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

John S. Ramberg

JUNE 1974

FINAL REPORT

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Development and Adaptation of A Control System for Optimization of Single and Multiple Operation Machining

John S. Ramberg

Intertech Corporation
Iowa City, Iowa 52240

OMDR, Rock Island Arsenal
GEN Thomas J. Rodman Laboratory, SARRI-LR
Rock Island, Illinois 61201

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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.
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.

This work was authorized as part of the Manufacturing Methods and Technology Program of the U.S. Army Material Command, which is administered by the U.S. Army Production Equipment Agency.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD FORM 1473 (Document Control Data R&amp;D)</td>
<td>i</td>
</tr>
<tr>
<td>FOREWORD</td>
<td>iii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2. The Performance Index Method (PIM) Program</td>
<td>4</td>
</tr>
<tr>
<td>2.1 Recommendations on the Use of the PIM Program</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Program Logic Check</td>
<td>5</td>
</tr>
<tr>
<td>2.3 Program Testing with Simulated Data</td>
<td>7</td>
</tr>
<tr>
<td>2.3.1 The Simulation Model</td>
<td>7</td>
</tr>
<tr>
<td>2.3.2 Analysis of Simulation Data</td>
<td>8</td>
</tr>
<tr>
<td>2.4 Program Testing with Rock Island Arsenal (RIA) Data</td>
<td>14</td>
</tr>
<tr>
<td>3. The Machine Optimization (MACHOP) Program</td>
<td>18</td>
</tr>
<tr>
<td>3.1 Computation of Performance Indices</td>
<td>20</td>
</tr>
<tr>
<td>3.2 Evolutionary Operation (EVOP)</td>
<td>22</td>
</tr>
<tr>
<td>3.2.1 EVOP Calculations</td>
<td>22</td>
</tr>
<tr>
<td>3.2.2 Direction of Movement on the Response Surface</td>
<td>26</td>
</tr>
<tr>
<td>3.3 Response Surface and Regression Analysis</td>
<td>27</td>
</tr>
<tr>
<td>3.3.1 General Methodology</td>
<td>29</td>
</tr>
<tr>
<td>3.3.2 Illustration of Regression Calculations for Phase 1, Cycle 1</td>
<td>32</td>
</tr>
<tr>
<td>4. Use of MACHOP</td>
<td>34</td>
</tr>
<tr>
<td>4.1 Collecting Data for MACHOP</td>
<td>34</td>
</tr>
<tr>
<td>4.2 Analysis of the MACHOP Output</td>
<td>35</td>
</tr>
<tr>
<td>4.3 Scope of Application</td>
<td>36</td>
</tr>
<tr>
<td>4.4 Data Handling System</td>
<td>37</td>
</tr>
<tr>
<td>5. MACHOP Analysis of RIA Data</td>
<td>38</td>
</tr>
<tr>
<td>6. Summary</td>
<td>76</td>
</tr>
<tr>
<td>7. Recommendations</td>
<td>76</td>
</tr>
<tr>
<td>Bibliography</td>
<td>77</td>
</tr>
<tr>
<td>Appendices</td>
<td></td>
</tr>
<tr>
<td>A. Verification of the Regression Modules of the PIM and MACHOP Programs</td>
<td>79</td>
</tr>
<tr>
<td>B. Simulation Program</td>
<td>81</td>
</tr>
<tr>
<td>C. Data Collection Forms</td>
<td>86</td>
</tr>
<tr>
<td>D. Analysis of the PIM Design Module</td>
<td>89</td>
</tr>
<tr>
<td>E. Carboly Systems Computerized Machinability Program</td>
<td>90</td>
</tr>
<tr>
<td>F. MACHOP Listing</td>
<td>92</td>
</tr>
<tr>
<td>G. MACHOP Program Documentation</td>
<td>121</td>
</tr>
<tr>
<td>Distribution</td>
<td>140</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Process Characteristics Which Are Favorable or Unfavorable to the Use of EVOP.</td>
</tr>
<tr>
<td>2.1</td>
<td>First Data Set.</td>
</tr>
<tr>
<td>2.2</td>
<td>Second Data Set</td>
</tr>
<tr>
<td>2.3</td>
<td>Third Data Set</td>
</tr>
<tr>
<td>2.4</td>
<td>Cost/Piece ($) as Given by Taylor’s Equation</td>
</tr>
<tr>
<td>2.5</td>
<td>Job Description for First Study</td>
</tr>
<tr>
<td>2.6</td>
<td>Data Summary for Experiment 1 Results for Recoil Cylinder - First Study</td>
</tr>
<tr>
<td>2.7</td>
<td>Cost/Piece Predictions ($) Using the PIM Program</td>
</tr>
<tr>
<td>3.1</td>
<td>Decision Table for Minimization of Cost</td>
</tr>
<tr>
<td>3.2</td>
<td>Analysis of Variance (ANOVA)</td>
</tr>
<tr>
<td>5.1</td>
<td>Summary of RIA Data.</td>
</tr>
</tbody>
</table>

# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Points Selected by Design Module</td>
</tr>
<tr>
<td>2.2</td>
<td>Simulation Flow Chart</td>
</tr>
<tr>
<td>2.3</td>
<td>Design Points for the PIM Method</td>
</tr>
<tr>
<td>2.4</td>
<td>Cost/Piece Estimates ($) at Observed Feeds and Speeds</td>
</tr>
<tr>
<td>3.1</td>
<td>Evolutionary Operation</td>
</tr>
<tr>
<td>3.2</td>
<td>Selection of the Regression Equation</td>
</tr>
<tr>
<td>5.1</td>
<td>MACHOP Output for Phase 1, Cycle 1</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>5.2</td>
<td>MACHOP Output for Phase 2, Cycle 1</td>
</tr>
<tr>
<td>5.3</td>
<td>MACHOP Output for Phase 2, Cycle 2</td>
</tr>
<tr>
<td>A.1</td>
<td>Sample Stepwise Regression Output</td>
</tr>
<tr>
<td>C.1</td>
<td>Single Tool Machine Optimization Study Form</td>
</tr>
<tr>
<td>C.2</td>
<td>Multiple Tool Machine Optimization Study Form</td>
</tr>
<tr>
<td>E.1</td>
<td>Sample Carboloy Computerized Machinability Program Output</td>
</tr>
<tr>
<td>G.1</td>
<td>MACHOP Input Formats</td>
</tr>
</tbody>
</table>
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 expediently.

