
00C7      RETURN
00C8      END

```

FORTTRAN IV G LEVEL 21

PERIND

DATE = 73361

17/31/11

```

00C1      SUBROUTINE PERIND(P,T,TP,CU,PR,PI,Q,PLD,TLC,NPT)
00C2      IMPLICIT REAL*8 (A-H,O-Z)
00C3      DIMENSION P(30),T(30),TP(30)
00C4      DIMENSION F(30), V(30),PR(30),CU(30),PI(30)
           C
00C5      DO 100 I=1,NPT
00C6      PR(I)=P(I)/T(I)
00C7      CU(I)=(KLC*T(I)+TLC*TP(I))/P(I)
00C8      100 PI(I)=(1.-Q)*PR(I)+(C/CU(I))
00C9      RETURN
0010      END

```

```

0001      SUBROUTINE SIM(I,F,V,NTC,NTPT,TTPD)
0002      IMPLICIT REAL*8 (A-H,O-Z)
0003      DIMENSION F(16),V(16)
0004      COMMON INT

C
C
C      IN THIS SUBROUTINE ALL THE PARAMETERS OF THE PRODUCTION PROCESS
C      ARE INITIALISED RATHER THAN TO BE READ BY A READ STATEMENT
C
C
C      TAYLOR'S TOOL LIFE CONSTANTS
C
0005      ALP = 0.3
0006      BETA = 0.2
0007      CONST = 400.0
C      XL -- LENGTH OF WORKPIECE
0008      XL = 47.5
C      D -- DIAMETER OF WORKPIECE
0009      D = 8.5
C      TCT -- TOOL CHANGING TIME
0010      TCT = 1.
C      TM -- MACHINING TIME / PIECE
0011      TM = XL/(V(1)*F(1))
C      TH -- HANDLING TIME / PIECE
0012      TH = 15.0
C      SHIFT -- TOTAL PRODUCTION TIME / SHIFT
0013      SHIFT = 420.0
C      ERR -- IS THE RANDOM ERROR
0014      ERR = 0.20
0015      XV = 3.14159*0*V(1)/12.
0016      SIG = (DLOG(CONST))-BETA*DLOG(F(1))-DLOG(XV)/ALP
0017      ICOUNT = 0
0018      TIME = 0.
0019      PARTS = 0.
0020      WRITE (6,15) I,V(1),F(1)
0021      15  FORMAT ('1',10X,'FOR DAY',I2 /10X,' SPEED=',F6.1,5X,'FEED=',F7.4/
1/)
0022      WRITE (6,30) TM
0023      30  FORMAT ('1' MACHINING TIME FOR THIS SPEED & FEED',F7.2,' MIN'//)
0024      10  ICOUNT = ICOUNT + 1
0025      Y = UNINOM(ERR,SIG)
0026      TLIFE = DEXP(SIG*Y)
0027      PARTS1 = TLIFE/TM
0028      WRITE (6,20) ICOUNT,TLIFE,PARTS1
0029      20  FORMAT ('1 TOOL #',I3,5X,'LIFE=',F5.1,'MIN',5X,'# OF PARTS =',F5.2/
1/)
0030      TIME1 = PARTS1*(TM+TH)+TCT
0031      PARTS = PARTS+PARTS1
0032      TIME = TIME+TIME1
0033      IF (TIME .LE. SHIFT) GO TO 10
0034      DIFF = TIME-SHIFT
0035      PARTMS = DIFF/(TM+TH)
0036      PARTS = PARTS-PARTMS
0037      WRITE (6,25) I,PARTS,ICOUNT,SHIFT
0038      25  FORMAT ('1 SO FOR DAY',I3,/10X,F5.1,'PARTS ARE PRODUCED'/10X,I3,
1' TOOLS ARE CHANGED DURING'/10X,F6.1,' MINUTES OF PRODUCTION TIME
1//)
0039      PARTS = PARTS + 0.25
0040      NTPT = PARTS
0041      TTPD = SHIFT
0042      NTC = ICOUNT
0043      RETURN
0044      END

```

SPEED= 192.0 FEED= 0.0187

MACHINING TIME FOR THIS SPEED & FEED 13.23 MIN

TOOL # 1	LIFE= 3.1MIN	# OF PARTS = 0.23
TOOL # 2	LIFE= 10.1MIN	# OF PARTS = 0.77
TOOL # 3	LIFE= 19.9MIN	# OF PARTS = 1.51
TOOL # 4	LIFE= 7.7MIN	# OF PARTS = 0.58
TOOL # 5	LIFE= 3.5MIN	# OF PARTS = 0.26
TOOL # 6	LIFE= 2.4MIN	# OF PARTS = 0.18
TOOL # 7	LIFE= 27.2MIN	# OF PARTS = 2.05
TOOL # 8	LIFE= 2.0MIN	# OF PARTS = 0.15
TOOL # 9	LIFE= 1.7MIN	# OF PARTS = 0.13
TOOL # 10	LIFE= 10.7MIN	# OF PARTS = 0.81
TOOL # 11	LIFE= 38.9MIN	# OF PARTS = 2.94
TOOL # 12	LIFE= 14.1MIN	# OF PARTS = 1.07
TOOL # 13	LIFE= 9.2MIN	# OF PARTS = 0.69
TOOL # 14	LIFE= 26.1MIN	# OF PARTS = 1.98
TOOL # 15	LIFE= 13.4MIN	# OF PARTS = 1.01

14.3PARTS ARE PRODUCED
15 TOOLS ARE CHANGED DURING
420.0 MINUTES OF PRODUCTION TIME

Appendix C. Data Collection Forms

Two types of data collection forms are given, one for single tool operations (Figure C.1) and the other for multiple tool operations (Figure C.2).

SINGLE TOOL MACHINE OPTIMIZATION STUDY FORM

Machine	Date	Stock Lot ID	Speed
Operator	Shift	Tool Material ID	Feed

[illegible]

Total Production Time (minutes)

Number of Pieces Produced

(Tally)

Total

Number of Insert Edges Used

(Tally)

Total

Comments:

Cost/edge

Overhead and Labor Cost

Figure C.1

MULTIPLE TOOL MACHINE OPTIMIZATION STUDY FORM

Sheet No.	Machine	Speed	Feed
Operator	Date	Shift	Stock Lot ID
Insert 1 ID	Insert 2 ID	Insert 3 ID	

<u>Production Startup Time</u>	<u>Production Stop Time</u>	<u>Subtotals (minutes)</u>
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____

Total Production Time (minutes) _____

Number of Pieces Produced

(Tally)

Total _____

Number of Insert 1 Edges Used

(Tally)

Total _____

Number of Insert 2 Edges Used

(Tally)

Total _____

Number of Insert 3 Edges Used

(Tally)

Total _____

Comments:

Cost/edge _____

Overhead and Labor Cost _____

Figure C.2

Appendix D. Analysis of the PIM Design Module

Following the determination of the optimum feed and speed based on a given set of experimental observations the next set of feed and speed combinations are chosen in the following manner:

1. In the event that the optimal point is not on a boundary, nine or fewer points are selected as follows. Initially a 3^2 design is selected with the previous optimal point as the center point, the distance between speeds is $L_4 = \text{number of usable speeds}/4$ and the distance between feeds is $M_4 = \text{number of usable feeds}/4$. Each point is checked with the boundary conditions to insure that it is feasible. If it is outside of the boundary condition, a replacement point is selected by moving the point in one step horizontally or vertically depending on the boundary condition. The procedure is repeated until a feasible point is selected. If this point does not duplicate another point already selected it is retained, otherwise it is discarded. Thus, fewer than nine points are possible.
2. In the event that the optimal point is on a boundary, five or fewer points are selected along the boundary with the previous optimal point in the middle. As in the previous case, each point picked is checked for feasibility and uniqueness. If the initial points selected are not feasible, they are moved in until they are feasible. In the process if some of the points duplicate other points already selected, they are discarded thus resulting in less than five points.

Appendix E. Carboloy Systems Computerized Machinability Program

This appendix contains the results obtained from General Electric's Carboloy computerized Machinability Program for the turning operation on the recoil cylinder. (See Table 2.5 for the job description.)

Access to this program may be made by acquisition of a G.E. terminal installation in the user's plant on a contractual basis or otherwise by sending the required information to the company for processing.

The program is based on historical machinability data and Taylor's tool life equation. If the tool material is entered into the program, the recommended feed and cutting speed for minimum cost and for maximum production rate will appear in the output data. If the feed and speed are entered, the recommended tool material will be indicated in the output data.

This approach has its limitations, for there are many variables which effect removal performance that cannot be accounted for in a generalized program. These variables include the condition and rigidity of the machine tool, type of tool holder, experience and ability of the machine operator, and the tool setting practice. Certainly, the program cannot be expected to predict precisely the optimum machining parameters. It may, however, serve as a good starting point to select the initial machine settings and/or tool material.

A copy of the program's output is given in Figure E.1. The Carboloy tool material, which was entered into the program by a G. E. representative and which was considered to be equivalent to the VR/Wesson, C5W Titanium Coated Carbide, was Carboloy Grade 350. The second choice was Grade 78. The equivalence of the entered grade to the one being used is questionable. The program recommended the following machining conditions:

Feed - 0.014 ipr,

Speed for Minimum Cost - 272 rpm, and

Speed for Maximum Production Rate - 358 rpm.

CUTTING FLUID ON CARBOLLOY MAY CAUSE TOOL FAILURE
DUE TO THERMAL CRACKS. CHECK TO MAKE SURE TOOLS ARE
WEARING OUT, NOT CHIPPING OR BREAKING

IDENTIFICATION	AISI 4140
STARTING SURFACE CONDITION	HTR
FINAL SURFACE FINISH	250 MU. IN. 'AA'
BRINELL HARDNESS	252
PART TOLERANCE	.015 IN.
COOLANT	EMU
MACHINE TOOL	
TYPE	LATHE
OPERATION	AXIAL TURN
MOTOR HORSEPOWER	50
SPINDLE SPEED LIMIT	380
CUTTING TOOL	
TOOL MATERIAL	CARBOLLOY
GRADE	350
2ND. CHOICE GRADE	78
SIDE CUTTING EDGE ANGLE	30 DEG.
NOSE RADIUS	0.047 IN.
OUTPUT DATA	
SET UP	
STARTING DIA.	8.500 IN.
FEED	.014 IN./REV
DEPTH OF CUT	0.125 IN.
SPEED MIN. COST	272 RPM
SPEED-MAX. PROD.	358 RPM
TECHNICAL	
WEAR LAND	.030 IN.
TOOL LIFE-MIN. COST	9 MIN.
SPEED-MIN. COST	606 FPM
H.P.-MIN. COST	11
TOOL LIFE-MAX. PROD.	3 MIN.
SPEED-MAX. PROD.	798 FPM
H.P.-MAX. PROD.	14

IF CHIPPING OF THE CUTTING EDGE OCCURS USE SECOND CHOICE GRADE.

Figure E.1 Sample Carboloy Computerized
Machinability Program Output

Appendix F. MACHOP Listing

FORTRAN IV G LEVEL 21

MAIN

DATE = 73362

14/04/07

PAGE 00Q1

C		MAIN 10
C		MAIN 20
C		MAIN 30
C	MACHOP	MAIN 40
C	(MACHINE OPTIMIZATION)	MAIN 50
C		MAIN 60
C		MAIN 70
C	THE MACHOP PROGRAM UTILIZES EVOLUTIONARY OPERATION (EVOP)	MAIN 80
C	AND REGRESSION ANALYSIS TO EXAMINE THE RESPONSE SURFACE OF	MAIN 90
C	MACHINING OPERATIONS TO DETERMINE THE OPTIMUM FEED-SPEED	MAIN 100
C	COMBINATIONS. TWO PERFORMANCE INDICIES, COST/PIECE AND	MAIN 110
C	PRODUCTION RATE ARE CONSIDERED AS RESPONSES. FIRST THE	MAIN 120
C	PROGRAM PERFORMS AN EVOP ANALYSIS AND RECOMMENDS TWO SETS	MAIN 130
C	OF OPERATING CONDITIONS. NEXT THE REGRESSION COEFFICIENTS	MAIN 140
C	FOR THE FOLLOWING EQUATION (OR A REDUCED FORM OF IT) ARE	MAIN 150
C	ESTIMATED	MAIN 160
C		MAIN 170
C	$P.I. = R_0 + R_1 \cdot \ln(\text{SPEED}) + R_2 \cdot \ln(\text{FEED}) + R_3 \cdot \ln(\text{SPEED})^2$	MAIN 180
C	$+ R_4 \cdot \ln(\text{FEED})^2 + R_5 \cdot \ln(\text{SPEED} \cdot \text{FEED})$	MAIN 190
C		MAIN 200
C	USING THESE RESULTS, THE PERFORMANCE INDICIES ARE PREDICTED	MAIN 210
C	FOR FEED - SPEED COMBINATIONS ADJACENT TO THOSE OBSERVED.	MAIN 220
C	THE PROGRAM IS APPLICABLE TO SINGLE-OPERATION AND	MAIN 230
C	MULTIPLE-OPERATION (NUMERICALLY CONTROLLED) MACHINING	MAIN 240
C	PROCESSES.	MAIN 250
C		MAIN 260
C		MAIN 270
C	REFERENCES ARE	MAIN 280
C		MAIN 290
C	BOX, G. & DRAPER, N., EVOLUTIONARY OPERATION A STATISTICAL	MAIN 300
C	METHOD FOR INCREASING PRODUCTIVITY, JOHN WILEY & SONS,	MAIN 310
C	1969.	MAIN 320
C		MAIN 330
C	BURCHFIELD, P.B., MULTIPLE LINEAR REGRESSION, JOURNAL OF	MAIN 340
C	QUALITY TECHNOLOGY, VOL. 3, NO. 4, OCTOBER 1971.	MAIN 350
C		MAIN 360
C	DRAPER, N. & SMITH, H., APPLIED REGRESSION ANALYSIS,	MAIN 370
C	JOHN WILEY & SONS, NEW YORK, 1968.	MAIN 380
C		MAIN 390
C		MAIN 400
0001	COMMON /C101/SPEED(100),FEED(100),SPND(100),NSPD,NFD,ISP,IFD	MAIN 410
0002	COMMON /C102/IPH,ICYC,SCYCLE,RLO,X(24,100),Y(2,100),NOBS,NCB1	MAIN 420
	*,IDP,BSP,NFD,NTLC,TLC(20)	MAIN 430
0003	COMMON /C103/DIFF(2,4),SUM(2,4),AVE(2,4),SUMS(2),AVES(2,2)	MAIN 440
0004	COMMON /C107/IND(4),SMAX,SMIN,FMAX,FMIN	MAIN 450
0005	DIMENSION B(5),TITLE(20),BCO(2),BP(2,5),IRR(2)	MAIN 460
		MAIN 470
C		MAIN 480
C	INPUT MAIN CONTROL CARD	MAIN 490
C		MAIN 500
0006	WRITE(6,5999)	MAIN 510
0007	IER=1	MAIN 520
0008	READ(5,5004,FND=9011,ERR=9012)TITLE	MAIN 530
0009	WRITE(6,6000)TITLE	MAIN 540
0010	READ(5,5001,END=9001,ERR=9002)	

```

      *IPH,ICYC,ICP,IMAX,NTLC,FLO,AVES(1,1),AVES(2,1),BSP,BFC
0011      IF(IPH.GT.0)GO TO 6C1
0012      WRITE(6,6C1)IPH
0013      IER=2
0014      GO TO 6C2
0015      601 WRITE(6,6002)IPH
0016      602 IF(ICYC.GT.0)GO TO 603
0017      WRITE(6,6C03)ICYC
0018      IER=2
0019      GO TO 604
0020      603 WRITE(6,6004)ICYC
0021      604 IF(IOP.GT.0.AND.ICP.LT.4)GO TO 605
0022      WRITE(6,6005)IOP
0023      IER=2
0024      605 GO TO (6J6,607,608),ICP
0025      606 WRITE(6,6C06)IOP
0026      GO TO 6C7
0027      607 WRITE(6,6C07)IOP
0028      GO TO 6C9
0029      608 WRITE(6,60J8)IOP
0030      609 IF(IMAX.NE.1)GO TO 610
0031      WRITE(6,6C09)
0032      GO TO 611
0033      610 WRITE(6,6010)
0034      611 WRITE(6,6C11)RLO
0035      IF(AVES(1,1).LE.0.0)GO TO 612
0036      WRITE(6,6C12)AVES(1,1)
0037      GO TO 613
0038      612 WRITE(6,6013)
0039      613 IF(AVES(2,1).LE.0.0)GO TO 6612
0040      WRITE(6,6615)AVES(2,1)
0041      GO TO 6014
0042      6612 WRITE(6,6615)
0043      6014 IF(IOP.NE.3)GO TO 628
0044      IF(BSP.LE.0.0.GR.BFC.LE.0.0)GO TO 615
0045      WRITE(6,6C14)BSP,BFC
0046      GO TO 628
0047      615 WRITE(6,6C15)
0048      IER=2
0049      628 IF(NTLC.EQ.0)NTLC=1
0050      IF(NTLC.LT.1.OR.NTLC.GT.20)GO TO 747
0051      WRITE(6,6024)NTLC
0052      READ(5,50J3,END=9C09,ERR=9010)(TLC(I),I=1,NTLC)
0053      DO 2276 I=1,NTLC
0054      IF(TLC(I).LT.0)GO TO 2277
0055      2276 CONTINUE
0056      WRITE(6,6029)(TLC(I),I=1,NTLC)
0057      GO TO 614
0058      2277 IER=2
0059      WRITE(6,5026)
0060      GO TO 614
0061      747 IER=2
0062      WRITE(6,6C25)NTLC
0063      614 GO TO (616,617),IER

```