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]

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

---

\(^1\)U.S. Army Weapons Command, now U.S. Army Armament Command.

\(^2\)Section 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 DAADF01-70-C-106a [10] as:

\[ \text{PI} = Q \cdot \text{Pr} + \frac{(1 - Q)}{\text{Cu}}. \]

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

\[ \text{PI} = (1 - Q) \cdot \text{Pr} + \frac{Q}{\text{Cu}}. \]

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](image-url)
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. 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

   \[ V \tau_f \beta = C, \]

   where \( \alpha, \beta, \) and \( C \) are constants,

   \[ V = \frac{\pi DN}{12}, \]

   \( D = \) Diameter of work piece in inches,

   \( N = \) spindle speed in rpm,

   \(^1\)The 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, \(\epsilon\), is added to the above equation to introduce variability into the tool life. The error term, \(\epsilon\), 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 \(\text{ERR}\) 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.
Initialize SHIFT, diameter of work piece (D), length of work piece (XL), Taylor's tool life constants, handling time (TH), tool changing time (TCT). PARTS = 0, TIME = 0, TOOLS = 0

Generate tool life (T)

Calculate the matching time/piece
(TM = XL/VF)

Calculate the no. of parts produced by this tool
PARTS1 = T/TM

Calculate the total time for each tool
TIME1 = PARTS1(TM + TH) + TCT

PARTS = PARTS + PARTS1
TIME = TIME + TIME1
TOOLS = TOOLS + 1

No
TIME ≤ SHIFT

Yes
Summarize Results

Figure 2.2 Simulation Flow Chart
### Table 2.1 First Data Set

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

### Table 2.2 Second Data Set

<table>
<thead>
<tr>
<th>Speed</th>
<th>Feed</th>
<th>No. of parts</th>
<th>Time</th>
<th>No. of edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>166</td>
<td>0.0337</td>
<td>17.0</td>
<td>420.0</td>
<td>9.0</td>
</tr>
<tr>
<td>220</td>
<td>0.0337</td>
<td>19.0</td>
<td>420.0</td>
<td>17.0</td>
</tr>
<tr>
<td>290</td>
<td>0.0337</td>
<td>19.0</td>
<td>420.0</td>
<td>45.0</td>
</tr>
<tr>
<td>330</td>
<td>0.0337</td>
<td>18.0</td>
<td>420.0</td>
<td>64.0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Feed (lpr)</th>
<th>No. of parts</th>
<th>Time (s)</th>
<th>No. of edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>0.0337</td>
<td>16</td>
<td>420.0</td>
<td>6.0</td>
</tr>
<tr>
<td>166</td>
<td>0.0337</td>
<td>18</td>
<td>420.0</td>
<td>2.0</td>
</tr>
<tr>
<td>220</td>
<td>0.0337</td>
<td>18</td>
<td>420.0</td>
<td>22.0</td>
</tr>
<tr>
<td>290</td>
<td>0.0337</td>
<td>19</td>
<td>420.0</td>
<td>46.0</td>
</tr>
<tr>
<td>330</td>
<td>0.0337</td>
<td>18</td>
<td>420.0</td>
<td>63.0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Feed (lpr)</th>
<th>145</th>
<th>166</th>
<th>192</th>
<th>220</th>
<th>255</th>
<th>290</th>
<th>330</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0153</td>
<td>11.76</td>
<td>10.89</td>
<td>10.24</td>
<td>10.47</td>
<td>10.05</td>
<td>10.44</td>
<td>10.95</td>
</tr>
<tr>
<td>0.0168</td>
<td>10.78</td>
<td>10.05</td>
<td>10.24</td>
<td>9.72</td>
<td>9.38</td>
<td>9.74</td>
<td>10.22</td>
</tr>
<tr>
<td>0.0187</td>
<td>10.78</td>
<td>10.08</td>
<td>9.51</td>
<td>9.07</td>
<td>9.38</td>
<td>9.74</td>
<td>10.22</td>
</tr>
<tr>
<td>0.0210</td>
<td>9.95</td>
<td>9.36</td>
<td>8.88</td>
<td>9.10</td>
<td>8.79</td>
<td>9.14</td>
<td>9.58</td>
</tr>
<tr>
<td>0.0240</td>
<td>9.24</td>
<td>8.74</td>
<td>8.35</td>
<td>8.53</td>
<td>8.30</td>
<td>8.60</td>
<td>9.02</td>
</tr>
<tr>
<td>0.0337</td>
<td>8.11</td>
<td>7.71</td>
<td>7.42</td>
<td>7.58</td>
<td>7.41</td>
<td>7.67</td>
<td>8.47</td>
</tr>
</tbody>
</table>
The circled numbers indicate the experiment number, i.e., 1 indicates that this point is in the 1\textsuperscript{st} experiment.
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

<table>
<thead>
<tr>
<th>Operation:</th>
<th>Turning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part:</td>
<td>Variable recoil cylinder</td>
</tr>
<tr>
<td>Material:</td>
<td>Steel tube 4140.</td>
</tr>
<tr>
<td>Dimensions:</td>
<td>47.5&quot; long, 8.5&quot; dia., depth of cut 1/8&quot;</td>
</tr>
<tr>
<td>Job order #:</td>
<td>0016011</td>
</tr>
<tr>
<td>Part #:</td>
<td>10895646</td>
</tr>
<tr>
<td>Cutting tool:</td>
<td>Titanium coated carbide insert, multi-edged</td>
</tr>
<tr>
<td>Tool cost/edge:</td>
<td>$0.42</td>
</tr>
<tr>
<td>Machine tool specifications:</td>
<td>Monarch stepped lathe. 50 HP. RIA ID #30303</td>
</tr>
<tr>
<td>Available speeds (in rpm):</td>
<td>84, 95, 110, 126, 145, 166, 192, 220, 255, 290, 330, 380, 435</td>
</tr>
<tr>
<td>Available feeds (in ipr):</td>
<td>0.0032, 0.0035, 0.0037, 0.0038, 0.0042, 0.0047, 0.0047, 0.0013, 0.0060, 0.0065, 0.0070, 0.0073, 0.0076, 0.0084, 0.0093, 0.0105, 0.0120, 0.0129, 0.0140, 0.0146, 0.0153, 0.0168, 0.0187, 0.0210, 0.0240, 0.0259, 0.0293, 0.0306, 0.0337, 0.0374, 0.0421, 0.0451, 0.0518, 0.0561, 0.0585, 0.0612, 0.0673, 0.0748, 0.0841, 0.0962, 0.1036, 0.1122, 0.1171, 0.1224, 0.1346, 0.1496, 0.1683.</td>
</tr>
<tr>
<td>Labor and overhead rate:</td>
<td>$18/hr.</td>
</tr>
</tbody>
</table>
A $3^2$ factorial experiment\(^1\) 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 $\text{PI} = b_0 + b_1V + b_2F + b_3V^2 + b_4F^2 + b_5V \cdot F$ to the data. (See Ham [10] for a more complete discussion.) The performance index is evaluated at all usable feed-speed combinations.

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

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

---

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

\(^2\)The reciprocal of $Cu$, the cost per piece, in $$/piece.
The feed-speed combination selected as optimal was $V = 95 \text{ rpm}$ and $F = 0.0187 \text{ ipr}$. At this combination the performance index prediction is $PI = 0.212$ and hence the cost estimate is $Cu = \$4.72/\text{piece}$. However, a few calculations illustrate that the predicted cost cannot be achieved at this feed and speed.

The machining time per piece is $47.5/(95 \times 0.0240) = 20.8 \text{ min/piece}$. Allowing nine min/piece handling and no time for tool change we arrive at a total time of $29.8 \text{ min/piece}$. Using the labor plus overhead rate of $\$18/\text{hr}$ and neglecting the tool costs, we obtain a conservative estimate of cost per piece of $\$9.00/\text{piece}$. 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>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>95</th>
<th>145</th>
<th>166</th>
<th>192</th>
<th>220</th>
<th>255</th>
<th>290</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed (ipr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0153</td>
<td>14.59</td>
<td>14.04</td>
<td>12.75</td>
<td>10.97</td>
<td>8.75</td>
<td>6.88</td>
<td></td>
</tr>
<tr>
<td>0.0168</td>
<td>8.67</td>
<td>9.81</td>
<td>9.90</td>
<td>9.66</td>
<td>9.01</td>
<td>7.87</td>
<td>6.61</td>
</tr>
<tr>
<td>0.0187</td>
<td>6.24</td>
<td>7.46</td>
<td>7.84</td>
<td>8.10</td>
<td>8.09</td>
<td>7.65</td>
<td>6.85</td>
</tr>
<tr>
<td>0.0210</td>
<td>5.10</td>
<td>6.49</td>
<td>7.08</td>
<td>7.76</td>
<td>8.32</td>
<td>8.59</td>
<td>8.19</td>
</tr>
<tr>
<td>0.0240</td>
<td>4.72 (^1)</td>
<td>6.69</td>
<td>7.82</td>
<td>9.53</td>
<td>11.71</td>
<td>14.98</td>
<td>16.62</td>
</tr>
</tbody>
</table>

\(^1\) 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. 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.

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 \((\text{Cu})\) in dollars/piece, and
2. the production rate \((\text{Pr})\) 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.

---

\(^1\)Actual cutting, work piece handling and tool changing time.

\(^2\)A 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

\[
\text{Cu} = \text{Cost per piece ($/piece), and}
\]

\[
\text{Pr} = \text{Production rate (pieces/minute).}
\]
These quantities are calculated for each of the test points.

For a given test point the following data are collected:

\[ N_p = \text{Number of parts produced}, \]
\[ N_{ti} = \text{Number of tool edges of tool } i \text{ used, and} \]
\[ T = \text{Time period of test (in minutes)}. \]

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

\[ Pr = \frac{N_p}{T}. \]

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

\[ Cu = \left[ \frac{(RLO)T + (TLC)N_t}{N_p} \right]/N_p \]

where

\[ RLO = \text{Labor and overhead rate in dollars per minute, and} \]
\[ TLC = \text{Tool cost in dollars per edge}. \]

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

\[ Cu = \left[ \frac{(RLO)T + \sum_{i=1}^{n} (TLC_i)N_{ti}}{N} \right]/N \]

where

\[ n = \text{Number of different tools, and} \]
\[ TLC_i = \text{Cost of tool } i \text{ in dollars per edge}. \]

\[ N_{ti} \text{ is shortened to } N_t. \]
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]. 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 accommodate 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

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

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

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

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

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

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

\[
\text{SPEED-FEED (INTERACTION) EFFECT} = \frac{1}{2} \left( (\bar{y}_1 + \bar{y}_2) - (\bar{y}_3 + \bar{y}_4) \right) = \frac{1}{2} \left( \bar{y}_1 + \bar{y}_2 - \bar{y}_3 - \bar{y}_4 \right).
\]
(2² Factorial)

PHASE =

CYCLE(n) =

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Previous cycle sum</td>
<td>PCS₁</td>
<td>PCS₂</td>
<td>PCS₃</td>
<td>PCS₄</td>
</tr>
<tr>
<td>(ii) Previous cycle average</td>
<td>$\bar{y}_1'$</td>
<td>$\bar{y}_2'$</td>
<td>$\bar{y}_3'$</td>
<td>$\bar{y}_4'$</td>
</tr>
<tr>
<td>(iii) New observations</td>
<td>$y_{1n}$</td>
<td>$y_{2n}$</td>
<td>$y_{3n}$</td>
<td>$y_{4n}$</td>
</tr>
<tr>
<td>(iv) Differences (ii) less (iii)</td>
<td>$d_1$</td>
<td>$d_2$</td>
<td>$d_3$</td>
<td>$d_4$</td>
</tr>
<tr>
<td>(v) New sums</td>
<td>NS₁</td>
<td>NS₂</td>
<td>NS₃</td>
<td>NS₄</td>
</tr>
<tr>
<td>(vi) New averages:</td>
<td>$\overline{y}_1$</td>
<td>$\overline{y}_2$</td>
<td>$\overline{y}_3$</td>
<td>$\overline{y}_4$</td>
</tr>
</tbody>
</table>