```

MAIN 550
MAIN 560
MAIN 570
MAIN 580
MAIN 590
MAIN 600
MAIN 610
MAIN 620
MAIN 630
MAIN 640
MAIN 650
MAIN 660
MAIN 670
MAIN 680
MAIN 690
MAIN 700
MAIN 710
MAIN 720
MAIN 730
MAIN 740
MAIN 750
MAIN 760
MAIN 770
MAIN 780
MAIN 790
MAIN 800
MAIN 810
MAIN 820
MAIN 830
MAIN 840
MAIN 850
MAIN 860
MAIN 870
MAIN 880
MAIN 890
MAIN 900
MAIN 910
MAIN 920
MAIN 930
MAIN 940
MAIN 950
MAIN 960
MAIN 970
MAIN 980
MAIN 990
MAIN1000
MAIN1010
MAIN1020
MAIN1030
MAIN1040
MAIN1050
MAIN1060
MAIN1070
MAIN1080

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0064	617	WRITE(6,6C16)	MAIN1090
0065		CALL EXIT	MAIN1100
	C		MAIN1110
	C	INPUT SPEED ENVIRONMENT	MAIN1120
	C		MAIN1130
0066	616	READ(5,50C2,END=90C3,ERR=9004)NSPD	MAIN1140
0067		IF(NSPD.LE.0.OR.NSPD.GT.100)GO TO 618	MAIN1150
0068		WRITE(6,6C18)NSPD	MAIN1160
0069		GO TO 619	MAIN1170
0070	618	WRITE(6,6C19)NSPD	MAIN1180
0071		GO TO 617	MAIN1190
0072	619	READ(5,5003,END=9003,ERR=90C4) (SPEED(I),I=1,NSPD)	MAIN1200
0073		DO 62C I=1,NSPD	MAIN1210
0074		IF(SPEED(I).LE.0.C)GO TO 621	MAIN1220
0075	620	CONTINUE	MAIN1230
0076		GO TO 622	MAIN1240
0077	621	WRITE(6,6020)	MAIN1250
0078		GO TO 617	MAIN1260
	C		MAIN1270
	C	INPUT FEED ENVIRONMENT	MAIN1280
	C		MAIN1290
0079	622	READ(5,50C2,END=90C5,ERR=90C6)NFD	MAIN1300
0080		IF(NFD.LE.0.OR.NFD.GT.50)GO TO 623	MAIN1310
0081		WRITE(6,6022)NFD	MAIN1320
0082		GO TO 624	MAIN1330
0083	623	WRITE(6,6021)NFD	MAIN1340
0084		GO TO 617	MAIN1350
0085	624	READ(5,5003,END=9005,ERR=9006) (FEED(I),I=1,NFD)	MAIN1360
0086		DO 625 I=1,NFD	MAIN1370
0087		IF(FEED(I).LE.0.0)GO TO 626	MAIN1380
0088	625	CONTINUE	MAIN1390
0089		GO TO 627	MAIN1400
0090	626	WRITE(6,6023)	MAIN1410
0091		GO TO 617	MAIN1420
	C		MAIN1430
	C	INPUT LIMITS FOR SPEED AND FEED	MAIN1440
	C		MAIN1450
0092	627	IF(IMAX.EQ.1)READ(5,5003,END=90C7,ERR=9008)SMAX,SMIN,FMAX,FMIN	MAIN1460
0093		IF(SMAX.EQ.0.0)SMAX=SPEED(NSPD)	MAIN1470
0094		IF(SMIN.EQ.0.0)SMIN=SPEED(1)	MAIN1480
0095		IF(FMAX.EQ.0.0)FMAX=FEED(NFD)	MAIN1490
0096		IF(FMIN.EQ.0.0)FMIN=FEED(1)	MAIN1500
	C		MAIN1510
	C	INSURE INPUT SPEEDS AND FEEDS ARE WITHIN DEFINED LIMITS	MAIN1520
	C		MAIN1530
0097		DO 7 J=1,NSPD	MAIN1540
0098		IF(SPEED(J).LT.SMIN)GO TO 7	MAIN1550
0099		IF(J.EQ.1)GO TO 8	MAIN1560
0100		NSPD=NSPD-J+1	MAIN1570
0101		DO 15 K=1,NSPD	MAIN1580
0102		SPEED(K)=SPEED(J)	MAIN1590
0103	15	J=J+1	MAIN1600
0104		GO TO 8	MAIN1610
0105	7	CONTINUE	MAIN1620

0106	8	DO 9 J=1,NSPD	MAIN1630
0107		IF(SPEED(J).GT.SMAX)GC TO 10	MAIN1640
0108	9	CONTINUE	MAIN1650
0109		GO TO 11	MAIN1660
0110	10	NSPD=J	MAIN1670
0111	11	DO 14 I=1,NFD	MAIN1680
0112		IF (FEED(I).LT.FMIN)GC TO 14	MAIN1690
0113		IF(I.EC.1)GO TO 12	MAIN1700
0114		NFD=NFD-I+1	MAIN1710
0115		DO 16 J=1,NFD	MAIN1720
0116		FEEC(J)=FLED(I)	MAIN1730
0117	16	I=I+1	MAIN1740
0118		GO TO 12	MAIN1750
0119	14	CONTINUE	MAIN1760
0120	12	DO 13 I=1,NFD	MAIN1770
0121		IF(FEEC(I).GT.FMAX)GO TO 17	MAIN1780
0122	13	CONTINUE	MAIN1790
0123		GO TO 64	MAIN1800
0124	17	NFD=1	MAIN1810
	C		MAIN1820
	C	PREPARE FOR E V O P ANALYSIS	MAIN1830
	C		MAIN1840
0125	64	CALL NUCYCL	MAIN1850
	C		MAIN1860
	C	IDENTIFY INPUT SPEED	MAIN1870
	C		MAIN1880
0126		DO 32 I=1,NSPD	MAIN1890
0127		IF(X(1,NJBL).EQ.SPEED(I)) GO TO 33	MAIN1900
0128	32	CONTINUE	MAIN1910
0129	33	ISP=1	MAIN1920
	C		MAIN1930
	C	IDENTIFY INPUT FEED	MAIN1940
	C		MAIN1950
0130		DO 34 I=1,NFD	MAIN1960
0131		IF(X(2,NJBL).EQ.FEED(I)) GO TO 35	MAIN1970
0132	34	CONTINUE	MAIN1980
0133	35	IFD=1	MAIN1990
0134		IF(ISP.LT.IND(1))IND(1)=ISP	MAIN2000
0135		ISPP1=ISP+1	MAIN2010
0136		IF(ISPP1.GT.IND(2))IND(2)=ISPP1	MAIN2020
0137		IF(IFC.LT.IND(3))IND(3)=IFD	MAIN2030
0138		IFDPL=IFD+1	MAIN2040
0139		IF(IFDPL.GT.IND(4))IND(4)=IFDPL	MAIN2050
	C		MAIN2060
	C	PERFORM THE E V O P ANALYSIS	MAIN2070
	C		MAIN2080
0140		CALL EVOP	MAIN2090
	C		MAIN2100
	C	PERFORM THE REGRESSION ANALYSIS	MAIN2110
	C		MAIN2120
0141		IF(IND(2)-IND(1)-1)41,42,43	MAIN2130
0142	41	WRITE(6,48)	MAIN2140
0143		GO TO 9033	MAIN2150
0144	42	I REGS=0	MAIN2160

0145		GO TC 44	MAIN2170
0146	43	IREGS=1	MAIN2180
0147	44	IF(IND(4)-IND(3)-1)41,45,46	MAIN2190
0148	45	IREF=C	MAIN2200
0149		GO TO 47	MAIN2210
0150	46	IREF=2	MAIN2220
0151	47	IREF=1+IREGS+IREF	MAIN2230
0152		IREF1=IREF	MAIN2240
0153		DO 595 IGC=1,2	MAIN2250
0154		IREF=IREF1	MAIN2260
0155		CALL REGRES(X,Y,NCBS,IREF,B0,B,IGC)	MAIN2270
	C		MAIN2280
	C	PRINT PREDICTION EQUATION AND RESPONSE SURFACE PREDICTION	MAIN2290
	C		MAIN2300
0156		GO TO (1,2,3,4,5),IREF	MAIN2310
0157	1	WRITE(6,51)B0,B(1),B(2)	MAIN2320
0158		GO TO 6	MAIN2330
0159	2	WRITE(6,52)B0,B(1),B(2),B(3),B(4)	MAIN2340
0160		GO TO 6	MAIN2350
0161	3	WRITE(6,53)B0,B(1),B(2),B(3),B(4)	MAIN2360
0162		GO TO 6	MAIN2370
0163	4	WRITE(6,54)B0,B(1),B(2),B(3),B(4),B(5)	MAIN2380
0164		GO TO 6	MAIN2390
0165	5	WRITE(6,55)B0,B(1),B(2),B(3)	MAIN2400
0166	6	CONTINUE	MAIN2410
0167		B00(IGC)=B0	MAIN2420
0168		IREF(IGC)=IREF	MAIN2430
0169		DO 585 I=1,5	MAIN2440
0170	585	BP(IGC,I)=B(I)	MAIN2450
0171	595	CONTINUE	MAIN2460
0172		CALL REGPLT(B00,BP,IND,IRR)	MAIN2470
	C		MAIN2480
	C	ERROR ANALYSIS	MAIN2490
	C		MAIN2500
0173	9001	WRITE(6,9017)	MAIN2510
0174	9033	CALL EXIT	MAIN2520
0175	9002	WRITE(6,9018)	MAIN2530
0176		GO TO 9033	MAIN2540
0177	9003	WRITE(6,9019)	MAIN2550
0178		GO TO 9033	MAIN2560
0179	9004	WRITE(6,9020)	MAIN2570
0180		GO TO 9033	MAIN2580
0181	9005	WRITE(6,9021)	MAIN2590
0182		GO TO 9033	MAIN2600
0183	9006	WRITE(6,9022)	MAIN2610
0184		GO TO 9033	MAIN2620
0185	9007	WRITE(6,9023)	MAIN2630
0186		GO TO 9033	MAIN2640
0187	9008	WRITE(6,9024)	MAIN2650
0188		GO TO 9033	MAIN2660
0189	9009	WRITE(6,9027)	MAIN2670
0190		GO TO 9033	MAIN2680
0191	9010	WRITE(6,9028)	MAIN2690
0192		GO TO 9033	MAIN2700

0193	9011	WRITE(6,6030)	MAIN2710
0194		GO TO 9033	MAIN2720
0195	9012	WRITE(6,6031)	MAIN2730
0196		GO TO 9033	MAIN2740
	C		MAIN2750
	C	FORMATS	MAIN2760
	C		MAIN2770
0197	48	FORMAT('1 *** ERROR *** UNABLE TO DISTINGUISH SPEED/FEED ',	MAIN2780
		'COMBINATIONS')	MAIN2790
0198	51	FORMAT('//',T10,'THE PREDICTION EQUATION IS//',PI = ',F10.4,	MAIN2800
		'* + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED)')	MAIN2810
0199	52	FORMAT('//',T10,'THE PREDICTION EQUATION IS//',PI = ',F10.4,	MAIN2820
		'* + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,	MAIN2830
		'*LN(SPEED)*LN(FEED)//',T9,' + ',F10.4,'*LN(SPEED)**2')	MAIN2840
0200	53	FORMAT('//',T10,'THE PREDICTION EQUATION IS//',PI = ',F10.4,	MAIN2850
		'* + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,	MAIN2860
		'*LN(SPEED)*LN(FEED)//',T9,' + ',F10.4,'*LN(SPEED)**2')	MAIN2870
0201	54	FORMAT('//',T10,'THE PREDICTION EQUATION IS//',PI = ',F10.4,	MAIN2880
		'* + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,	MAIN2890
		'*LN(SPEED)*LN(FEED)//',T9,' + ',F10.4,'*LN(SPEED)**2 + ',	MAIN2900
		'F10.4,'*LN(FEED)**2')	MAIN2910
0202	55	FORMAT('//',T10,'THE PREDICTION EQUATION IS//',PI = ',F10.4,	MAIN2920
		'* + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,	MAIN2930
		'*LN(SPEED)*LN(FEED)')	MAIN2940
0203	5001	FORMAT(5I3,T21,5F10.4)	MAIN2950
0204	5002	FORMAT(I3)	MAIN2960
0205	5003	FORMAT(8F10.4)	MAIN2970
0206	5004	FORMAT(2J4)	MAIN2980
0207	5959	FORMAT('1',T61,'M A C H O P')	MAIN2990
0208	6000	FORMAT('//',T26,20A4)	MAIN3000
0209	6001	FORMAT('//',T10,'PHASE IS',T35,I10,' *** ERROR ***')	MAIN3010
0210	6002	FORMAT('//',T10,'PHASE IS ',T35,I10)	MAIN3020
0211	6003	FORMAT('J',T10,'CYCLE IS ',T35,I10,' *** ERROR ***')	MAIN3030
0212	6004	FORMAT('J',T10,'CYCLE IS',T35,I10)	MAIN3040
0213	6005	FORMAT('J',T10,'TYPE OF PROCESS IS',T35,I10,' *** ERROR ***')	MAIN3050
0214	6006	FORMAT('J',T10,'TYPE OF PROCESS IS',T35,I10,' SINGLE')	MAIN3060
0215	6007	FORMAT('J',T10,'TYPE OF PROCESS IS',T35,I10,' MULTIPLE')	MAIN3070
0216	6008	FORMAT('J',T10,'TYPE OF PROCESS IS',T35,I10,' NUMERICAL CONTROL')	MAIN3080
0217	6009	FORMAT('J',T10,'SPEED-FEED LIMITS SPECIFIED')	MAIN3090
0218	6010	FORMAT('J',T10,'SPEED-FEED LIMITS NOT SPECIFIED')	MAIN3100
0219	6011	FORMAT('J',T10,'LABOR-OVERHEAD (1/4IN)',T35,F10.4)	MAIN3110
0220	6012	FORMAT('J',T10,'COST STD. DEV. EST. IS',T35,F10.4)	MAIN3120
0221	6013	FORMAT('J',T10,'COST STD. DEV. EST. IS NOT SPECIFIED')	MAIN3130
0222	6014	FORMAT('J',T10,'BASE SPEED IS',T35,F10.4//',T10,	MAIN3140
		'*BASE FEED IS',T35,F10.4)	MAIN3150
0223	6015	FORMAT('J',T10,'BASE SPEED AND/OR FEED INCORRECTLY SPECIFIED')	MAIN3160
0224	6016	FORMAT('J',T10,'*** PROGRAM TERMINATION DUE TO SPECIFIED ERROR',	MAIN3170
		'* CONDITIONS ***')	MAIN3180
0225	6018	FORMAT('J',T10,'NUMBER OF SPEEDS IS',T35,I10)	MAIN3190
0226	6019	FORMAT('J',T10,'NUMBER OF SPEEDS IS',T35,I10,' *** ERROR ***')	MAIN3200
0227	6020	FORMAT('J',T10,'SPECIFIED SPEEDS ARE L/E ZERO')	MAIN3210
0228	6021	FORMAT('J',T10,'NUMBER OF FEEDS IS',T35,I10,' *** ERROR ***')	MAIN3220
0229	6022	FORMAT('J',T10,'NUMBER OF FEEDS IS',T35,I10)	MAIN3230
0230	6023	FORMAT('J',T10,'SPECIFIED FEEDS ARE L/E ZERO')	MAIN3240

0231	6024	FORMAT('J',T10,'NUMBER OF TOOLS IS',T35,I10)	MAIN3250
0232	6025	FORMAT('J',T10,'NUMBER OF TOOLS IS',T35,I10,' *** ERROR ***')	MAIN3260
0233	6026	FORMAT('J',T10,'SPECIFIED TOOL COST NEGATIVE *** ERROR ***')	MAIN3270
0234	6027	FORMAT('L *** ERROR *** UNEXPECTED TERMINATION OF DATA ...')	MAIN3280
		*,/'J',T10,'TOOL COSTS MISSING')	MAIN3290
0235	6028	FORMAT('L *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'J')	MAIN3300
		*,T10,'ON TOOL COST INPUT')	MAIN3310
0236	6029	FORMAT('J',T10,'SPECIFIED TOOL COST/EDGE',(' ',T37,10F8.4))	MAIN3320
0237	6030	FORMAT('L *** ERROR *** UNEXPECTED TERMINATION OF DATA ...')	MAIN3330
		*,/'J',T10,'TITLE CARD MISSING')	MAIN3340
0238	6031	FORMAT('L *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'O')	MAIN3350
		*,T10,'ON TITLE CARD')	MAIN3360
0239	6613	FORMAT('J',T10,'P.F. STD. DEV. EST. IS',T35,F10.4)	MAIN3370
0240	6615	FORMAT('J',T10,'P.F. STD. DEV. EST. IS NOT SPECIFIED')	MAIN3380
0241	9017	FORMAT('L *** ERROR *** UNEXPECTED TERMINATION OF DATA ...')	MAIN3390
		*,/'J',T10,'MAIN PROBLEM CARD MISSING')	MAIN3400
0242	9018	FORMAT('L *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'O')	MAIN3410
		*,T10,'ON MAIN PROBLEM CARD')	MAIN3420
0243	9019	FORMAT('L *** ERROR *** UNEXPECTED TERMINATION OF DATA ...')	MAIN3430
		*,/'J',T10,'INPUT SPEED PARAMETERS MISSING')	MAIN3440
0244	9020	FORMAT('L *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'O')	MAIN3450
		*,T10,'ON INPUT SPEED PARAMETERS')	MAIN3460
0245	9021	FORMAT('L *** ERROR *** UNEXPECTED TERMINATION OF DATA ...')	MAIN3470
		*,/'C',T10,'INPUT FEED PARAMETERS MISSING')	MAIN3480
0246	9022	FORMAT('L *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'O')	MAIN3490
		*,T10,'ON INPUT FEED PARAMETERS')	MAIN3500
0247	9023	FORMAT('L *** ERROR *** UNEXPECTED TERMINATION OF DATA ...')	MAIN3510
		*,/'J',T10,'INPUT SPEED/FEED LIMITS MISSING')	MAIN3520
0248	9024	FORMAT('L *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'O')	MAIN3530
		*,T10,'ON INPUT SPEED/FEED LIMITS')	MAIN3540
0249		END	MAIN3550