Calculation of Averages

Calculation of Standard Deviation

Previous average $S =$

New $S = \text{range} \times f_{4,n} =$

Range$=\text{MAX}[d_i]-\text{MIN}[d_i] =$

New sum $S=S'+\text{New } S =$

New average $S =$

New sum $S/2 =$

Calculation of Effects

SPEED effect $= \frac{1}{2} ( \overline{y}_2 + \overline{y}_3 - \overline{y}_1 - \overline{y}_4 ) =$

FEED effect $= \frac{1}{2} ( \overline{y}_2 + \overline{y}_4 - \overline{y}_1 - \overline{y}_3 ) =$

SPEED-FEED effect $= \frac{1}{2} ( \overline{y}_1 + \overline{y}_2 - \overline{y}_3 - \overline{y}_4 ) =$

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{4,n}$</td>
<td>0</td>
<td>0.34</td>
<td>0.40</td>
<td>0.42</td>
<td>0.43</td>
<td>0.44</td>
<td>0.45</td>
<td>0.45</td>
<td>0.46</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Calculation of 2 S.E. Limits

For new effects:

$\pm \frac{2}{\sqrt{n}} S =$

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:

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

where $\text{Range} = \left[ \text{MAX}(d_i) - \text{MIN}(d_i) \right]$. 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:

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

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.

---

1 The 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.,

   \[ |\text{EFFECT}| \geq 2SE \]
   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.,

   \[ |\text{EFFECT}| < 2SE, \]
   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 \( Cu \) 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:

\[
\begin{align*}
(3.1) \quad y &= b_0 + b_1 \ln V + b_2 \ln F \\
(3.2) \quad y &= b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F \\
(3.3) \quad y &= b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln V)^2 \\
(3.4) \quad y &= b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln F)^2 \\
(3.5) \quad y &= b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln V)^2 + b_5 (\ln F)^2 
\end{align*}
\]
<table>
<thead>
<tr>
<th>Speed(V)</th>
<th>Feed(F)</th>
<th>Interaction (VxF)</th>
<th>Reobserve same settings</th>
<th>Inc. Speed</th>
<th>Decr. Speed</th>
<th>Inc. Feed</th>
<th>Decr. Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>P</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>P</td>
<td>If $\bar{y}_1$ is min., decr. speed and feed;</td>
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</tr>
<tr>
<td>0</td>
<td>0</td>
<td>N</td>
<td>If $\bar{y}_2$ is min., incr. speed and feed;</td>
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<td>P</td>
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<tr>
<td>P</td>
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<td>P</td>
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<tr>
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<td>P</td>
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</tr>
</tbody>
</table>

*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:

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

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

Given the set of observations:

\[
x_{11} \quad x_{21} \ldots x_{m1} \quad y_1 \\
x_{12} \quad x_{22} \ldots x_{m2} \quad y_2 \\
\vdots \quad \vdots \quad \ldots \quad \vdots \\
x_{1n} \quad x_{2n} \ldots x_{mn} \quad y_n
\]

the \( X \) matrix is defined as

\[
X = \begin{bmatrix}
(x_{11} - \bar{x}_1) & (x_{21} - \bar{x}_2) & \ldots & (x_{m1} - \bar{x}_m) \\
(x_{12} - \bar{x}_1) & (x_{22} - \bar{x}_2) & \ldots & (x_{m2} - \bar{x}_m) \\
\vdots & \vdots & \ddots & \vdots \\
(x_{1n} - \bar{x}_1) & (x_{2n} - \bar{x}_2) & \ldots & (x_{mn} - \bar{x}_m)
\end{bmatrix}
\]

where

\[
\bar{x}_i = \frac{\sum_{j=1}^{n} x_{ij}}{n}
\]
Selection of the Regression Equation

Figure 3.2
The \( \mathbf{b} \) vector contains the unknown coefficients

\[
\mathbf{b} = \begin{bmatrix}
  b_1 \\
  b_2 \\
  \vdots \\
  b_m
\end{bmatrix}
\]

and the \( \mathbf{y} \) vector is calculated from the dependent variable observations by

\[
\mathbf{y} = \begin{bmatrix}
  (y_1 - \bar{y}) \\
  (y_2 - \bar{y}) \\
  \vdots \\
  (y_n - \bar{y})
\end{bmatrix}
\]

where

\[
\bar{y} = \frac{\sum_{j=1}^{n} y_j}{n}.
\]

The least squares estimates of the unknown coefficients are

\[
\hat{\mathbf{b}} = (X'X)^{-1}X'y,
\]

and the resulting prediction equation is

\[
y = \bar{y} + b_1(x_1 - \bar{x}_1) + \ldots + b_m(x_m - \bar{x}_m).
\]

The analysis of variance table is given in Table 3.2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>( F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>( n - 1 )</td>
<td>( \mathbf{y}'\mathbf{y} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>( m )</td>
<td>( \mathbf{b}'(X'y) )</td>
<td>( \frac{\mathbf{b}'(X'y)}{m} )</td>
<td>( \frac{\mathbf{b}'(X'y)(n-1-m)}{m[\mathbf{y}'\mathbf{y}-\mathbf{b}'(X'y)]} )</td>
</tr>
<tr>
<td>Residual</td>
<td>( n - 1 - m )</td>
<td>( \mathbf{y}'\mathbf{y}-\mathbf{b}'(X'y) )</td>
<td>( \frac{\mathbf{y}'\mathbf{y}-\mathbf{b}'(X'y)}{n-1-m} )</td>
<td></td>
</tr>
</tbody>
</table>

31
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 $\alpha$ is the significance level for the test.