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NUCYCL

DATE = 74053

10/32/02

0001		SUBROUTINE NUCYCL	NUCY 10
	C		NUCY 20
	C		NUCY 30
	C	SUBROUTINE NUCYCL IS USED FOR PROCESSING ALL PHASE/CYCLE	NUCY 40
	C	COMBINATIONS. NUCYCL PREPARES THE INPUT DATA FOR BOTH	NUCY 50
	C	THE EVOP AND REGRESSION PROCESSES.	NUCY 60
	C		NUCY 70
	C		NUCY 80
0002		DIMENSION TEMP(4,24)	NUCY 90
0003		COMMON /C102/ IPH, ICYC, SCYCLE, RLC, X(24,100), Y(2,100), NUBS, NOB1	NUCY 100
		*, IDP, RSP, BUF, NTIC, TIC(20)	NUCY 110
0004		COMMON /C103/ DIFF(2,4), SUM(2,4), AVE(2,4), SUMS(2), AVES(2,2)	NUCY 120
0005		COMMON /C107/ IND(4), SMAX, SMIN, FMAX, FMIN	NUCY 130
0006	702	SCYCLE=ICYC	NUCY 140
0007		NTICP=NTIC+4	NUCY 150
0008		DO 9 I=1,2	NUCY 160
0009		AVES(I,2)=0.0	NUCY 170
0010		SUMS(I)=0.0	NUCY 180
	9		NUCY 190
	C	INPUT NEW OBSERVATIONS	NUCY 200
	C		NUCY 210
0011		NUBS=1	NUCY 220
0012	703	NOB1=ACBS+1	NUCY 230
0013		NOB4=NOBS+3	NUCY 240
0014		READ(5,53C2,END=9017,ERR=9016) (X(J,NOBS),J=1,NTICP)	NUCY 250
0015		IF(X(1,NOBS).EQ.0.12345)GO TO 701	NUCY 260
0016		DO 66 J=NOB1,NOB4	NUCY 270
0017	66	READ(5,5302,END=9015,ERR=9016) (X(I,J),I=1,NTICP)	NUCY 280
0018		NOBS=NOB5+4	NUCY 290
0019		GO TO 703	NUCY 300
	C		NUCY 310
	C	INPUT THE DATA FROM THE PREVIOUS CYCLE	NUCY 320
	C		NUCY 330
0020	701	READ(5,53C1,END=9011,ERR=9012)	NUCY 340
		*(SUM(J,I),I=1,4),SUMS(J), (AVE(J,I),I=1,4),AVES(J,2),J=1,2),	NUCY 350
		*(INC(I),I=1,4)	NUCY 360
0021		IF(AVES(1,2).NE.0.0)AVES(1,1)=AVES(1,2)	NUCY 370
0022		IF(AVES(2,2).NE.0.0)AVES(2,1)=AVES(2,2)	NUCY 380
	C		NUCY 390
	C	SCRT POINTS INTO CORRECT SEQUENCE	NUCY 400
	C		NUCY 410
0023	9017	NOB3=NOBS-1	NUCY 420
0024		NOB1=NOB3-3	NUCY 430
0025		DO 45 I=1,4	NUCY 440
0026		DO 45 J=1,NTICP	NUCY 450
0027	45	TEMP(I,J)=X(J,NOB1+I-1)	NUCY 460
0028		SPM1=TEMP(I,1)	NUCY 470
0029		SPM4=TEMP(I,1)	NUCY 480
0030		FDM1=TEMP(I,2)	NUCY 490
0031		FDM4=TEMP(I,2)	NUCY 500
0032		DO 10 I=2,4	NUCY 510
0033		IF(TEMP(I,1).LE.SPM1)SPM1=TEMP(I,1)	NUCY 520
0034		IF(TEMP(I,1).GE.SPM4)SPM4=TEMP(I,1)	NUCY 530
0035		IF(TEMP(I,2).LE.FDM1)FDM1=TEMP(I,2)	NUCY 540

0036		IF (TEMP(I,2).GE.FDMA)FDMA=TEMP(I,2)	NUCY 550
0037	10	CONTINUE	NUCY 560
0038		DO 11 I = 1,4	NUCY 570
0039		J=0	NUCY 580
0040		IF (TEMP(I,1).EQ.SPMI.AND.TEMP(I,2).EQ.FDMI) J=1	NUCY 590
0041		IF (TEMP(I,1).EQ.SPMA.AND.TEMP(I,2).EQ.FDMA) J=2	NUCY 600
0042		IF (TEMP(I,1).EQ.SPM4.AND.TEMP(I,2).EQ.FDMI) J=3	NUCY 610
0043		IF (TEMP(I,1).EQ.SPMI.AND.TEMP(I,2).EQ.FDMA) J=4	NUCY 620
0044		IF (J.EQ.0) GO TO 15	NUCY 630
	C		NUCY 640
	C	CALCULATE THE RESPONSE VARIABLES	NUCY 650
	C		NUCY 660
0045		DO 11 K=1,NTLCP	NUCY 670
0046		X(K,NCB1+J-1)=TEMP(I,K)	NUCY 680
0047	11	CONTINUE	NUCY 690
0048		DO 46 I=1,NOBS	NUCY 700
0049		Y(2,I)=X(3,I)/X(4,I)	NUCY 710
0050		Y(1,I)=FLO*X(4,I)	NUCY 720
0051		DO 47 J=5,NTLCP	NUCY 730
0052	47	Y(1,I)=Y(1,I)+X(J,I)*TLC(J-4)	NUCY 740
0053	46	Y(1,I)=Y(1,I)/X(3,I)	NUCY 750
	C		NUCY 760
	C	PLOT THE INPUT POINTS	NUCY 770
	C		NUCY 780
0054		CALL ORGPTS(SPMI,SPMA,FDMI,FDMA,3)	NUCY 790
	C		NUCY 800
	C	PRINT THE INPUT DATA AND RESPONSES	NUCY 810
	C		NUCY 820
0055		WRITE(6,6002)	NUCY 830
0056		DO 6004 J=1,NOBS	NUCY 840
0057		WRITE(6,6003)(X(I,J),I=1,NTLCP)	NUCY 850
0058	6004	WRITE(6,6005)(Y(K,J),K=1,2)	NUCY 860
	C		NUCY 870
	C	TABULATE THE RESPONSES	NUCY 880
	C		NUCY 890
0059		CALL PLOTPM(NCBI)	NUCY 900
0060		IF(ICYC.EQ.1)GO TO 12	NUCY 910
0061		RETURN	NUCY 920
	C		NUCY 930
	C	PREPARE THE DATA FOR E V O P	NUCY 940
	C		NUCY 950
0062	12	DO 14 I=1,4	NUCY 960
0063		DO 14 J=1,2	NUCY 970
0064		SUM(J,I)=0.0	NUCY 980
0065	14	AVE(J,I)=0.0	NUCY 990
0066		RETURN	NUCY1000
0067	9011	WRITE(6,9027)	NUCY1010
0068		GO TO 9033	NUCY1020
0069	9012	WRITE(6,9028)	NUCY1030
0070		GO TO 9033	NUCY1040
0071	9013	WRITE(6,9029)	NUCY1050
0072		GO TO 9033	NUCY1060
0073	9014	WRITE(6,9030)	NUCY1070
0074		GO TO 9033	NUCY1080

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NUCYCL

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15/21/16

0075	9015	WRITE(6,9031)	NUCY1090
0076		GO TO 9033	NUCY1100
0077	9016	WRITE(6,9032)	NUCY1110
0078	9033	CALL EXIT	NUCY1120
0079	15	JK=1	NUCY1130
0080		IF(TEMP(1,1).NE.SPM1.AND.TEMP(1,1).NE.SPM2)JK=3	NUCY1140
0081		IF(TEMP(1,2).NE.FDM1.AND.TEMP(1,2).NE.FDM2)JK=JK+1	NUCY1150
0082		GO TO (17,18,19),JK	NUCY1160
0083	17	WRITE(6,9034)	NUCY1170
0084		GO TO 9033	NUCY1180
0085	18	WRITE(6,9035)	NUCY1190
0086		GO TO 9033	NUCY1200
0087	19	WRITE(6,9036)	NUCY1210
0088		GO TO 9033	NUCY1220
	C		NUCY1230
	C	FORMATS	NUCY1240
	C		NUCY1250
0089	5301	FORMAT(6E13.8/6E13.8/6E13.8/2E13.8,4I2)	NUCY1260
0090	5302	FORMAT(8F10.4)	NUCY1270
0091	6002	FORMAT('1',T20,31X,' INPUT VALUES AND COMPUTED RESPONSES '///	NUCY1280
		'0', ' SPEED FEED PARTS TIME',T51,20X,	NUCY1290
		'TJOL-EDGES',T105,' COST PRD RATE/' 'T51,	NUCY1300
		' (1) (2) (3) (4) (5) (6) (7) (8)',	NUCY1310
		' (9) (10),T105, ' (1/Piece) (PIECES/MIN)'	NUCY1320
		'/' 'T51,' (11) (12) (13) (14) (15) (16) (17) (18)',	NUCY1330
		' (19) (20)')	NUCY1340
0092	6003	FORMAT('J',F10.0,F10.4,5X,2F10.0,(' 'T51,10F5.0))	NUCY1350
0093	6005	FORMAT('J',T105,F10.2,F10.4)	NUCY1360
0094	9027	FORMAT('1 *** ERROR *** UNEXPECTED TERMINATION OF DATA ..'	NUCY1370
		*,/'J',T19,'PUNCHED OUTPUT FROM PREVIOUS EVJP CYCLE MISSING')	NUCY1380
0095	9028	FORMAT('1 *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'0'	NUCY1390
		*,T19,'IN PUNCH OUTPUT FROM PREVIOUS EVJP CYCLE')	NUCY1400
0096	9029	FORMAT('1 *** ERROR *** UNEXPECTED TERMINATION OF DATA ..'	NUCY1410
		*,/'J',T19,'PUNCHED OUTPUT FROM PREVIOUS REGRESSION STEP MISSING')	NUCY1420
0097	9030	FORMAT('1 *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'0'	NUCY1430
		*,T19,'IN PUNCH OUTPUT FROM PREVIOUS REGRESSION STEP')	NUCY1440
0098	9031	FORMAT('1 *** ERROR *** UNEXPECTED TERMINATION OF DATA ..'	NUCY1450
		*,/'J',T19,'NEW OBSERVATIONS MISSING')	NUCY1460
0099	9032	FORMAT('1 *** ERROR *** INVALID CHARACTER ENCOUNTERED '/'0'	NUCY1470
		*,T19,'IN NEW OBSERVATIONS -- CHECK YOUR KEYPUNCHING')	NUCY1480
0100	9034	FORMAT('J *** ERROR *** MORE THAN TWO FEED SETTINGS WERE '	NUCY1490
		*FOUND IN THE NEW OBSERVATIONS ---/'0',T10,' PROGRAM TERMINATING	NUCY1500
		'')	NUCY1510
0101	9035	FORMAT('J *** ERROR *** MORE THAN TWO SPEED SETTINGS WERE '	NUCY1520
		*FOUND IN THE NEW OBSERVATIONS ---/'0',T10,' PROGRAM '	NUCY1530
		*,TERMINATING')	NUCY1540
0102	9036	FORMAT('J *** ERROR *** MORE THAN TWO SPEED SETTINGS AND '	NUCY1550
		*MORE THAN TWO FEED SETTINGS WERE FOUND IN THE NEW OBSERVATIONS,	NUCY1560
		* ---/'0',T10,' PROGRAM TERMINATING')	NUCY1570
0103		END	NUCY1580

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0001      SUBROUTINE EVOP                                EVOP 10
          C                                              EVOP 20
          C                                              EVOP 30
          C      SUBROUTINE EVOP PERFORMS THE EVOLUTIONARY OPEATION ANALYSIS EVOP 40
          C      FOR THE INPUT OBSERVATIONS. THE PROCEDURE USED AND THE RESULTS EVOP 50
          C      REPORTED ARE MODIFICATIONS OF THOSE GIVEN BY BOX AND DPAVER. EVOP 60
          C                                              EVOP 70
          C                                              EVOP 80
0002      COMMON /C101/SPEED(100),FEED(100),SPND(100),NSPD,NFD,ISP,IFD EVOP 90
0003      COMMON /C102/IPH,ICYC,SCYCLE,RLO,X(24,100),Y(2,100),NCBS,NOB1 EVOP 100
          C      *, IOP,PSP,BFD,NILC,TLC(20) EVOP 110
0004      COMMON /C103/DIFF(2,4),SUM(2,4),AVE(2,4),SUMS(2),AVES(2,2) EVOP 120
0005      COMMON /C104/F4M(10) EVOP 130
0006      COMMON /C107/IND(4),SMAX,SMIN,FMAX,FMIN EVOP 140
0007      DIMENSION RANGE(2),SEAVES(2),SNAVES(2),SNSUM(2),SNEW(2),SEMEAN(2) EVOP 150
          C                                              EVOP 160
          C      BEGIN PRINTING EVOP TABLE EVOP 170
          C                                              EVOP 180
0008      IEST=1 EVOP 190
0009      IF(ICYC.EQ.2) IEST=2 EVOP 200
0010      WRITE(6,6600)IPH,ICYC EVOP 210
0011      N2=NOB1+1 EVOP 220
0012      N3=N2+1 EVOP 230
0013      WRITE(6,6553)((X(1,NCB1),X(1,N2),X(1,N3),X(1,NCBS),I=1,2), EVOP 240
          C      *(X(2,NOB1),X(2,N2),X(2,N3),X(2,NOBS),I=1,2) EVOP 250
0014      JCYC=SCYCLE EVOP 260
0015      IF(JCYC.LT.2) JCYC=2 EVOP 270
0016      IF(JCYC.GT.10) JCYC=10 EVOP 280
0017      WRITE(6,6601)((SUM(J,I),I=1,4),J=1,2) EVOP 290
0018      WRITE(6,6602)((AVE(J,I),I=1,4),J=1,2) EVOP 300
0019      SCYCLE=ICYC EVOP 310
          C                                              EVOP 320
          C      COMPUTE THE DIFFERENCES EVOP 330
          C                                              EVOP 340
0020      DO 10 I=1,4 EVOP 350
0021      DIFF(1,I)=AVE(1,I)-Y(1,NOB1+I-1) EVOP 360
0022      DIFF(2,I)=AVE(2,I)-Y(2,NOB1+I-1) EVOP 370
          C                                              EVOP 380
          C      CALCULATE THE RANGE EVOP 390
          C                                              EVOP 400
0023      DO 120 I=1,2 EVOP 410
0024      YMAX=AMAX1(DIFF(I,1),DIFF(I,2),DIFF(I,3),DIFF(I,4)) EVOP 420
0025      YMIN=AMIN1(DIFF(I,1),DIFF(I,2),DIFF(I,3),DIFF(I,4)) EVOP 430
0026      RANGE(I)=YMAX-YMIN EVOP 440
0027      IF(ICYC.LT.2) GO TO 44 EVOP 450
          C                                              EVOP 460
          C      CALCULATE NEW S, NEW SUM S, NEW AVERAGE S EVOP 470
          C                                              EVOP 480
          C                                              EVOP 490
0028      DO 466 I=1,2 EVOP 500
0029      SNEW(I)=(RANGE(I)*F4N(JCYC) EVOP 510
0030      SNSUM(I)=(SNEW(I) +SUMS(I)) EVOP 520
0031      IF(SUMS(I).EQ.0.0)SNSUM(I)=SNEW(I)*2. EVOP 530
0032      SNAVES(I)= (SNSUM(I))/2. EVOP 540
0033      466 CONTINUE

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0034		GO TO 45	EVOP 550
0035	44	DO 467 I=1,2	EVOP 560
0036		SNEW(I)=J.0	EVOP 570
0037		SNSUM(I)=SUMS(I)	EVOP 580
0038	467	SNAVES(I)=AVES(I,1)	EVOP 590
	C		EVOP 600
	C	CALCULATE 2 STANDARD ERROR ESTIMATES	EVOP 610
	C		EVOP 620
0039	45	DO 468 I=1,2	EVOP 630
0040		SEAVES(I)=2./SQRT(SCYCLE)*SNAVES(I)	EVOP 640
0041		SEMEAN(I)=1.73/SQRT(SCYCLE)*SNAVES(I)	EVOP 650
0042		IF(SNAVES(I).EQ.AVES(I,1))SNAVES(I)=AVES(I,2)	EVOP 660
0043	468	CONTINUE	EVOP 670
	C		EVOP 680
	C	COMPUTE SUMS AND AVERAGES	EVOP 690
	C		EVOP 700
0044	47	DO 11 I=1,4	EVOP 710
0045		DO 11 J=1,2	EVOP 720
0046		SUM(J,I)=SUM(J,I)+Y(J,NOR1+I-1)	EVOP 730
0047	11	AVE(J,I)=SUM(J,I)/SCYCLE	EVOP 740
	C		EVOP 750
	C	FINISH PRINTING THE EVOP TABLE	EVOP 760
	C		EVOP 770
0048		WRITE(6,6603)((Y(J,I),I=NOR1,NOR5),J=1,2)	EVOP 780
0049		WRITE(6,6604)((DIFF(J,I),I=1,4),J=1,2)	EVOP 790
0050		WRITE(6,6605)((SLP(J,I),I=1,4),J=1,2)	EVOP 800
0051		WRITE(6,6606)((AVE(J,I),I=1,4),J=1,2)	EVOP 810
0052		WRITE(6,6620)	EVOP 820
	C	WRITE(6,6621)SUMS(1),SUMS(2)	EVOP 830
0053		WRITE(6,6622)AVES(1,ICST),AVES(2,ICST)	EVOP 840
0054		WRITE(6,6623)SNEW(1),SNEW(2)	EVOP 850
0055		WRITE(6,6624)RANGE(1),RANGE(2)	EVOP 860
0056		WRITE(6,6625)SNSUM(1),SNSUM(2)	EVOP 870
0057		WRITE(6,6626)SNAVES(1),SNAVES(2)	EVOP 880
0058		WRITE(6,6607) SEAVES	EVOP 890
	C		EVOP 900
	C	SAVE COMPUTED VALUES FOR FUTURE CYCLES	EVOP 910
	C		EVOP 920
0059		WRITE(7,7000)	EVOP 930
		*((SUM(J,I),I=1,4),SNSUM(J),(AVE(J,I),I=1,4),SNAVES(J),J=1,2),	EVOP 940
		*((INC(I),I=1,4)	EVOP 950
	C		EVOP 960
	C	ANALYZE THE EFFECTS	EVOP 970
	C		EVOP 980
0060		DO 144 I=1,4	EVOP 990
0061	144	AVE(2,I)=-AVE(2,I)	EVOP1000
0062		IGU=1	EVOP1010
0063		ISP1=ISP	EVOP1020
0064		IFD1=IFD	EVOP1030
0065	145	GO TO (146,147),IGU	EVOP1040
0066	146	WRITE(6,148)	EVOP1050
0067		GO TO 149	EVOP1060
0068	147	WRITE(6,150)	EVOP1070
0069	149	IF(SEAVES(IGU).EQ.0.0)GO TO 999	EVOP1080