The ratio $(\text{regression sum of squares})/(\text{total sum of squares})$, 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 $b_1 = b_2 = \ldots = b_m = 0$. The variance, $\sigma^2$, 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 ($m = 2, n = 4$):

$$
\begin{array}{cccccc}
V_1 & F_1 & NPT_1 & NTC_1 & NT_1 \\
V_2 & F_2 & NPT_2 & NTC_2 & NT_2 \\
V_3 & F_3 & NPT_3 & NTC_3 & NT_3 \\
V_4 & F_4 & NPT_4 & NTC_4 & NT_4 \\
\end{array}
$$

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

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

where $\bar{\ln}$ denotes the averages of the logarithms.
The $\mathbf{b}$ vector is

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

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

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

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

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

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:

<table>
<thead>
<tr>
<th>Feed (ipr)</th>
<th>0.0210</th>
<th>0.0240</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (rpm)</td>
<td>192</td>
<td>220</td>
</tr>
</tbody>
</table>

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. 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 - 5.1t. 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 5.1r) 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 - 5.2t. 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 - 5.3t. 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 5.3t) 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:

<table>
<thead>
<tr>
<th>Speed</th>
<th>Feed</th>
<th>Speed</th>
<th>Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>166</td>
<td>0.0210</td>
<td>166</td>
<td>0.0240</td>
</tr>
<tr>
<td>166</td>
<td>0.0240</td>
<td>or</td>
<td>166</td>
</tr>
<tr>
<td>192</td>
<td>0.0210</td>
<td>192</td>
<td>0.0240</td>
</tr>
<tr>
<td>192</td>
<td>0.0240</td>
<td></td>
<td>192</td>
</tr>
</tbody>
</table>

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 5.3t 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

<table>
<thead>
<tr>
<th>Date</th>
<th>Speed</th>
<th>Feed</th>
<th>No. of Parts</th>
<th>Time</th>
<th>No. of Tool Edges</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 6/12/73</td>
<td>192</td>
<td>0.0187</td>
<td>18</td>
<td>410</td>
<td>18</td>
<td>None</td>
</tr>
<tr>
<td>2) 6/13/73</td>
<td>220</td>
<td>0.0210</td>
<td>20</td>
<td>440</td>
<td>44</td>
<td>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.</td>
</tr>
<tr>
<td>3) 6/27/73</td>
<td>255</td>
<td>0.0187</td>
<td>11</td>
<td>267</td>
<td>29</td>
<td>None</td>
</tr>
<tr>
<td>4) 6/28/73</td>
<td>192</td>
<td>0.0210</td>
<td>14</td>
<td>377</td>
<td>18</td>
<td>Chips are still too tight. Tips of inserts are chipping at times depending on out of round condition of piece. Good chips. Finish real good considering the condition of the pieces.</td>
</tr>
<tr>
<td>5) 6/29/73</td>
<td>220</td>
<td>0.0189</td>
<td>15</td>
<td>393</td>
<td>15</td>
<td>None</td>
</tr>
<tr>
<td>6) 7/5/73</td>
<td>192</td>
<td>0.0168</td>
<td>14</td>
<td>434</td>
<td>17</td>
<td>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.</td>
</tr>
<tr>
<td>7) 7/10/73</td>
<td>220</td>
<td>0.0168</td>
<td>13</td>
<td>396</td>
<td>23</td>
<td>None</td>
</tr>
<tr>
<td>8) 7/17/73</td>
<td>255</td>
<td>0.0168</td>
<td>10</td>
<td>217</td>
<td>17</td>
<td>Inserts break down about 1/4 way across cut. Finish is horrible.</td>
</tr>
<tr>
<td>9) 7/18/73</td>
<td>255</td>
<td>0.0210</td>
<td>14</td>
<td>357</td>
<td>31</td>
<td>None</td>
</tr>
<tr>
<td>10) 8/3/73</td>
<td>192</td>
<td>0.0187</td>
<td>14</td>
<td>374</td>
<td>16</td>
<td>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.)</td>
</tr>
<tr>
<td>11) 8/6/73</td>
<td>220</td>
<td>0.0187</td>
<td>15</td>
<td>394</td>
<td>17</td>
<td>None</td>
</tr>
<tr>
<td>12) 8/7/73</td>
<td>220</td>
<td>0.0187</td>
<td>9</td>
<td>220</td>
<td>15</td>
<td>None</td>
</tr>
<tr>
<td>13) 8/16/73</td>
<td>192</td>
<td>0.0187</td>
<td>8</td>
<td>214</td>
<td>16</td>
<td>None</td>
</tr>
<tr>
<td>14) 8/17/73</td>
<td>220</td>
<td>0.0187</td>
<td>13</td>
<td>381</td>
<td>20</td>
<td>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.</td>
</tr>
</tbody>
</table>
MACHOP

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

Figure 5.1 MACHOP Output for Phase 1, Cycle 1
Figure 5.1 (continued)
## Input Values and Computed Responses

<table>
<thead>
<tr>
<th>Speed</th>
<th>Feed</th>
<th>Parts</th>
<th>Time</th>
<th>Tool-Edges</th>
<th>Cost</th>
<th>Prod Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>192</td>
<td>0.0168</td>
<td>14</td>
<td>434</td>
<td>(1) (2)</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.0187</td>
<td>15</td>
<td>393</td>
<td>(3) (4)</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.0168</td>
<td>13</td>
<td>356</td>
<td>(5) (6)</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>0.0187</td>
<td>18</td>
<td>410</td>
<td>(7) (8)</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

Cost ($/Piece): 9.31, 8.28, 9.88, 7.25
Prod Rate (Pieces/Min): 0.0323, 0.0382, 0.0328, 0.0439

---

Figure 5.1 (continued)
<table>
<thead>
<tr>
<th>FEED (IPR)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0187</td>
<td>COST = 7.25</td>
<td>COST = 8.28</td>
</tr>
<tr>
<td></td>
<td>PROD. RT. = 0.0439</td>
<td>PROD. PT. = 0.0382</td>
</tr>
<tr>
<td>0.0168</td>
<td>COST = 9.81</td>
<td>COST = 9.88</td>
</tr>
<tr>
<td></td>
<td>PROD. RT. = 0.0323</td>
<td>PROD. PT. = 0.0328</td>
</tr>
</tbody>
</table>