	C		EVOP1090
	C		EVOP1100
	C	CALCULATE THE EFFECTS OF THE VARIABLES	EVOP1110
0070		EFFA=(AVE(IGO,2)+AVE(IGO,3)-AVE(IGO,1)-AVE(IGO,4))/2.	EVJP1120
0071		EFFB=(AVE(IGO,2)+AVE(IGO,4)-AVE(IGO,1)-AVE(IGO,3))/2.	EVOP1130
0072		EFFAB=(AVE(IGO,1)+AVE(IGO,2)-AVE(IGO,3)-AVE(IGO,4))/2.	EVOP1140
0073		IA=C	EVOP1150
0074		IF(ABS(EFFA)-SEAVES(IGO))30,31,31	EVOP1160
	C		EVOP1170
	C	THE EFFECT OF SPEED IS NOT SIGNIFICANT	EVOP1180
	C		EVJP1190
0075	30	WRITE(6,6610)EFFA	EVJP1200
0076		GO TO 32	EVJP1210
	C		EVOP1220
	C	THE EFFECT OF SPEED IS SIGNIFICANT	EVJP1230
	C		EVJP1240
0077	31	IA=IA+1	EVJP1250
0078		WRITE(6,6611)EFFA	EVOP1260
0079	32	IF(ABS(EFFB)-SEAVES(IGO))33,34,34	EVJP1270
	C		EVJP1280
	C	THE EFFECT OF FEED IS NOT SIGNIFICANT	EVOP1290
	C		EVJP1300
0080	33	WRITE(6,6612)EFFB	EVJP1310
0081		GO TO 35	EVJP1320
	C		EVOP1330
	C	THE EFFECT OF FEED IS SIGNIFICANT	EVOP1340
	C		EVJP1350
0082	34	IA=IA+2	EVJP1360
0083		WRITE(6,6613)EFFB	EVJP1370
0084	35	IF(ABS(EFFAB)-SEAVES(IGO))36,37,37	EVJP1380
	C		EVJP1390
	C	THE EFFECT OF THE INTERACTION IS NOT SIGNIFICANT	EVOP1400
	C		EVJP1410
0085	36	WRITE(6,6614)EFFAB	EVJP1420
0086		GO TO 38	EVOP1430
	C		EVJP1440
	C	THE EFFECT OF THE INTERACTION IS SIGNIFICANT	EVJP1450
	C		EVOP1460
0087	37	IA=IA+3	EVOP1470
0088		WRITE(6,6615)EFFAB	EVOP1480
0089	38	IA=IA+1	EVJP1490
	C		EVJP1500
	C	RECOMMEND THE NEW OPERATING CONDITIONS	EVOP1510
	C		EVJP1520
	C	THE BASE POINT FOR SHIFTING OPERATIONS IS TAKEN TO BE THE	EVOP1530
	C	LOWER LEFT POINT. ALL OTHER POINTS ARE DETERMINED AS	EVJP1540
	C	DISPLACEMENTS FROM THIS POINT. SHIFTS TO A NEW SET OF	EVJP1550
	C	OBSERVATIONS ARE DETERMINED BY SHIFTING THE BASE POINT	EVOP1560
	C	AND RECOMPUTING THE OTHER THREE POINTS FROM THE NEW BASE.	EVJP1570
	C		EVOP1580
0090		GO TO (999,1001,1002,1012,1013,1023,1123),IA	EVJP1590
	C		EVOP1600
	C	NONE OF THE EFFECTS ARE SIGNIFICANT	EVOP1610
	C		EVOP1620

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0091	999	WRITE(6,6617)	EVOP1630
0092		GO TO 1000	EVOP1640
	C		EVOP1650
	C	SPEED IS SIGNIFICANT	EVOP1660
	C		EVOP1670
0093	1001	IF(EFFA)2000,2001,2001	EVOP1680
0094	2000	ISP=ISP+1	EVOP1690
	C		EVOP1700
	C	DETERMINE IF THE SELECTED POINTS ARE WITHIN THE DEFINED	EVOP1710
	C	ENVIRONMENT.	EVOP1720
	C		EVOP1730
0095	1000	IF (ISP+1-NSPD)2033,2033,2034	EVOP1740
0096	2034	ISP=ISP-1	EVOP1750
0097		WRITE(6,6018)	EVOP1760
0098	2035	IF (IFD+1-NFD)2035,2035,2036	EVOP1770
0099	2036	IFD=IFD-1	EVOP1780
0100		WRITE(6,6019)	EVOP1790
0101	2035	IF (ISP)2037,2037,2038	EVOP1800
0102	2037	ISP=ISP+1	EVOP1810
0103		WRITE(6,6020)	EVOP1820
0104	2038	IF (IFC)2039,2039,2040	EVOP1830
0105	2039	IFD=IFD+1	EVOP1840
0106		WRITE(6,6021)	EVOP1850
0107	2040	WRITE(6,6616)SPEED(ISP),SPEED(ISP+1),FEED (IFD+1),FEED (IFD+1),	EVOP1860
		ISPEED(ISP),SPEED(ISP+1),FEED (IFD),FEED (IFD)	EVOP1870
	C		EVOP1880
	C	PLOT RECOMMENDED OPERATING CONDITIONS	EVOP1890
	C		EVOP1900
0108		CALL CROPTS(SPEED(ISP),SPEED(ISP+1),FEED (IFD),FEED (IFC+1),IGO)	EVOP1910
0109		ISP=ISP1	EVOP1920
0110		IFD=IFC1	EVOP1930
0111		IGO=IGO+1	EVOP1940
0112		IF (IGO.E3.2)GO TO 145	EVOP1950
0113		RETURN	EVOP1960
0114	2001	ISP=ISP-1	EVOP1970
0115		GO TO 1000	EVOP1980
	C		EVOP1990
	C	FEED IS SIGNIFICANT	EVOP2000
	C		EVOP2010
0116	1002	IF(EFFB)2003,2004,2004	EVOP2020
0117	2003	IFD=IFD+1	EVOP2030
0118		GO TO 1000	EVOP2040
0119	2004	IFD=IFD-1	EVOP2050
0120		GO TO 1000	EVOP2060
	C		EVOP2070
	C	SPEED & FEED OR THE INTERACTION ARE SIGNIFICANT	EVOP2080
	C		EVOP2090
0121	1012	IF (ABS(EFFA)-SEAVES (IG))2005,2006,2006	EVOP2100
0122	2005	YMIN=AMIN(Y(IG,NB1),Y(IG,NB1+1),Y(IGO,NB1+2),Y(IGO,NB1+3))	EVOP2110
0123		DO 2007 I=1,4	EVOP2120
0124		IF (Y(IGO,NB1+I-1).EQ.YMIN)GO TO 2008	EVOP2130
0125	2007	CONTINUE	EVOP2140
0126	2008	GO TO (2009,2010,2011,2012),I	EVOP2150
0127	2009	ISP=ISP-1	EVOP2160

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0128		IFD=IFD-1	EVJP2170
0129		GU TO 1000	EVOP2180
0130	2010	ISP=ISP+1	EVOP2190
0131		IFU=IFU+1	EVOP2200
0132		GU TO 1000	EVJP2210
0133	2011	ISP=ISP+1	EVJP2220
0134		IFU=IFU-1	EVOP2230
0135		GU TO 1000	EVJP2240
0136	2012	ISP=ISP-1	EVOP2250
0137		IFU=IFU+1	EVOP2260
0138		GU TO 1000	EVJP2270
0139	2006	IF(EFFA)2013,2014,2014	EVJP2280
0140	2013	ISP=ISP+1	EVJP2290
0141		GU TO 2015	EVJP2300
0142	2014	ISP=ISP-1	EVJP2310
0143	2015	IF(EFFB)2016,2017,2017	EVJP2320
0144	2016	IFU=IFU+1	EVJP2330
0145		GU TO 1000	EVJP2340
0146	2017	IFU=IFU-1	EVJP2350
0147		GU TO 1000	EVJP2360
	C		EVJP2370
	C	SPEED AND THE INTERACTION ARE SIGNIFICANT	EVJP2380
	C		EVJP2390
0148	1013	IF(EFFA)2018,2019,2019	EVJP2400
0149	2018	ISP=ISP+1	EVJP2410
0150		GU TO 2020	EVJP2420
0151	2019	ISP=ISP-1	EVJP2430
0152		IF(Y(IGC,NOBS)-Y(IGC,NOB1))2021,2021,2022	EVJP2440
0153	2021	IFU=IFU+1	EVJP2450
0154		GU TO 1000	EVJP2460
0155	2022	IFU=IFU-1	EVJP2470
0156		GU TO 1000	EVJP2480
0157	2020	IF(Y(IGC,NOB1+1)-Y(IGC,NOB1+2))2021,2022,2022	EVJP2490
	C		EVJP2500
	C	FEED AND THE INTERACTION ARE SIGNIFICANT	EVJP2510
	C		EVJP2520
0158	1023	IF(EFFB)2023,2024,2024	EVJP2530
0159	2023	IFU=IFU+1	EVJP2540
0160		GU TO 2025	EVJP2550
0161	2024	IFU=IFU-1	EVJP2560
0162		IF(Y(IGC,NOB1+2)-Y(IGC,NOB1))2027,2026,2026	EVJP2570
0163	2026	ISP=ISP-1	EVJP2580
0164		GU TO 1000	EVJP2590
0165	2027	ISP=ISP+1	EVJP2600
0166		GU TO 1000	EVJP2610
0167	2025	IF(Y(IGC,NOB1+1)-Y(IGC,NOBS))2027,2026,2026	EVJP2620
	C		EVJP2630
	C	ALL TERMS ARE SIGNIFICANT	EVJP2640
	C		EVJP2650
0168	1123	IF(EFFA)2028,2029,2029	EVJP2660
0169	2028	ISP=ISP+1	EVJP2670
0170		GU TO 2030	EVJP2680
0171	2029	ISP=ISP-1	EVJP2690
0172	2030	IF(EFFB)2031,2032,2032	EVJP2700

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0173      2031 IFD=IFD+1                                EVOP2710
0174      GO TO 1000                                    EVOP2720
0175      2032 IFD=IFD-1                                EVOP2730
0176      GO TO 1000                                    EVOP2740
C                                                EVOP2750
C      FORMATS                                         EVOP2760
C                                                EVOP2770
0177      148 FORMAT('1',T46,'COST ANALYSIS')          EVOP2780
0178      150 FORMAT('1',T46,'PRODUCTION RATE ANALYSIS') EVOP2790
0179      6018 FORMAT('JTHE RECOMMENDED SPEED HAS EXCEEDED THE MAXIMUM DEFINED ',EVOP2800
1'SPEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',EVOP2810
2'ED')                                              EVOP2820
0180      6019 FORMAT('JTHE RECOMMENDED FEED HAS EXCEEDED THE MAXIMUM DEFINED ',EVOP2830
1'FEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',EVOP2840
2'ED')                                              EVOP2850
0181      6020 FORMAT('JTHE RECOMMENDED SPEED HAS FALLEN BELOW THE MINIMUM ',EVOP2860
**DEFINED ',EVOP2870
1'SPEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',EVOP2880
2'ED')                                              EVOP2890
0182      6021 FORMAT('JTHE RECOMMENDED FEED HAS FALLEN BELOW THE MINIMUM ',EVOP2900
**DEFINED ',EVOP2910
1'FEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',EVOP2920
2'ED')                                              EVOP2930
0183      6553 FORMAT('J',T10,'SPEED (RPM)',T25,4F10.0,10X,4F10.0/'0',T10,'FEED',EVOP2940
*,', (IPM)',T25,4F10.4,10X,4F10.4)              EVOP2950
0184      6600 FORMAT('1',T42,'EVOLUTINARY OPERATION ANALYSIS',/T47,EVOP2960
**PHASE ',13,EVOP2970
1' CYCLE ',13/'0',T46,'CALCULATION OF AVERAGES'/'0',T45,'COST',EVOP2980
2T90,'PRODUCTION RATE'/'0',T45,'OPERATING CONDITIONS') EVOP2990
0185      6601 FORMAT('JOPREVIOUS CYCLE SUM',T25,4F10.2,10X,4F10.4) EVOP3000
0186      6602 FORMAT('JOPREVIOUS CYCLE AVERAGE',T25,4F10.2,10X,4F10.4) EVOP3010
0187      6603 FORMAT('JNEW OBSERVATIONS',T25,4F10.2,10X,4F10.4) EVOP3020
0188      6604 FORMAT('JDIFFERENCES',T25,4F10.2,10X,4F10.4) EVOP3030
0189      6605 FORMAT('JNEW SUMS',T25,4F10.2,10X,4F10.4) EVOP3040
0190      6606 FORMAT('JNEW AVERAGES: Y(I)',T25,4F10.2,10X,4F10.4) EVOP3050
0191      6607 FORMAT('J',T46,'CALCULATION OF 2 S.E. LIMITS:'/'0',EVOP3060
**FOR NEW EFFECTS',T35,4F10.4,T85,4F10.4) EVOP3070
0192      6610 FORMAT('JTHE EFFECT OF SPEED IS ',T53,4F10.4,' --- NOT ',EVOP3080
**SIGNIFICANT ---') EVOP3090
0193      6611 FORMAT('JTHE EFFECT OF SPEED IS ',T88,4F10.4,' *** -- SIGNIFICANT' EVOP3100
*,', -- **') EVOP3110
0194      6612 FORMAT('JTHE EFFECT OF FEED IS ',T53,4F10.4,' --- NOT SIGNIFICANT' EVOP3120
*,', ---') EVOP3130
0195      6613 FORMAT('JTHE EFFECT OF FEED IS ',T88,4F10.4,' *** -- SIGNIFICANT' EVOP3140
*,', -- **') EVOP3150
0196      6614 FORMAT('JTHE EFFECT OF THE INTERACTION OF SPEED AND FEED IS ',EVOP3160
1F10.4,' --- NOT SIGNIFICANT ---') EVOP3170
0197      6615 FORMAT('JTHE EFFECT OF THE INTERACTION OF SPEED AND FEED IS',T88, EVOP3180
1F10.4,' *** -- SIGNIFICANT -- **') EVOP3190
0198      6616 FORMAT('J',T15,'RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT 'EVOP3200
1,'POINTS:'/'0',T15,'4) SPEED = ',F10.0,T45,'2) SPEED = ',F10.0/ EVOP3210
1' ',T15,' FEED = ',F10.4,T45,' FEED = ',F10.4/'/'0', EVOP3220
1T15,'1) SPEED = ',F10.0,T45,'3) SPEED = ',F10.0/' ', EVOP3230
1' ',T15,' FEED = ',F10.4,T45,' FEED = ',F10.4) EVOP3240

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0159	6617	FORMAT('ONE PARAMETERS ARE SIGNIFICANT'/'0', 'THE PREVIOUS SETTING'	EVOP3250
		1, 'S SHOULD BE RE-EXAMINED')	
0200	6620	FORMAT('/'/'0', '44, 'CALCULATION OF STANDARD DEVIATIONS'//)	EVOP3260
	C 6621	FORMAT('0', 'PREVIOUS SUM S', T35, F10.4, T85, F10.4)	EVOP3270
0201	6622	FORMAT('0PREVIOUS AVERAGE S', T35, F10.4, T85, F10.4)	EVOP3280
0202	6623	FORMAT('ONE S = RANGE * F4, N', T35, F10.4, T85, F10.4)	EVOP3290
0203	6624	FORMAT('ORANGE', T35, F10.4, T85, F10.4)	EVOP3300
0204	6625	FORMAT('ONE SUM S', T35, F10.4, T85, F10.4)	EVOP3310
0205	6626	FORMAT('ONE AVERAGE S = NEW SUM S/2', T35, F10.4, T85, F10.4)	EVOP3320
0206	7000	FORMAT('0.12345'/'6E13.8/6E13.8/6E13.8/2E13.8, 412)	EVOP3330
0207		END	EVOP3340
			EVOP3350