**Figure 5.1 (continued)**
## Evolutionary Operation Analysis
### Phase I Cycle 1

#### Calculation of Averages

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>Cost</th>
<th>Production Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEED (KPM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>192.</td>
<td>192.</td>
<td></td>
</tr>
<tr>
<td>220.</td>
<td>220.</td>
<td></td>
</tr>
<tr>
<td>220.</td>
<td>220.</td>
<td></td>
</tr>
<tr>
<td>192.</td>
<td>192.</td>
<td></td>
</tr>
<tr>
<td>FEED (IPR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0168</td>
<td>0.0168</td>
<td></td>
</tr>
<tr>
<td>0.0187</td>
<td>0.0187</td>
<td></td>
</tr>
<tr>
<td>0.0168</td>
<td>0.0168</td>
<td></td>
</tr>
<tr>
<td>0.0187</td>
<td>0.0187</td>
<td></td>
</tr>
<tr>
<td>Previous Cycle Sum</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Previous Cycle Average</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>New Observations</td>
<td>9.81</td>
<td>0.0323</td>
</tr>
<tr>
<td>Differences</td>
<td>-9.81</td>
<td>-0.0323</td>
</tr>
<tr>
<td>New SLPS</td>
<td>9.81</td>
<td>0.0323</td>
</tr>
<tr>
<td>New Averages: Y(1)</td>
<td>9.81</td>
<td>0.0323</td>
</tr>
</tbody>
</table>

#### Calculation of Standard Deviations

| Previous Average S   | 0.6666 |
| New S = Range * F4,N | 0.0    |
| Range                | 2.6282 |
| New SLPS S           | 0.0    |
| New Averages S = New Sum S/2 | 0.0 |

#### Calculation of 2 S.E. Limits:

For new effects

1.2000

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.  2) SPEED = 220.
   FEED = 0.0210  FEED = 0.0210

1) SPEED = 192.  3) SPEED = 220.
   FEED = 0.0187  FEED = 0.0187

f.

Figure 5.1 (continued)
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:

1) SPEED = 192, FEED = 0.0168
2) SPEED = 220, FEED = 0.0187
3) SPEED = 220, FEED = 0.0168
4) SPEED = 192, FEED = 0.0187

Figure 5.1 (continued)
Figure 5.1 (continued)
MULTIPLE REGRESSION ON 2 VARIABLES WITH 4 OBSERVATIONS

COST EQUATION

ANOVA

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>3</td>
<td>0.48522356E+01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REGRESSION</td>
<td>2</td>
<td>0.46241693E+01</td>
<td>0.23120842E+01</td>
<td>0.10117594E+02</td>
</tr>
<tr>
<td>RESIDUAL</td>
<td>1</td>
<td>0.22807026E+00</td>
<td>0.22807026E+00</td>
<td></td>
</tr>
</tbody>
</table>

COEFFICIENT OF MULTIPLE DETERMINATION ($R^2$) = 0.95299685E+00

COEFFICIENTS

<table>
<thead>
<tr>
<th></th>
<th>T VALUES</th>
<th>STANDARD DEV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSUBC</td>
<td>-0.90530115E+02</td>
<td></td>
</tr>
<tr>
<td>B/HAT(1)</td>
<td>0.4033564E+01</td>
<td>0.35081120E+01</td>
</tr>
<tr>
<td>B/HAT(2)</td>
<td>-0.19404631E+02</td>
<td>0.44572296E+01</td>
</tr>
</tbody>
</table>

T VALUES

<table>
<thead>
<tr>
<th></th>
<th>T(1) = 0.11497908E+01</th>
<th>0.35081120E+01</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(2)</td>
<td>-0.4355252E+01</td>
<td>0.44572296E+01</td>
</tr>
</tbody>
</table>

THE PREDICTION EQUATION IS

$$PI = -90.9301 + 4.0336*LN(SPEED) + -19.4047*LN(FEED)$$

Figure 5.1 (continued)
MULTIPLE REGRESSION ON 2 VARIABLES WITH 4 OBSERVATIONS

Production rate equation

ANOVA

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3</td>
<td>0.68719113E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>2</td>
<td>0.78761657E-04</td>
<td>0.39390841E-04</td>
<td>0.39638910E 01</td>
</tr>
<tr>
<td>Residual</td>
<td>1</td>
<td>0.99374156E-05</td>
<td>0.99374156E-05</td>
<td></td>
</tr>
</tbody>
</table>

Coefficient of multiple determination ($R^2$) = 0.88799012E 00

Coefficients

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>T Values</th>
<th>Standard Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bsubc = 0.45743413E 00</td>
<td>T(1) = -0.81911176E 00</td>
<td>SD(1) = 0.23156650E-01</td>
</tr>
<tr>
<td>Bhat(1) = -0.109676855E-01</td>
<td>T(2) = 0.289338515E 01</td>
<td>SD(2) = 0.29421683E-01</td>
</tr>
<tr>
<td>Bhat(2) = 0.792575671E-01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The prediction equation is

$\Pi = 0.4574 + -0.0193*\ln(\text{speed}) + 0.0793*\ln(\text{feed})$ $k$.

Figure 5.1 (continued)
<table>
<thead>
<tr>
<th>FEED (IPR)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0210</td>
<td>4.65</td>
<td>5.24</td>
<td>5.79</td>
<td>6.39</td>
</tr>
<tr>
<td></td>
<td>(0.0543)</td>
<td>(0.0515)</td>
<td>(0.0489)</td>
<td>(0.0461)</td>
</tr>
<tr>
<td>0.0187</td>
<td>6.91</td>
<td>7.49</td>
<td>8.04</td>
<td>8.64</td>
</tr>
<tr>
<td></td>
<td>(0.0451)</td>
<td>(0.0423)</td>
<td>(0.0397)</td>
<td>(0.0369)</td>
</tr>
<tr>
<td>0.0168</td>
<td>8.98</td>
<td>9.57</td>
<td>10.12</td>
<td>10.72</td>
</tr>
<tr>
<td></td>
<td>(0.0366)</td>
<td>(0.0338)</td>
<td>(0.0313)</td>
<td>(0.0285)</td>
</tr>
<tr>
<td>0.0153</td>
<td>10.80</td>
<td>11.35</td>
<td>11.94</td>
<td>12.53</td>
</tr>
<tr>
<td></td>
<td>(0.0292)</td>
<td>(0.0264)</td>
<td>(0.0238)</td>
<td>(0.0210)</td>
</tr>
</tbody>
</table>

166. 192. 220. 255.  
SPEED (RPM)

Figure 5.1 (continued)
Figure 5.2 MACHOP Output for Phase 2, Cycle 1
Figure 5.2 (continued)
## INPUT VALUES AND COMPUTED RESPONSES