0001		SUBROUTINE ORGPTS (SP1,SP2,FD1,FD2,IG0)	ORGP 10
	C		ORGP 20
	C	SUBROUTINE ORGPTS PLOTS EACH DEFINED FEED-SPEED COMBINATION	ORGP 30
	C	AS A '0' ON A GRAPH AND INDICATES THE FOUR POINTS OF PARTICULAR	ORGP 40
	C	INTEREST WITH AN '*'	ORGP 50
	C		ORGP 60
0002		COMMON /C101/SPEED(100),FEED(100),SPND(100),NSPD,NFD,ISP,IFD	ORGP 70
0003		COMMON /C105/PT1,PT2,PT3,NAME(50),CHART(100,50)	ORGP 80
0004		DIMENSION FND(50)	ORGP 90
0005		DO 6 I=1,50	ORGP 100
0006	6	FND(I)=0.0	ORGP 110
0007		NS=100/NSPD	ORGP 120
0008		NF=50/NFD	ORGP 130
0009		NS1=NS*NSPD	ORGP 140
0010		NF1=NF*NFD	ORGP 150
0011		ISP1=1	ORGP 160
0012		ISP2=1	ORGP 170
0013		NFD1=1	ORGP 180
0014		NFD2=1	ORGP 190
0015		DO 1 IS=1,NSPD	ORGP 200
0016		IF (SP1.E).SPEED(1S))ISP1=(IS-1)*NS+1	ORGP 210
0017		IF (SP2.E).SPEED(1S))ISP2=(IS-1)*NS+1	ORGP 220
0018	1	CONTINUE	ORGP 230
0019		DO 2 JS=1,NFD	ORGP 240
0020		IF (FD1.E).FEED(JS))NF1=(JS-1)*NF+1	ORGP 250
0021		IF (FD2.E).FEED(JS))NF2=(JS-1)*NF+1	ORGP 260
0022	2	CONTINUE	ORGP 270
0023		K=0	ORGP 280
0024		DO 3 I=1,NF1,NF	ORGP 290
0025		K=K+1	ORGP 300
0026	3	FND(I)=FEED(K)	ORGP 310
	C	DO 3 J=1,NS1,NS	ORGP 320
	C 3	CHART(J,I)=PT1	ORGP 330
0027		CHART(ISP1,NFD1)=PT2	ORGP 340
0028		CHART(ISP1,NFD2)=PT2	ORGP 350
0029		CHART(ISP2,NFD1)=PT2	ORGP 360
0030		CHART(ISP2,NFD2)=PT2	ORGP 370
0031		GO TO (31,32,33),IG0	ORGP 380
0032	31	WRITE(6,64)	ORGP 390
0033		GO TO 34	ORGP 400
0034	32	WRITE(6,65)	ORGP 410
0035		GO TO 34	ORGP 420
0036	33	WRITE(6,66)	ORGP 430
0037	34	I=50	ORGP 440
0038	4	IF (FND(I).EQ.0.0)GO TO 5	ORGP 450
0039		WRITE(6,67)NAME(I),FND(I),(CHART(J,I),J=1,100)	ORGP 460
0040		GO TO 8	ORGP 470
0041	5	WRITE(6,69)NAME(I),(CHART(J,I),J=1,100)	ORGP 480
0042	8	I=I-1	ORGP 490
0043		IF (I.GT.0)GO TO 4	ORGP 500
0044		K=0	ORGP 510
0045		DO 11 I=1,10	ORGP 520
0046		DO 11 J=1,NSPD,10	ORGP 530
0047		K=K+1	ORGP 540

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ORGPTS

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0048	11	SPND(I)=SPEED(K)	ORGP 550
0049		WRITE(6,7C)	ORGP 560
0050		WRITE(6,71)(SPND(I),I=1,NSPD)	ORGP 570
0051		WRITE(6,72)	ORGP 580
0052		CHART(ISP1,NFD1)=PT3	ORGP 590
0053		CHART(ISP1,NFD2)=PT3	ORGP 600
0054		CHART(ISP2,NFD1)=PT3	ORGP 610
0055		CHART(ISP2,NFD2)=PT3	ORGP 620
0056		RETURN	ORGP 630
	C		ORGP 640
	C	FORMATS	ORGP 650
	C		ORGP 660
0057	64	FORMAT('1',T54,'NEW COST ENVIRONMENT')	ORGP 670
0058	65	FORMAT('1',T54,'NEW PRODUCTION RATE ENVIRONMENT')	ORGP 680
0059	66	FORMAT('1',T54,'SPECIFIED ENVIRONMENT'/ ' ')	ORGP 690
0060	67	FORMAT(' ',1A1,F10.4,2X,'I',2X,100A1)	ORGP 700
0061	69	FORMAT(' ',1A1,12X,'I',2X,100A1)	ORGP 710
0062	70	FORMAT(' ',13X,'I'/	ORGP 720
		' ',13X,'I'-----',	ORGP 730
		*'-----')	ORGP 740
0063	71	FORMAT(' ',7X,10F10.0)	ORGP 750
0064	72	FORMAT(' ',T60,'S P E E D (RPM)')	ORGP 760
0065		END	ORGP 770

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FLOTPM

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0001		SUBROUTINE PLOTPM(II)	PLOT 10
	C		PLOT 20
	C	SUBROUTINE PLOTPM TABULATES THE RESPONSES VERSUS FEEDS	PLOT 30
	C	AND SPEEDS.	PLOT 40
	C		PLOT 50
0002		CU4MDX /C102/IPH,ICYC,SCYCLE,RLO,X(24,100),Y(2,100),NOBS,NOB1	PLOT 60
		* ,IUP,BSP,BFD,NILC,TLC(20)	PLOT 70
0003		I2=I1+1	PLOT 80
0004		I3=I1+2	PLOT 90
0005		I4=I1+3	PLOT 100
0006		WRITE(6,72)	PLOT 110
0007		*WRITE(5,71)X(2,I4),Y(1,I4),Y(1,I2),Y(2,I4),Y(2,I2),X(2,I1),	PLOT 120
		*Y(1,I1),Y(1,I3),Y(2,I1),Y(2,I3),X(1,I1),X(1,I3)	PLOT 130
0008		RETURN	PLOT 140
	C		PLOT 150
	C	FORMATS	PLOT 160
	C		PLOT 170
0009	71	FORMAT('0',30X,F10.4,' COST = ',F10.2,10X,' COST = ',	PLOT 180
		*F10.2	PLOT 190
		*/'0',40X,' PRCD. F1. = ',F10.4,10X,' PRCD. R1. = ',F10.4,///	PLOT 200
		*'0',30X,F10.4,' COST = ',F10.2,10X,' COST = ',F10.2	PLOT 210
		*/'0',40X,' PRCD. F1. = ',F10.4,10X,' PRCD. R1. = ',F10.4/	PLOT 220
		*'0',54X,F10.0,24X,F10.0/'0',69X,'S P E E D (RPM)'	PLOT 230
0010	72	FORMAT('1',30X,' TABLE OF RESPONSES '///'0',33X,' FEED (IPF)')	PLOT 240
0011		END	PLOT 250

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REGPLT

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0001		SUBROUTINE REGPLT(BC,E,INC,IREG,IGO)	REGP 10
	C		REGP 20
	C	SUBROUTINE REGPLT PREDICTS THE PERFORMANCE INDICIES FOR	REGP 30
	C	FIELDS AND SPEEDS ADJACENT TO THE OBSERVATIONS.	REGP 40
	C		REGP 50
0002		COMMON /C101/SPEED(100),FEED(100),SPDC(100),NSPD,NFD,ISP,IFD	REGP 60
0003		DIMENSION IND(4),B(2,5),SPDD(2,100),BO(2),IREG(2)	REGP 70
0004		DATA PTT1,PTT2/'(',')'	REGP 80
0005		WRITE(6,71)	REGP 90
	C		REGP 100
	C	COMPUTE PREDICTED VALUES	REGP 110
	C		REGP 120
0006	81	ISP1=IND(1)-1	REGP 130
0007		IF (ISP1.LE.0) ISP1=1	REGP 140
0008		ISP2=IND(2)+1	REGP 150
0009		IF (ISP2.GT.NSPD) ISP2=NSPD	REGP 160
0010		IFD1=IND(3)-1	REGP 170
0011		IF (IFD1.LE.0) IFD1=1	REGP 180
0012		IFD2=IND(4)+1	REGP 190
0013		IF (IFD2.GT.NFD) IFD2=NFD	REGP 200
0014		I=IFD2	REGP 210
0015	505	C=ALOG(FEED(I))	REGP 220
0016		DO 506 J=ISP1,ISP2	REGP 230
0017		A=ALOG(SPEED(J))	REGP 240
0018		DO 506 K=1,2	REGP 250
0019		IRE=IREG(K)	REGP 260
0020		SPDD(K,J) = BO(K) + B(K,1)*A + B(K,2)*C	REGP 270
0021		GO TO (506,511,512,513,514), IRE	REGP 280
0022	511	SPDC(K,J) = SPDD(K,J) + B(K,3)*A*C + B(K,4)*A*A	REGP 290
0023		GO TO 506	REGP 300
0024	512	SPDC(K,J) = SPDD(K,J) + B(K,3)*A*C + B(K,4)*C*C	REGP 310
0025		GO TO 506	REGP 320
0026	513	SPDC(K,J) = SPDD(K,J) + B(K,3)*A*C + B(K,4)*A*A + B(K,5)*C*C	REGP 330
0027		GO TO 506	REGP 340
0028	514	SPDC(K,J) = SPDD(K,J) + B(K,3)*A*C	REGP 350
0029	506	CONTINUE	REGP 360
	C		REGP 370
	C	PLOT PREDICTED VALUES	REGP 380
	C		REGP 390
0030		ID=ISP2-ISP1+1	REGP 400
0031		IF (ID.EQ.1) GO TO 11	REGP 410
0032		WRITE(6,72) FEED(I), (SPDD(1,J), J=ISP1,ISP2)	REGP 420
0033		WRITE(6,78) (PTT1, SPDC(2,J), PTT2, J=ISP1,ISP2)	REGP 430
0034		GO TO 77	REGP 440
0035	11	IST=ISP1	REGP 450
0036	33	IEND=IST+9	REGP 460
0037		IEND=MIN(IEND,ISP2)	REGP 470
0038		IF (IST.EQ.ISP1) WRITE(6,72) FEED(I), (SPDD(1,J), J=IST,IEND)	REGP 480
0039		IF (IST.NE.ISP1) WRITE(6,82) (SPDD(1,J), J=IST,IEND)	REGP 490
0040		WRITE(6,78) (PTT1, SPDC(2,J), PTT2, J=IST,IEND)	REGP 500
0041		IF (IST.EQ.ISP2) GO TO 77	REGP 510
0042		IST=IST+10	REGP 520
0043		GO TO 33	REGP 530
0044	77	I=I-1	REGP 540

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REGPLT

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0045		IF(1.GE.IFD1)GO TC 505	REGP 550
0046		WRITE(6,7C)	REGP 560
0047		WRITE(6,73)(SPEED(I),I=ISP1,ISP2)	REGP 570
0048		IF(ID.GT.5)GO TC 98	REGP 580
0049		WRITE(6,74)	REGP 590
0050	99	CALL EXIT	REGP 600
0051	98	WRITE(6,75)	REGP 610
0052		GO TO 99	REGP 620
	C		REGP 630
	C	FORMATS	REGP 640
	C		REGP 650
	C		REGP 660
0053	70	FORMAT(' ',12X,'I ' /	REGP 670
		* ' ',12X,'I-----'	REGP 680
		*-----')	REGP 690
0054	71	FORMAT('I',T50,'PREDICTED COSTS '/' ' ,T44,'(PREDICTED PRODUCTION'	REGP 700
		*, ' RATES) '/' '0 FEED (IPR) '/' '0')	REGP 710
0055	72	FORMAT(' ',12X,'I '/' ' ,F10.4,2X,'I',2X,10F10.2)	REGP 720
0056	73	FORMAT('J',15X,10F10.0)	REGP 730
0057	74	FORMAT('J',T30,'S P E E D (RPM)')	REGP 740
0058	75	FORMAT('J',T50,'S P E E D (RPM)')	REGP 750
0059	78	FORMAT(' ',12X,'I',3X,10(2X,A1 ,F6.4,A1))	REGP 760
0060	82	FORMAT(' ',12X,'I '/' ' ,12X,'I',2X,10F10.2)	REGP 770
0061		END	REGP 780

```

0001      SUBROUTINE REGRES (X,Y,N,IREF,BSUBO,BHAT,IDEP)
C
C      SUBROUTINE REGRES COMPUTES A MULTIPLE LINEAR REGRESSION ON
C      M VARIABLES WITH N OBSERVATIONS. EQUATIONS USED ARE:
C
C       $PI = BC + B1 \text{ LN}(SPEED) + B2 \text{ LN}(FEED)$ 
C
C       $PI = B0 + B1 \text{ LN}(SPEED) + B2 \text{ LN}(FEED) + B3 \text{ LN}(SPEED) \text{ LN}(FEED)$ 
C
C       $PI = B0 + B1 \text{ LN}(SPEED) + B2 \text{ LN}(FEED) + B3 \text{ LN}(SPEED) \text{ LN}(FEED)$ 
C       $+ B4 \text{ LN}(SPEED)**2$ 
C
C       $PI = B0 + B1 \text{ LN}(SPEED) + B2 \text{ LN}(FEED) + B3 \text{ LN}(SPEED) \text{ LN}(FEED)$ 
C       $+ B4 \text{ LN}(FEED)**2$ 
C
C       $PI = B0 + B1 \text{ LN}(SPEED) + B2 \text{ LN}(FEED) + B3 \text{ LN}(SPEED) \text{ LN}(FEED)$ 
C       $+ B4 \text{ LN}(SPEED)**2 + B5 \text{ LN}(FEED)**2$ 
C
0002      DIMENSION PHAT(5),YBAR(2)
0003      DIMENSION X(25,100),Y(2,100),DUM1(5,5),XPX(5,6)
0004      DIMENSION XBAR(5), RAD(5),STD(5),T(5),YHAT(100),
*DIFF(100), APY(2,5),SST(2)
0005      DIMENSION XPXC(5,6),XPYC(2,5)
0006      NP = N
0007      EPS = 1.0E-05
0008      M = 5
0009      XN = N
0010      MP = M+1
0011      IF (IDEP.EQ.1) GO TO 30
0012      DO 10 I=1,5
0013      DO 10 J=1,5
0014      10  APX(I,J)=DUM1(I,J)
0015      DO 11 I=1,5
0016      11  APX(I,6)=APY(2,I)
0017      GO TO 130
C
C      COMPUTE THE MEANS
C
0018      30  DO 40 J = 1,NP
0019      X(1,J) = ALOG(X(1,J))
0020      X(2,J) = ALOG(X(2,J))
0021      X(3,J) = X(1,J)*X(2,J)
0022      X(4,J) = X(1,J)*X(1,J)
0023      X(5,J) = X(2,J)*X(2,J)
0024      40  CONTINUE
0025      DO 60 J=1,2
0026      YBAR(J) = 0.0
0027      DO 60 I=1,N
0028      60  YBAR(J) = YBAR(J) + Y(J ,I)/XN
0029      DO 70 J=1,M
0030      XBAR(J) = 0.0
0031      DO 70 I=1,N
0032      70  XBAR(J) = XBAR(J) + X(J,I)/XN

```

```

REGR 10
REGR 20
REGF 30
REGR 40
REGR 50
REGR 60
REGR 70
REGR 80
REGF 90
REGR 100
REGR 110
REGR 120
REGR 130
REGR 140
REGF 150
REGR 160
REGR 170
REGF 180
REGR 190
REGF 200
REGR 210
REGR 220
REGF 230
REGF 240
REGF 250
REGF 260
REGF 270
REGF 280
REGF 290
REGR 300
REGF 310
REGF 320
REGR 330
REGF 340
REGR 350
REGF 360
REGF 370
REGF 380
REGR 390
REGF 400
REGR 410
REGF 420
REGR 430
REGF 440
REGF 450
REGF 460
REGR 470
REGF 480
REGR 490
REGF 500
REGF 510
REGF 520
REGR 530
REGF 540

```

0033	80	CONTINUE	REGP 550
	C		REGP 560
	C	COMPUTE THE SUMS OF SQUARES	REGP 570
	C		REGP 580
0034		DO 90 I=1,2	REGP 590
0035		SST(I)=0.0	REGP 600
0036		DO 90 J=1,N	REGP 610
0037	90	SST(I)=SST(I)+(Y(I,J)-YBAR(I))*(Y(I,J)-YBAR(I))	REGP 620
0038		DO 110 J=1,M	REGP 630
0039		DO 110 I=1,M	REGP 640
0040		APX(J,I) = 0.0	REGP 650
0041		DO 100 K=1,N	REGP 660
0042	100	APX(J,I)=XPK(J,I)+(X(I,K)-XBAR(I))*(X(J,K)-XBAR(J))	REGP 670
0043		APXC(J,I)=APX(J,I)	REGP 680
0044	110	CONTINUE	REGP 690
0045		DO 130 K=1,2	REGP 700
0046		DO 130 J=1,M	REGP 710
0047		APY(K ,J) = 0.0	REGP 720
0048		DO 120 I=1,N	REGP 730
0049	120	APY(K ,J)=XPK(I,J)+(X(J,I)-XBAR(J))*(Y(K ,I)-YBAR(K))	REGP 740
0050		APYC(K,J)=APY(K,J)	REGP 750
0051	130	CONTINUE	REGP 760
0052		DO 140 I=1,M	REGP 770
0053	140	APX(I,6)=XPY(IDEF,I)	REGP 780
0054		DO 135 I=1,5	REGP 790
0055		DO 135 J=1,5	REGP 800
0056		DUM1(I,J) = APX(I,J)	REGP 810
0057	135	CONTINUE	REGP 820
	C		REGP 830
	C	DETERMINE THE FORM OF THE REGRESSION EQUATION AND	REGP 840
	C	INVERT THE X'X MATRIX	REGP 850
	C		REGP 860
0058	136	GO TO (141,143,142,146), IREG	REGP 870
0059	142	DO 144 I=1,3	REGP 880
0060		XPX(4,I)=XPX(5,I)	REGP 890
0061	144	XPX(I,4)=XPX(I,5)	REGP 900
0062		XPX(4,4)=XPX(5,5)	REGP 910
0063	143	M=4	REGP 920
0064		DO 141 I = 1,M	REGP 930
0065	141	APX(I,5) = XPX(I,6)	REGP 940
0066		CALL CIMEQN(XPX,M,EPS,D,1)	REGP 950
0067		IF (ABS(D) .GE. EPS) GO TO 145	REGP 960
0068		GO TO 143	REGP 970
0069	151	M = 2	REGP 980
0070		XPX (1,3) = XPX(1,6)	REGP 990
0071		XPX(2,3) = XPX(2,6)	REGP 1000
0072		GO TO 154	REGP 1010
0073	146	CALL CIMEQN(XPX,M,EPS,D,1)	REGP 1020
0074		IF (ABS(D) .GE. EPS) GO TO 145	REGP 1030
0075	148	IREG = 5	REGP 1040
0076		DO 149 I=1,3	REGP 1050
0077		DO 149 J=1,3	REGP 1060
0078	149	XPX(1,J)=DUM1(I,J)	REGP 1070
0079		M = 3	REGP 1080