<table>
<thead>
<tr>
<th>SPEED</th>
<th>FEED</th>
<th>PARTS</th>
<th>TIME</th>
<th>TOOL-EDGES</th>
<th>COST</th>
<th>PROD RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>192</td>
<td>0.0168</td>
<td>14</td>
<td>434</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>0.0187</td>
<td>18</td>
<td>410</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.0168</td>
<td>13</td>
<td>356</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.0187</td>
<td>15</td>
<td>393</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>0.0187</td>
<td>8</td>
<td>214</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.0210</td>
<td>20</td>
<td>440</td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.0187</td>
<td>15</td>
<td>394</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>0.0210</td>
<td>14</td>
<td>377</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.2 (continued)
### TABLE OF RESPONSES

<table>
<thead>
<tr>
<th>FEED (IPR)</th>
<th>COST</th>
<th>PROD. RT.</th>
<th>COST</th>
<th>PROD. RT.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0210</td>
<td>8.62</td>
<td>0.0371</td>
<td>7.52</td>
<td>0.0455</td>
</tr>
<tr>
<td>0.0187</td>
<td>8.86</td>
<td>0.0374</td>
<td>8.36</td>
<td>0.0381</td>
</tr>
</tbody>
</table>

**SPEED (RPM)**

- 192.
- 220.

---

**Figure 5.2 (continued)**
**EVLUTIONARY OPERATION ANALYSIS**  
**PHASE 2 CYCLE 1**

**CALCULATION OF AVERAGES**

<table>
<thead>
<tr>
<th>OPERATING CONDITIONS</th>
<th>COST</th>
<th>PRODUCTION RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEED (RPM)</td>
<td>192.</td>
<td>0.0187</td>
</tr>
<tr>
<td>FEED (IPR)</td>
<td>0.0210</td>
<td>0.0187</td>
</tr>
<tr>
<td>PREVIOUS CYCLE SUM</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>PREVIOUS CYCLE AVERAGE</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NEW OBSERVATIONS</td>
<td>8.86</td>
<td>0.0374</td>
</tr>
<tr>
<td>DIFFERENCES</td>
<td>-9.86</td>
<td>-0.0374</td>
</tr>
<tr>
<td>NEW SLPs</td>
<td>8.86</td>
<td>0.0374</td>
</tr>
<tr>
<td>NEW AVERAGES: Y(1)</td>
<td>8.86</td>
<td>0.0374</td>
</tr>
</tbody>
</table>

**CALCULATION OF STANDARD DEVIATIONS**

| PREVIOUS AVERAGE S  | 0.6000 | 0.00 |
| NEW S = RANGE * F4,N | 0.00 | 0.00 |
| RANGE               | 1.3410 | 0.0083 |
| NEW SUM S           | 0.00 | 0.00 |
| NEW AVERAGE S = NEW SUM S/2 | 0.00 | 0.00 |

**CALCULATION OF 2 S.E. LIMITS:**

FOR NEW EFFECTS  
1.2000  e.

Figure 5.2 (continued)
COST ANALYSIS

THE EFFECT OF SPEED IS
-0.8018 --- NOT SIGNIFICANT ---

THE EFFECT OF FEED IS
-0.5392 --- NOT SIGNIFICANT ---

THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS
-0.2928 --- NOT SIGNIFICANT ---

NO PARAMETERS ARE SIGNIFICANT

THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

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

f.

Figure 5.2 (continued)
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:

<table>
<thead>
<tr>
<th>Speed</th>
<th>Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>192</td>
<td>0.0210</td>
</tr>
<tr>
<td>220</td>
<td>0.0210</td>
</tr>
<tr>
<td>192</td>
<td>0.0187</td>
</tr>
<tr>
<td>220</td>
<td>0.0187</td>
</tr>
</tbody>
</table>

h.

Figure 5.2 (continued)
Figure 5.2 (continued)
MULTIPLE REGRESSION ON 3 VARIABLES WITH 8 OBSERVATIONS

COST EQUATION

\[ \text{ANGVA} \]

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>7</td>
<td>0.63046255E 01</td>
<td>0.10321312E 01</td>
<td>0.12868528E 01</td>
</tr>
<tr>
<td>REGRESSION</td>
<td>3</td>
<td>0.30963536E 01</td>
<td>0.10321312E 01</td>
<td>0.12868528E 01</td>
</tr>
<tr>
<td>RESIDUAL</td>
<td>4</td>
<td>0.32082319E 01</td>
<td>0.80205798E 00</td>
<td></td>
</tr>
</tbody>
</table>

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

COEFFICIENTS

<table>
<thead>
<tr>
<th>BSUB0</th>
<th>B(1)</th>
<th>B(2)</th>
<th>B(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13522461E 02</td>
<td>-0.678432846E 01</td>
<td>0.64294243E-02</td>
<td>-0.147253323E 01</td>
</tr>
</tbody>
</table>

T VALUES

<table>
<thead>
<tr>
<th>T(1)</th>
<th>T(2)</th>
<th>T(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.12261572E 01</td>
<td>0.64037174E 00</td>
<td>-0.19548788E 01</td>
</tr>
</tbody>
</table>

STANDARD DEV.

<table>
<thead>
<tr>
<th>SD(1)</th>
<th>SD(2)</th>
<th>SD(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55330000E 01</td>
<td>0.25656072E-02</td>
<td>0.75326025E 00</td>
</tr>
</tbody>
</table>

THE PREDICTION EQUATION IS

\[ \text{PI} = 13.5224 + -6.7843* \ln(\text{SPEED}) + 0.0016* \ln(\text{FEED}) + -1.4725* \ln(\text{SPEED})* \ln(\text{FEED}) \]

Figure 5.2 (continued)
MULTIPLE REGRESSION ON 3 VARIABLES WITH 8 OBSERVATIONS

PRODUCTION RATE EQUATION

\[ \text{ANGVA} \]