008C	DO 147 I=1,3	REGP1090
0081	147 XPX(I,4)=XPX(I,6)	REGP1100
0082	154 CALL DIMEN(XPX,M,EP5,D,1)	REGP1110
	C	REGP1120
	C COMPUTE THE REGRESSION PARAMETERS	REGP1130
	C	REGP1140
0083	145 DO 15C I = 1,M	REGP1150
0084	150 BHAT (I)=XPX(I,M+1)	REGP1160
0085	W = 0.0	REGP1170
0086	SSR = 0.0	REGP1180
0087	DO 16C I=1,M	REGP1190
0088	W = W + BHAT(I)*XBAR(I)	REGP1200
0089	BSUBU = YBAR(IDEP) - W	REGP1210
009C	16C SSR=SSR + BHAT(I) * XPY (IDEP,I)	REGP1220
0091	XM = W	REGP1230
0092	XMSR = SSR/XM	REGP1240
0093	SSE = SST(IDEP) - SSR	REGP1250
0094	XE = N-M-1	REGP1260
0095	K = XE	REGP1270
0096	XMSE = SSE/XE	REGP1280
0097	F = XMSR/XMSE	REGP1290
0098	DO 17C I=1,M	REGP1300
0099	RAU(I) = XPX(I,I)*XMSE	REGP1310
010C	STD(I)=SQRT(RAU(I))	REGP1320
0101	T(I) = BHAT(I)/STD(I)	REGP1330
0102	17C CONTINUE	REGP1340
0103	DO 190 I=1,N	REGP1350
0104	YHAT(I) = BSUBU	REGP1360
0105	DO 180 J=1,M	REGP1370
0106	180 YHAT (I)=YHAT(I)+BHAT(J)*X(J,I)	REGP1380
0107	DIFF(I) = Y(IDEP,I)- YHAT(I)	REGP1390
0108	190 CONTINUE	REGP1400
0109	WRITE (6,503) M,N	REGP1410
	C	REGP1420
	C OUTPUT THE REGRESSION RESULTS	REGP1430
	C	REGP1440
	C	REGP1450
	C	REGP1460
	C IF OUTPUT OF THE X'X, X'Y, (X'X) ⁻¹ & RESIDUALS IS DESIRED,	REGP1470
	C THE FOLLOWING COMMENT CARDS SHOULD BE ACTIVATED BY	REGP1480
	C REMOVING THE C'S	REGP1490
	C	REGP1500
0110	GO TO (521,522),IDEP	REGP1510
0111	521 WRITE(6,523)	REGP1520
0112	GO TO 525	REGP1530
0113	522 WRITE(6,524)	REGP1540
0114	525 RSU = SSR/SST(IDEP)	REGP1550
	C WRITE (6,505)	REGP1560
	C DO 200 I=1,M	REGP1570
C200	WRITE (6,506) I,(XPXC(I,J),J=1,M)	REGP1580
	C WRITE (6,515)	REGP1590
	C DO 210 I=1,M	REGP1600
C210	WRITE (6,516) I,XPYC(IDEP,I)	REGP1610
	C WRITE (6,507)	REGP1620

	C	DO 240 I=1,M	REG1630
	C220	WRITE (6,508) I,(XPX(I,J),J=1,M)	REG1640
0115		N1 = N - 1	REG1650
0116		WRITE (6,509) N1,SST(IGEP),M,SSR,XMSR,F,K,SSE,XMSE,PSQ	REG1660
0117		WRITE (6,510) BSUBC	REG1670
0118		DO 230 I=1,M	REG1680
0119	230	WRITE (6,511) I,BFAT (I),I,T(I),I,STD(I)	REG1690
	C	WRITE (6,512)	REG1700
	C	DO 240 I=1,N	REG1710
	C240	WRITE (6,513) I,Y(IGEP,I),YHAT (I),DIFF(I)	REG1720
0120		KEYUKN	REG1730
	C		REG1740
	C	FORMATS	REG1750
	C		REG1760
0121	503	FORMAT (1H1,26X, 22H MULTIPLE REGRESSION ON, 13, 15H VARIABLES WITH	REG1770
		15, 13H OBSERVATIONS ///)	REG1780
	C504	FORMAT (1H, 1X, 4HROW, 13, 3X, 6E18.8/(12X, 6E18.8))	REG1790
	C505	FORMAT (1H, 10X, 'CORRECTED X'X MATRIX' ///)	REG1800
	C506	FORMAT (1H, 1X, 4HROW, 13, 3X, 6E18.8/(12X, 6E18.8))	REG1810
	C507	FORMAT (///11X, 'CORRECTED X'X INVERSE MATRIX' ///)	REG1820
	C508	FORMAT (1H, 1X, 4HROW, 13, 3X, 6E18.8/(12X, 6E18.8))	REG1830
0122	509	FORMAT (1H, //, 44X, 5H ANOVA ///11X, 6H SOURCE, 9X, 2H OF, 10X, 2H SS,	REG1840
		*10X, 2H MS, 10X, 1H, 17X ///11X, 5H TOTAL, 9X, 13, 2X, 6E18.8 ///11X,	REG1850
		*10H REGRESSION, 4X, 13, 2X, 3E18.8 ///11X, 9H RESIDUAL, 6X, 13, 2X,	REG1860
		*2E18.8 ///11X, 'COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = '	REG1870
		*, 6E18.8 ///)	REG1880
0123	510	FORMAT (22X, 12H COEFFICIENTS, 15X, 6H VALUES, 20X 13H STANDARD DEV. ///11X	REG1890
		* 9H RESIDU = , 6E18.8)	REG1900
0124	511	FORMAT (11X, 5H HAT (1,2,2H) =, 6E18.8, 10X, 2H T (1,2,2H) =, 6E18.8, 10X, 3H SD (	REG1910
		*12, 2H) =, 6E18.8)	REG1920
	C512	FORMAT (1H1, 10X, 'OBSERVATION', 12X, 'Y-OBSERVED', 10X, 'Y-ESTIMATED'	REG1930
	C	* , 5X, ' DIFFERENCE ', ///11X)	REG1940
	C513	FORMAT (1H, 10X, 13, 19X, 6E18.8, 5X, 6E18.8, 5X, 6E18.8)	REG1950
	C514	FORMAT (12, 2X, 13, 2X, 13)	REG1960
	C515	FORMAT (///11X, 20H CORRECTED X'Y MATRIX ///)	REG1970
	C516	FORMAT (2X, 4HROW, 13, 3X, 6E18.8/(11X, 6E18.8))	REG1980
0125	523	FORMAT ('J', T50, 'CONST EQUATION')	REG1990
0126	524	FORMAT ('J', T50, 'PRODUCTION RATE EQUATION')	REG2000
0127		END	REG2010

0001	SUBROUTINE DIMEQN(A,N,EPS,DET,NSOLUT)	DIME 10
C		DIME 20
C	SUBROUTINE DIMEQN IS A SINGLE PRECISION MATRIX INVERSION ROUTINE	DIME 30
C	THAT SPEKS MAXIMUM PIVOT ELEMENTS AND INVERTS IN PLACE.	DIME 40
C	A= ARRAY CONTAINING MATRIX OF C COEFFICIENTS TO BE INVERTED.	DIME 50
C	N= ORDER OF MATRIX A.	DIME 60
C	EPS= MINIMUM ALLOWABLE VALUE OF MATRIX PIVOT BEFORE MATRIX IS	DIME 70
C	TERMED SINGULAR.	DIME 80
C	DET= VALUE OF DETERMINANT OF MATRIX A.	DIME 90
C	NSOLUT= NO. SOLUTION VECTORS IN THE AUGMENTED MATRIX.	DIME 100
C		DIME 110
0002	DIMENSION IPIV(2, 20), ICJ (20), Y(20), A(5,6)	DIME 120
0003	IF(N.LT.1) RETURN	DIME 130
0004	IF(N.GT. 1) GO TO 250	DIME 140
0005	DET=1(1,1)	DIME 150
0006	A(1,1)=1./A(1,1)	DIME 160
0007	A(1,2)=A (1,1)*A(1,2)	DIME 170
0008	RETURN	DIME 180
0009	250 CONTINUE	DIME 190
0010	M = N + NSOLUT	DIME 200
0011	DET = 1.	DIME 210
0012	ASSIGN 205 TO IZERO	DIME 220
0013	DO 100 K=1,N	DIME 230
0014	KM1 = K-1	DIME 240
0015	IF(KM1.GT.0) ASSIGN 95 TO IZERO	DIME 250
0016	BIGA = 0.0	DIME 260
0017	DO 101 I=1,N	DIME 270
0018	DO 101 J=1,N	DIME 280
0019	GO TO IZERO , (95,205)	DIME 290
0020	95 DO 102 II=1,KM1	DIME 300
0021	IF(1.EQ.IPIV(1,II).OR.J.EQ.IPIV(2,II)) GO TO 101	DIME 310
0022	102 CONTINUE	DIME 320
0023	205 CONTINUE	DIME 330
0024	IF (ABS(A(I,J)).LT.BIGA) GO TO 101	DIME 340
0025	BIGA = ABS(A(I,J))	DIME 350
0026	IPIV(1,K) = I	DIME 360
0027	IPIV(2,K) = J	DIME 370
0028	101 CONTINUE	DIME 380
0029	IF(BIGA.GE.EPS) GO TO 201	DIME 390
0030	DET = C.J	DIME 400
0031	GO TO 203	DIME 410
0032	201 IR = IPIV(1,K)	DIME 420
0033	JC = IPIV(2,K)	DIME 430
0034	BIGA = A(IR,JC)	DIME 440
0035	DET = DET*BIGA	DIME 450
0036	DO 103 LL= 1,M	DIME 460
0037	103 A(1,LL) = A(IR,LL)/BIGA	DIME 470
0038	A(IR,JC) = 1.0/BIGA	DIME 480
0039	DO 100 LLL= 1,N	DIME 490
0040	AJCK = A(LL,JC)	DIME 500
0041	IF(LL.EQ.IR) GO TO 100	DIME 510
0042	A(LL,JC) = -AJCK/BIGA	DIME 520
0043	DO 104 L4 = 1,M	DIME 530
0044	IF(L4.EQ.JC) GO TO 104	DIME 540

0045		A(LLL,L4) = A(LLL,L4) -AJCK*A(IR,L4)	DIME 550
0046	104	CONTINUE	DIME 560
0047	100	CONTINUE	DIME 570
0048		DO 105 I=1,N	DIME 580
0049		IR = IPIV(1,I)	DIME 590
0050		ICJ(IR) = JC	DIME 600
0051	105	CONTINUE	DIME 610
0052		ICT = 0	DIME 620
0053		NM1 = N-1	DIME 630
0054		DO 106 I=1,NM1	DIME 640
0055		IP1 = I + 1	DIME 650
0056		DO 106 J= IP1,N	DIME 660
0057		IF((ICJ(J).GE.ICJ(I)) GO TO 106	DIME 670
0058		ITEMP = ICJ(J)	DIME 680
0059		ICJ(J) = ICJ(I)	DIME 690
0060		ICJ(I) = ITEMP	DIME 700
0061		ICT = ICT + 1	DIME 710
0062	106	CONTINUE	DIME 720
0063		IF((ICT/2)*2.NE.ICT) DET = -DET	DIME 730
0064		DO 107 J=1,M	DIME 740
0065		DO 108 I=1,N	DIME 750
0066		JC = IPIV(2,I)	DIME 760
0067		IR = IPIV(1,I)	DIME 770
0068	108	Y(JC) = A(IR,J)	DIME 780
0069		DO 107 K= 1,N	DIME 790
0070	107	A(K,J) = Y(K)	DIME 800
0071		DO 110 I= 1,N	DIME 810
0072		DO 111 J= 1,N	DIME 820
0073		IR = IPIV(1,J)	DIME 830
0074		JC = IPIV(2,J)	DIME 840
0075	111	Y(IR) = A(I,JC)	DIME 850
0076		DO 110 K = 1,N	DIME 860
0077	110	A(I,K) = Y(K)	DIME 870
0078	200	RETLKN	DIME 880
0079		END	DIME 890

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00C1	BLOCK DATA	BLCK 10
C		BLCK 20
C	DEFINITION OF CCNstants	BLCK 30
C		BLCK 40
00C2	CO4MLN /C104/F4N(1C)	BLCK 50
00C3	CO4MLN /C105/PT1,PT2,PT3,NAME(50),CHART(100,50)	BLCK 60
00C4	CO4MLN /C107/IND(4),SMAX,SMIN,FMAX,FMIN	BLCK 70
00C5	DATA F4N/0.,.34,.40,.42,.43,.44,.45,.45,.46,.46/	BLCK 80
00C6	DATA PT1,PT2,PT3/' ','*', ' ' /	BLCK 90
00C7	DATA NAME/50*' ' /	BLCK 100
00C8	DATA NAME(16),NAME(17),NAME(18),NAME(19),NAME(20) /'-','R','P',	BLCK 110
	*'I','-' /	BLCK 120
00C9	DATA NAME(22),NAME(24),NAME(26),NAME(28) /'D','E','E','F' /	BLCK 130
0010	DATA CHA1/5J00*' ' /	BLCK 140
0011	DATA IND/100,0,100,C /	BLCK 150
0012	DATA SMAX,SMIN,FMAX,FMIN/0.C,0.0,0.0,0.0 /	BLCK 160
0013	END	BLCK 170

Appendix G. MACHOP Program Documentation

G.1 Program Description

- G.1.1 Synopsis
- G.1.2 MACHOP Block Diagram
- G.1.3 Program Sequence
- G.1.4 Program Requirements and Restrictions

G.2 Input-Output Descriptions

- G.2.1 Program Set-ups
- G.2.2 Input Formats
- G.2.3 Input Requirements
- G.2.4 Output Description

G.3 Systems Material

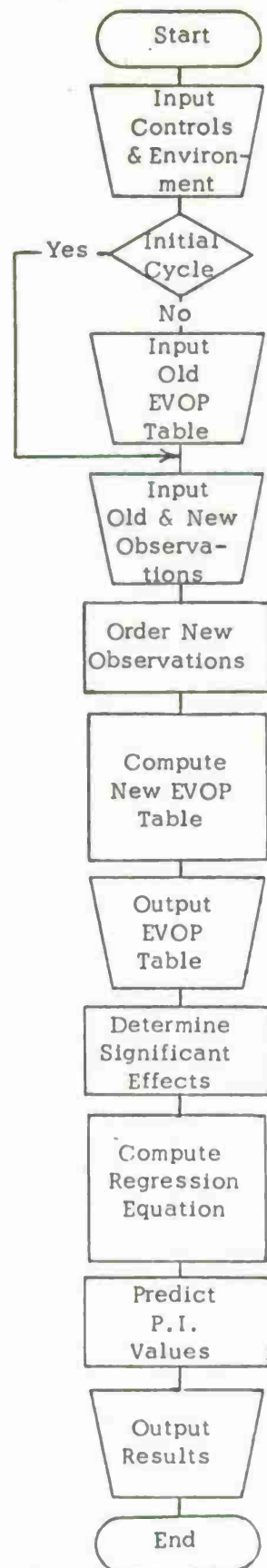
- G.3.1 Flow Chart
- G.3.2 Glossary of Important Variables

G.1 Program Description

G.1.1 Synopsis

The MACHOP program is written in FORTRAN IV for an IBM System 360/65 Data Processing System using the standard IBM FORTRAN(G) compiler. The following documentation outlines all aspects of this application unique to this program.

G.1.2 MACHOP BLOCK DIAGRAM



G.1.3 Program Sequence

MACHOP consists of one main routine and eight subroutines. The normal sequence is:

```
MAIN  
NUCYCL  
EVOP  
ORGPTS  
PLOTPM  
REGPLT  
REGRES  
DIMEQN  
BLOCK DATA
```

Functions which are required, but are not supplied with this program, are available in most IBM FORTRAN IV compilers. These are as follows:

```
Square Root (SQRT)  
Absolute Value (ABS)  
Maximum (AMAX1)  
Minimum (AMIN1)  
Natural Logarithm (ALOG)
```

G.1.4 Program Requirements and Restrictions

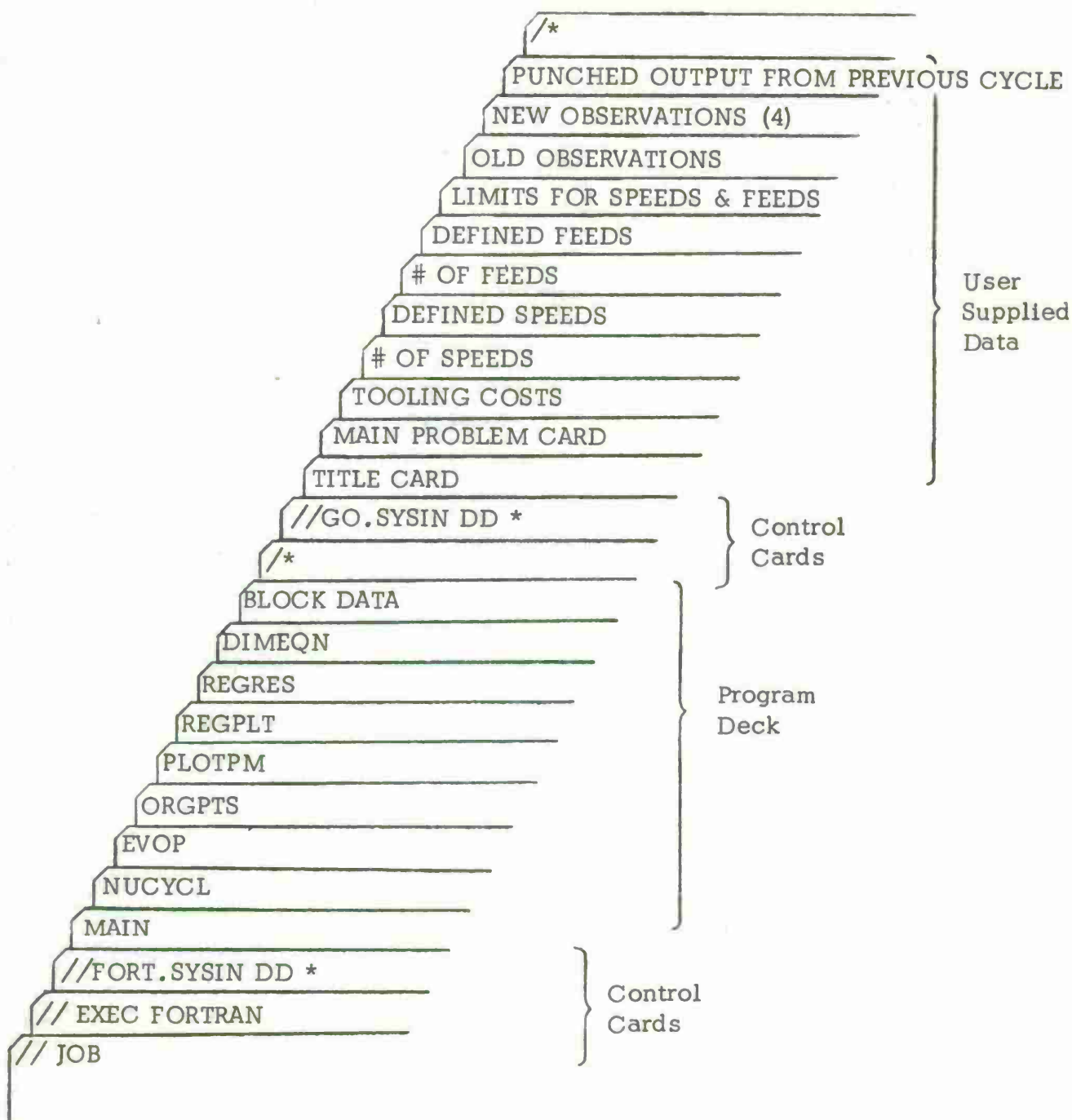
The MACHOP routine uses a building block approach to examine the response surface. The output from a cycle must be included in the input for the next cycle in order to evaluate correctly the new observations. If at any point in this process, output from the previous cycle is omitted from the input of a subsequent cycle, the results will be invalid.

The following restrictions apply to the MACHOP program:

1. The number of speeds defined for this operation must be less than or equal to 100.
2. The number of feeds defined for this operation must be less than or equal to 50.
3. Observations must be inputted in groups of four.
4. No constraints other than the limits on the speeds and feeds are taken into account by this program.

G.2 Input-Output Descriptions

G.2.1 Program Set-ups



MACHOP Deck Set-up

G.2.2 Input Formats

The input formats for the MACHOP program are given in Figure G.1. These include:

1. Title Card (20A4) (Required)

The Title Card consists of user supplied identification information punched in columns 1-80.

2. Main Problem Card (5I3, T21, 5F10.4) (Required)

<u>cc</u>	<u>Variable</u>	<u>Description</u>
1-3	IPH	Current Phase Number (Right justified)
4-6	ICYC	Current Cycle Number (Right justified)
7-9	IOP	Operation Type: IOP= 1: single operation (Right justified) 2: multiple operation 3: numerically controlled operation (N/C)
10-12	IMAX	1: If limits for speed and feed are specified (Right justified) 0: Otherwise
13-15	NTLC	Number of different tools (Right justified)
21-30	RLO	Rate for labor and overhead
31-40	AVES(COST)	Preliminary estimate of the standard deviation of the cost observations
41-50	AVES(P/R)	Preliminary estimate of the standard deviation of the production rate observations
51-60	BSP	Base speed for N/C operations (Must be present when IOP=3, cc 7-9)
61-70	BFD	Base feed for N/C operations (Must be present when IOP=3, cc 7-9)

3. Tool Cost Card (Required)

<u>cc</u>	<u>Variable</u>	<u>Description</u>
1-10	TLC (1)	Cost of a tool edge for tool no. 1
11-20	TLC (2)	Cost of a tool edge for tool no. 2
21-30	TLC (3)	...

Note: there must be exactly NTLC (cc. 13-15, M.P.C.) tool edge costs reported.

4. Speed Environment (I3/8F10.4) (Required)

Card 1: cc 1-3, NSPD, Number of speeds defined in the speed environment ($\text{NSPD} \leq 100$; Right justified)

*Cards 2, 3, ...: Defined speeds (rpm) for the environment in ascending order. (There must be exactly NSPD speeds inputted.)

5. Feed Environment (I3/8F10.4) (Required)

Card 1: cc 1-3, NFD, Number of feeds defined in the feed environment ($\text{NFD} \leq 50$; Right justified)

*Cards 2, 3, ...: Defined feeds (ipr) for the environment in ascending order. (There must be exactly NFD feeds inputted.)

6. Feed-Speed Limits (4F10.4) (Optional)

This card must be present if $\text{IMAX} = 1$, cc. 10-12 M.P.C.

<u>cc</u>	<u>Variable</u>	<u>Description</u>
1-10	S MAX	Maximum speed allowed for this operation
11-20	S MIN	Minimum speed allowed for this operation
21-30	F MAX	Maximum feed allowed for this operation
31-40	F MIN	Minimum feed allowed for this operation

*For N/C operations the speeds and feeds are the percentage overrides to be considered in this analysis (not fractional equivalents).

7. Observation Cards (8F10.4) (Required)

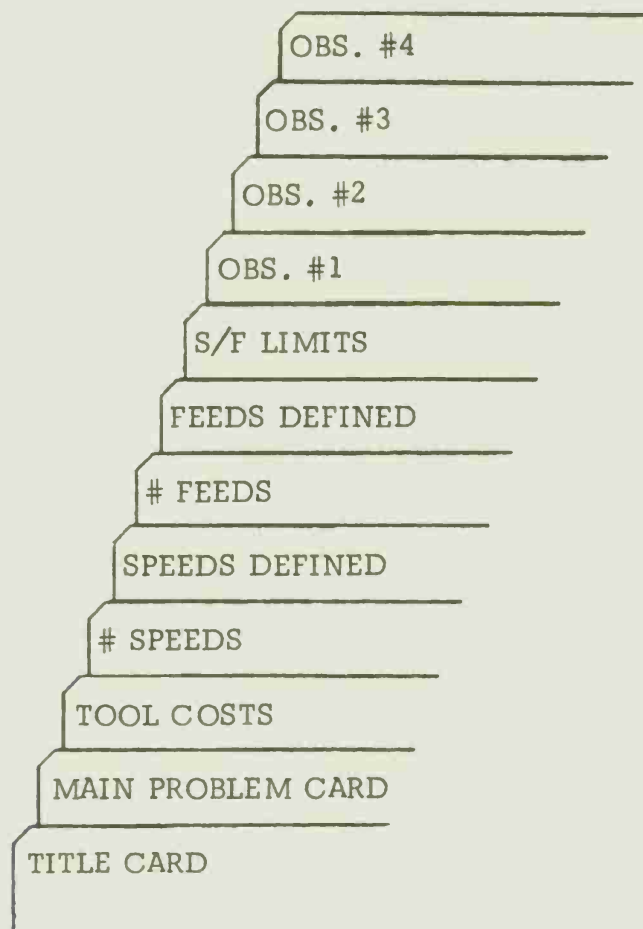
<u>cc</u>	<u>Variable</u>	<u>Description</u>
1-10	X(1,i)	Observed speed setting (rpm)
11-20	X(2,i)	Observed feed setting (ipr)
21-30	X(3,i)	Number of parts produced
31-40	X(4,i)	Time (in minutes) expended on this operation
41-50	X(5,i)	Number of tool edges for tool #1
51-60	X(6,i)	Number of tool edges for tool #2
61-70	X(7,i)	...

NOTE: Tool edges must be reported for exactly NTLC (cc. 13-15, M.P.C.) tools for each observation.

G.2.3 Input Requirements

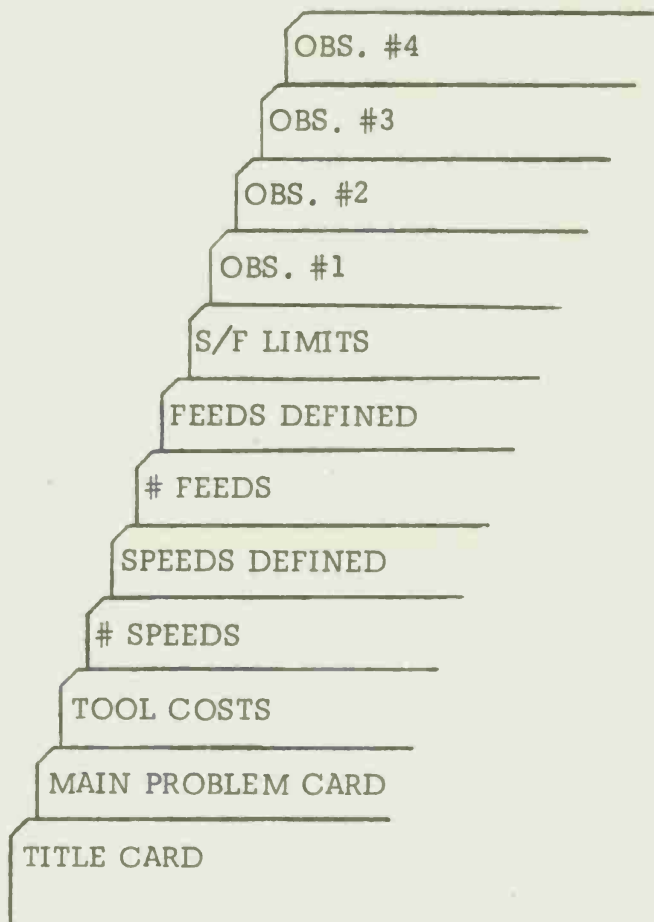
1. General input requirements for the use of the MACHOP routine are:
 - a. All variables indicated to be right justified are integer values and must not have decimal points punched.
 - b. All other values are real numbers and should have their decimal points punched.
 - c. Observations must be read in groups of four.
 - d. Phase and cycle numbers must be accurate. (Phase indicates which set of four points is being observed and cycle indicates the number of observations which have been taken at each point.)
 - e. Punched output from one cycle must be included in the input of the next cycle.
2. Specific input requirements for the MACHOP routine differ for each category of input. For clarity, sample deck set-ups are defined for each major situation.

- a. Case I: Initial phase and cycle with an estimate of the standard deviation.



1. Title Card (Required)
2. Main Problem Card (Required)
 - IPH = 1 (cc 1-3)
 - ICYC = 1 (cc 4-6)
 - IOP = 1,2,3 (cc 7-9)
 - IMAX (optional)
 - NTLC (cc 13-15)
 - RLO = Value (cc 21-30)
 - AVES (COST) = Standard Deviation Estimate (cc 31-40)
 - AVES (P/R) = Standard Deviation Estimate (cc 41-50)
3. Tool Costs (Required)
4. Speed Definitions (Required)
5. Feed Definitions (Required)
6. Speed and Feed Limits (Optional)
7. Observations (Exactly four (4) required)

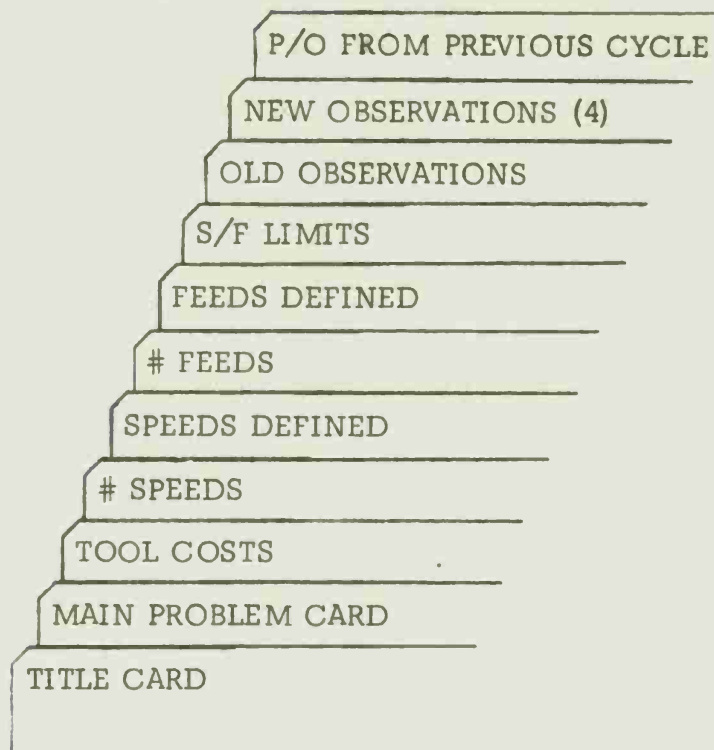
- b. Case II: Initial phase and cycle without an estimate of the standard deviation.*



1. Title Card (Required)
2. Main Problem Card (Required)
 - IPH = 1 (cc 1-3)
 - ICYC = 1 (cc 4-6)
 - IOP = 1,2,3 (cc 7-9)
 - IMAX (optional)
 - NTLC (cc 13-15)
 - RLO = value (cc 21-30)
3. Tool Costs (Required)
4. Speed Definitions (Required)
5. Feed Definitions (Required)
6. Speed and Feed Limits (Optional)
7. Observations (Exactly four (4) required)

*A limited output will result since no estimates of the standard deviation are available.

c. Case III: Non-initial cycle.



1. Title Card (Required)
2. Main Problem Card (Required)
 - IPH = Phase Number (cc 1-3)
 - ICYC = Cycle Number (cc 4-6)
 - (NOTE: IPH = 1 and ICYC = 1 not used)
 - IOP = 1, 2, 3 (cc 7-9)
 - IMAX (optional)
 - NTLC (cc 13-15)
 - RLO = value (cc 21-30)
3. Tool Costs (Required)
4. Speed Definitions (Required)
5. Feed Definitions (Required)
6. Speed and Feed Limits (Optional)
7. Old Observations (Required)
8. New Observations (Exactly four (4) required)
9. Punched Output from Previous Cycle (Required)*

*Note: After each cycle, the old punched output is discarded and is replaced by the new observations and new punched output.

Title Card	Identification of the Study																																																																															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Main Prob Card	IPH	ICVC	IGP	IMAX	NTLC	Not Used	RLO					AVES (cost)					AVES (P/R)					BSP					BFD					Not Used																																																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Tool Cost Card	Tool Change Cost #1					Tool Change Cost #2					Tool Change Cost #3					Tool Change Cost #4					Tool Change Cost #5					Tool Change Cost #6					Tool Change Cost #7					Tool Change Cost #8																																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Speed	NSPD	Not Used																																																																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Envi-ron-ment	Speed #1					Speed #2					Speed #3					Speed #4					Speed #5					Speed #6					Speed #7					Speed #8																																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Feed	NFD	Not Used																																																																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Envi-ron-ment	Feed #1					Feed #2					Feed #3					Feed #4					Feed #5					Feed #6					Feed #7					Feed #8																																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Speed & Feed Limits	MAX Speed					MIN Speed					MAX Feed					MIN Feed					Not Used																																																											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Observations	Speed					Feed					# Parts					Time					# Tools 1					# Tools 2					# Tools 3					# Tools 4																																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80

Figure G.1 MACHOP Input Formats

G.2.4 Output Description

Output from the MACHOP program generally consists of less than 2000 printed lines and five punched cards. The output is as follows:

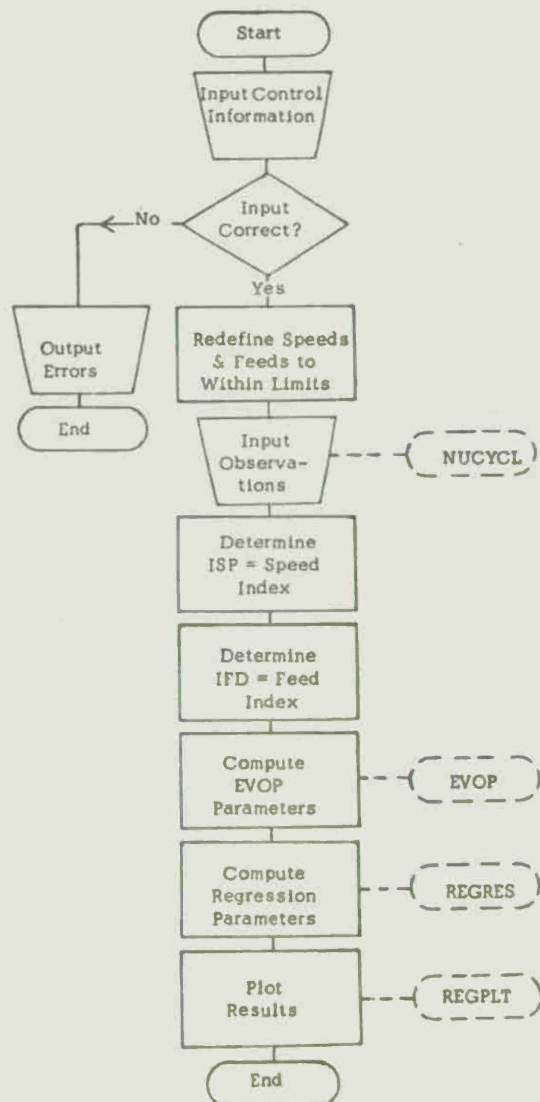
- a. Input information such as feed-speed limits, labor and overhead rates, tool costs, and prior estimates of standard deviations of the response variables (if any).
- b. The specified feed-speed environment represented "graphically."
- c. The cumulative input data and the computed responses (cost per piece and production rate).
- d. A table of the computed responses for this phase and cycle.
- e. Evolutionary operation calculations for both the cost per piece and production rate responses.
- f. A recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the cost per piece analysis.
- g. A graphical representation of the operating conditions recommended in f.
- h. The recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the production rate analysis.
- i. A graphical representation of the operating conditions recommended in h.
- j. The results of the regression analysis and the accompanying analysis of variance table for the cost per piece analysis.
- k. The results of the regression analysis and the accompanying analysis of variance table for the production rate analysis.
- l. The predicted response surfaces for cost/piece and production rate calculated from the respective prediction equations.

Optional output includes a listing of observations, the predicted values, the residuals, the matrices $X'X$ and $(X'X)^{-1}$, and the vector $X'y$.

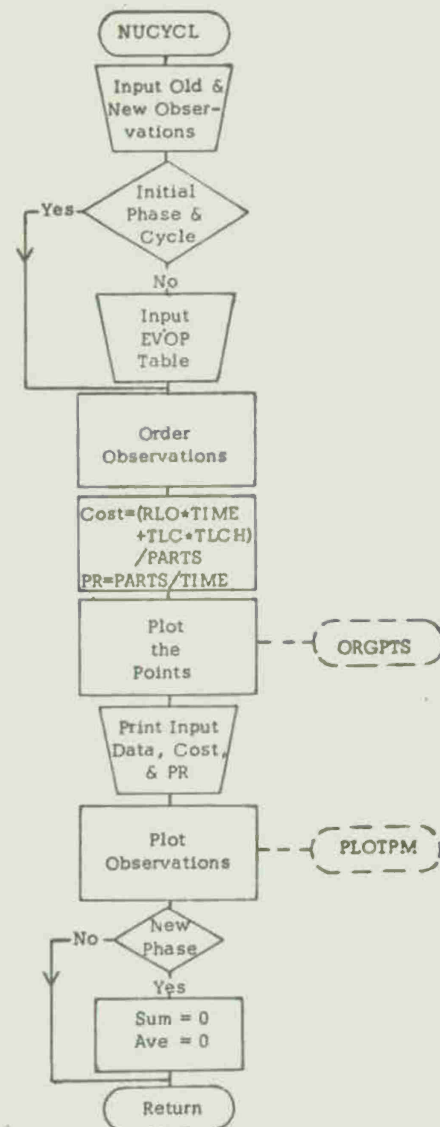
G.3 Systems Material

G.3.1 Flow Chart

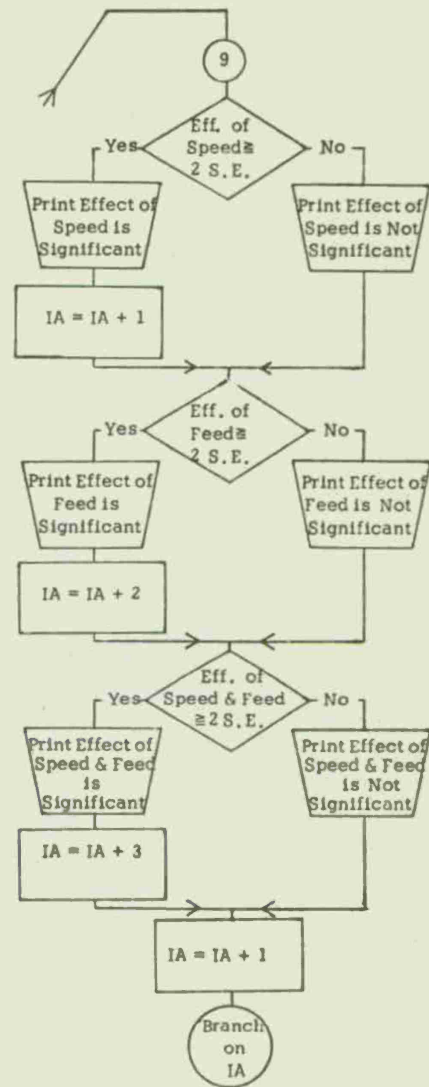
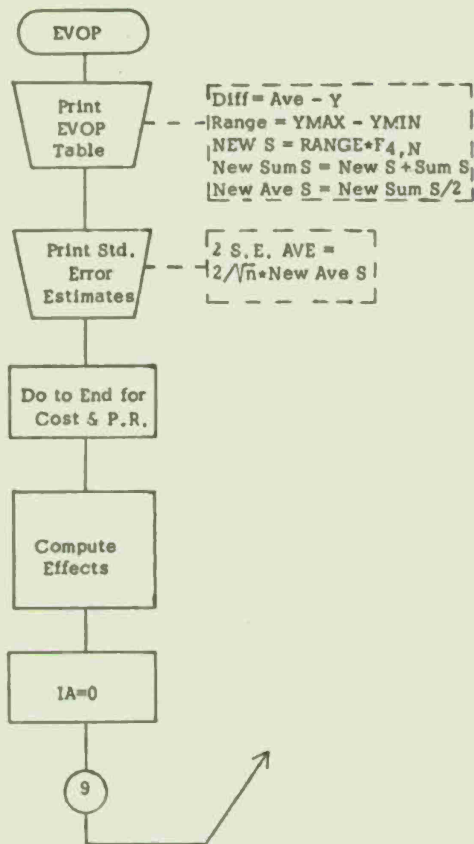
MAIN PROGRAM

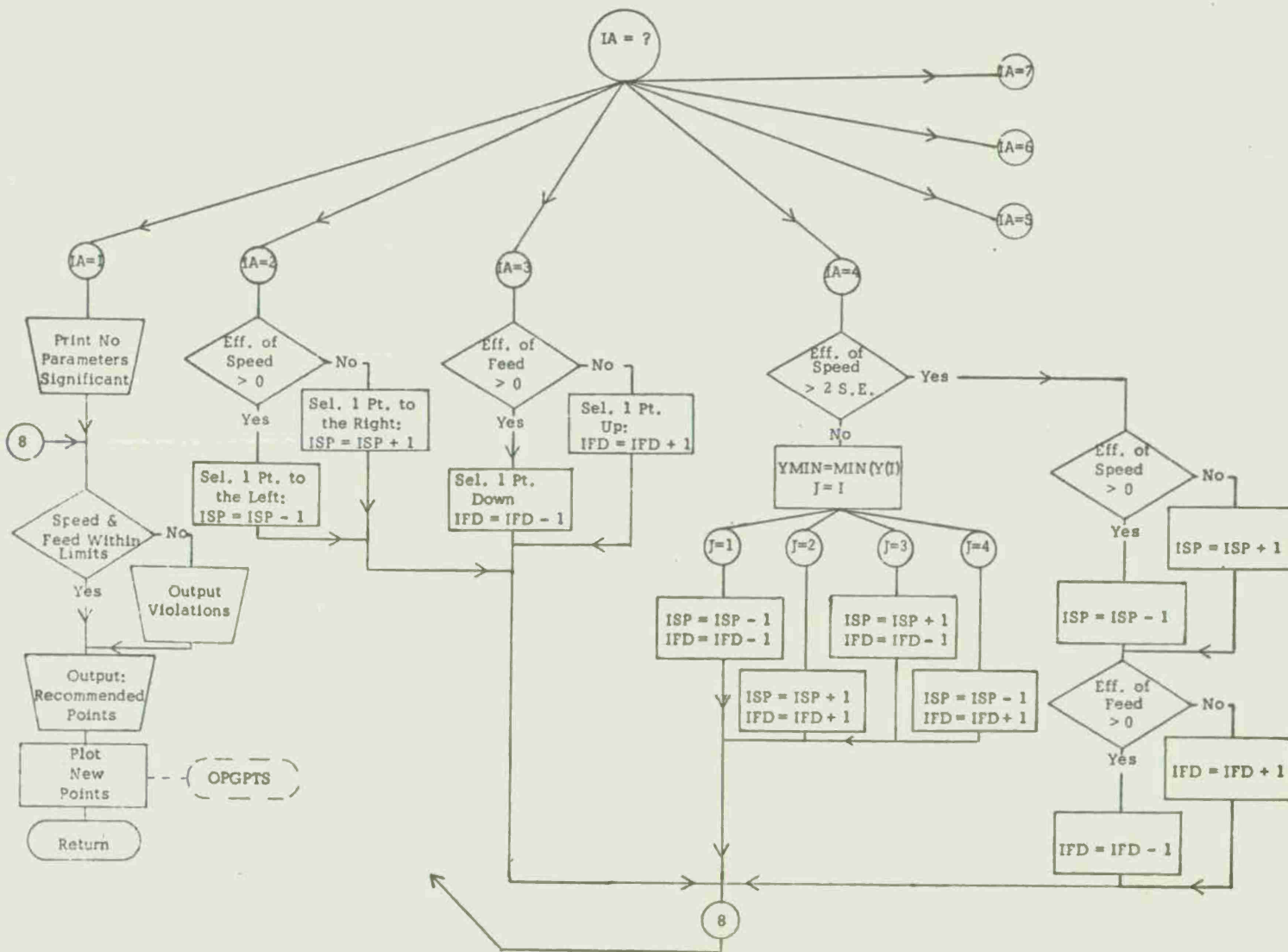


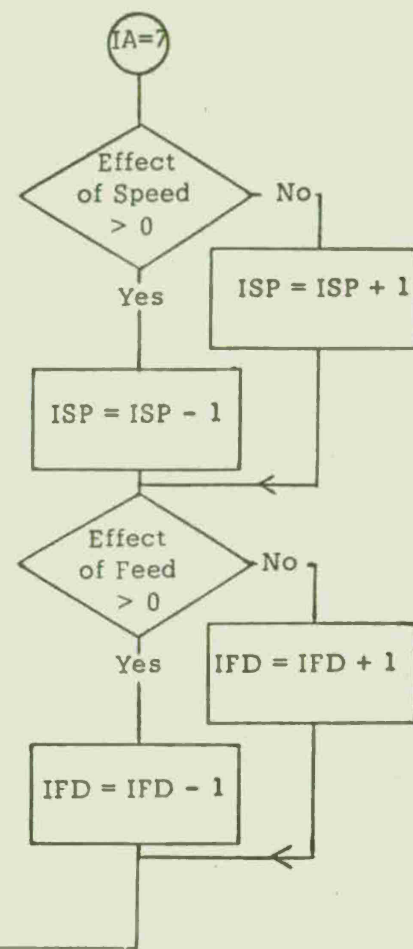
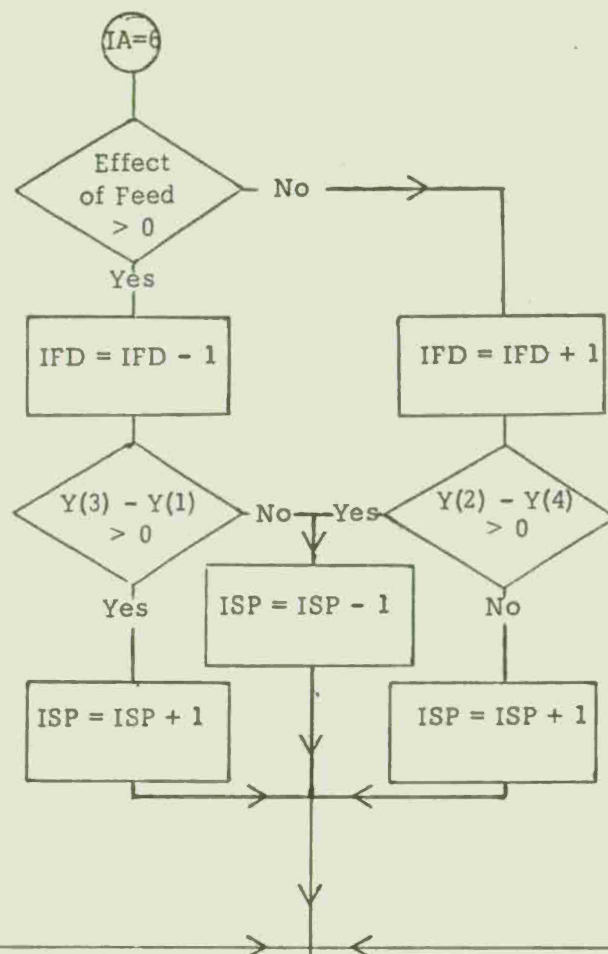
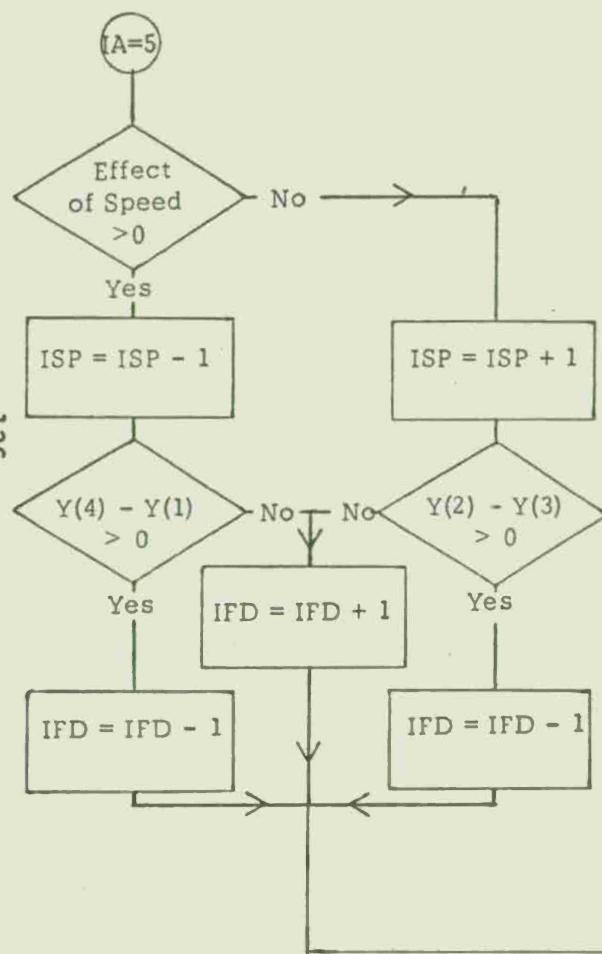
SUBROUTINE NUCYCL



SUBROUTINE EVOP



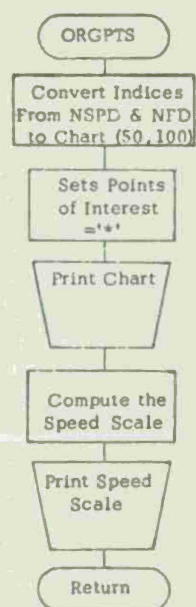




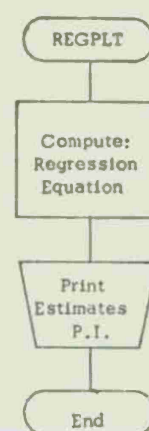
SUBROUTINE PLOTPM



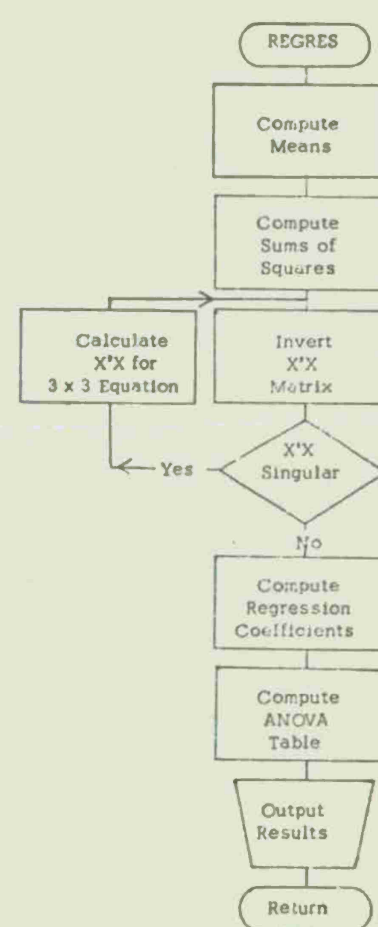
SUBROUTINE ORGPTS



SUBROUTINE REGPLT



SUBROUTINE REGRES



G.3.2 Glossary of Important Variables

<u>Variable Name</u>	<u>Description</u>
ANS	Vector of regression results returned from REGRES subroutine
AVE	Vector of the averages in the EVOP routine
AVES	Estimate of the standard error in the EVOP table
B	Vector of estimates of the b-coefficients in the regression equation
CHART	100 x 50 matrix containing the plot output in the ORGPTS routine
DIFF	Vector of the differences between the average cost at a given point and the newly observed cost
FEED	Vector containing all defined feed settings in ascending sequence
F4N	Vector of the values of $f_{4,n}$ as defined in Box and Draper [3]
ICYC	Cycle number
IFD	Index containing the current feed setting
IPH	Phase number
ISP	Index containing the current speed setting
NFD	Number of feed settings defined in the environment of this operation
NOBS	Number of observations in the current cycle
NSPD	Number of speed settings defined in the environment of this operation
RLO	Labor and overhead rate as reported on the main problem card

<u>Variable Name</u>	<u>Description</u>
SPEED	Vector of all defined speed settings in ascending sequence
SUM	Vector of the sums of the observations
SUMS	Sum of the estimates of the standard error of the observations
TLC	Tool edge cost
TLCH	Observed number of tool edges used
X	Matrix (5xn) of the input observations, both old and new. For observation n, $X(1,n)$ = speed (rpm), $X(2,n)$ = feed (ipr), $X(3,n)$ = number of parts produced, $X(4,n)$ = production time in minutes, and $X(5,n)$ = number of tool edges used.
Y	Matrix (2xn) of the performance indices, both old and new. For observation n, $Y(1,n)$ = cost (dollars/piece), and $Y(2,n)$ = production rate (pieces/minute).

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DEVELOPMENT AND ADAPTATION OF A CONTROL SYSTEM FOR
OPTIMIZATION OF SINGLE AND MULTIPLE OPERATION MACHINING,
by John S. Ramberg

Report R-CR-74-031, June 74, 146 p. Incl. illus. tables,
(Contract DAAF03-73-C-0110, AMS Code 3297.16.6779)
Unclassified report.

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This system is applicable to analysis and control of
single-operation as well as multiple-operations (numer-
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a computer program which provides an evolutionary oper-
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 11. Program
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AD _____ Accession No. _____
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