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>7</td>
<td>0.15110668E-03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REGRESSION</td>
<td>3</td>
<td>0.77535209E-04</td>
<td>0.25845060E-04</td>
<td>0.14051676E 01</td>
</tr>
<tr>
<td>RESIDUAL</td>
<td>4</td>
<td>0.73571471E-04</td>
<td>0.18392864E-04</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>COEFFICIENTS</th>
<th>T VALUES</th>
<th>STANDARD DEV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0 ( = 0.52316526E-03 )</td>
<td>T( 1) = 0.13648310E 01</td>
<td>SD( 1) = 0.26496135E-01</td>
</tr>
<tr>
<td>B1 = 0.361627676E-01</td>
<td>T( 2) = 0.90573573E 00</td>
<td>SD( 2) = 0.12236042E-04</td>
</tr>
<tr>
<td>B2 = -0.111279078E-04</td>
<td>T( 3) = -0.202836776 01</td>
<td>SD( 3) = 0.36071721E-02</td>
</tr>
<tr>
<td>B3 = 0.73184748E-02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

THE PREDICTION EQUATION IS

\[
\text{PI} = 0.0005 + 0.0362*\text{LN(SPEED)} + -0.0000*\text{LN(FEED)} + 0.0073*\text{LN(SPEED)}*\text{LN(FEED)}
\]

Figure 5.2 (continued)
## Predicted Costs
(Predicted Production Rates)

### Feed (IPR)

<table>
<thead>
<tr>
<th>RPM</th>
<th>0.240</th>
<th>0.210</th>
<th>0.187</th>
<th>0.168</th>
<th>0.153</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.91</td>
<td>7.92</td>
<td>8.79</td>
<td>9.59</td>
<td>10.30</td>
</tr>
<tr>
<td></td>
<td>(0.0459)</td>
<td>(0.0409)</td>
<td>(0.0366)</td>
<td>(0.0326)</td>
<td>(0.0291)</td>
</tr>
<tr>
<td></td>
<td>6.72</td>
<td>7.76</td>
<td>8.65</td>
<td>9.48</td>
<td>10.21</td>
</tr>
<tr>
<td></td>
<td>(0.0472)</td>
<td>(0.0420)</td>
<td>(0.0376)</td>
<td>(0.0355)</td>
<td>(0.0329)</td>
</tr>
<tr>
<td></td>
<td>6.55</td>
<td>7.61</td>
<td>8.53</td>
<td>9.38</td>
<td>10.12</td>
</tr>
<tr>
<td></td>
<td>(0.0484)</td>
<td>(0.0431)</td>
<td>(0.0385)</td>
<td>(0.0343)</td>
<td>(0.0309)</td>
</tr>
<tr>
<td></td>
<td>6.35</td>
<td>7.45</td>
<td>8.39</td>
<td>9.27</td>
<td>10.03</td>
</tr>
<tr>
<td></td>
<td>(0.0497)</td>
<td>(0.0443)</td>
<td>(0.0396)</td>
<td>(0.0352)</td>
<td>(0.0314)</td>
</tr>
</tbody>
</table>

**Speed (RPM):**

| 166 | 192 | 220 | 255 |

---

Figure 5.2 (continued)
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

Figure 5.3 MACHOP Output for Phase 2, Cycle 2
Figure 5.3 (continued)
## Input Values and Computed Responses

<table>
<thead>
<tr>
<th>Speed</th>
<th>Feed</th>
<th>Parts</th>
<th>Time</th>
<th>Tool-Edges</th>
<th>Cost ($/piece)</th>
<th>PPOD Rate (pieces/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>192.</td>
<td>0.0168</td>
<td>14</td>
<td>434.</td>
<td>17</td>
<td>9.31</td>
<td>0.0323</td>
</tr>
<tr>
<td>192.</td>
<td>0.0187</td>
<td>18</td>
<td>410.</td>
<td>18</td>
<td>7.25</td>
<td>0.0439</td>
</tr>
<tr>
<td>220.</td>
<td>0.0168</td>
<td>13</td>
<td>396.</td>
<td>23</td>
<td>9.88</td>
<td>0.0328</td>
</tr>
<tr>
<td>220.</td>
<td>0.0187</td>
<td>15</td>
<td>393.</td>
<td>15</td>
<td>8.28</td>
<td>0.0382</td>
</tr>
<tr>
<td>220.</td>
<td>0.0210</td>
<td>20</td>
<td>440.</td>
<td>44</td>
<td>7.52</td>
<td>0.0455</td>
</tr>
<tr>
<td>192.</td>
<td>0.0187</td>
<td>8</td>
<td>214.</td>
<td>16</td>
<td>8.86</td>
<td>0.0374</td>
</tr>
<tr>
<td>220.</td>
<td>0.0187</td>
<td>15</td>
<td>394.</td>
<td>17</td>
<td>8.36</td>
<td>0.0381</td>
</tr>
<tr>
<td>192.</td>
<td>0.0210</td>
<td>14</td>
<td>377.</td>
<td>18</td>
<td>8.62</td>
<td>0.0371</td>
</tr>
<tr>
<td>192.</td>
<td>0.0187</td>
<td>14</td>
<td>374.</td>
<td>14</td>
<td>8.43</td>
<td>0.0374</td>
</tr>
<tr>
<td>220.</td>
<td>0.0210</td>
<td>6</td>
<td>173.</td>
<td>47</td>
<td>11.94</td>
<td>0.0347</td>
</tr>
<tr>
<td>220.</td>
<td>0.0187</td>
<td>13</td>
<td>381.</td>
<td>20</td>
<td>9.44</td>
<td>0.0341</td>
</tr>
<tr>
<td>192.</td>
<td>0.0210</td>
<td>6</td>
<td>149.</td>
<td>18</td>
<td>8.71</td>
<td>0.0403</td>
</tr>
</tbody>
</table>

Figure 5.3 (continued)
<table>
<thead>
<tr>
<th>FEED (IPR)</th>
<th>COST</th>
<th>PROD. RT.</th>
<th>SPEED (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0210</td>
<td>8.71</td>
<td>0.0403</td>
<td>192.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>220.</td>
</tr>
<tr>
<td>0.0187</td>
<td>8.43</td>
<td>0.0374</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.44</td>
<td>0.0341</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 5.3 (continued)*
## Evolutionary Operation Analysis

### Phase 2 Cycle 2

#### Calculation of Averages

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>Cost</th>
<th>Production Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed (RPM)</strong></td>
<td>192.</td>
<td>192.</td>
</tr>
<tr>
<td></td>
<td>220.</td>
<td>220.</td>
</tr>
<tr>
<td></td>
<td>220.</td>
<td>220.</td>
</tr>
<tr>
<td></td>
<td>192.</td>
<td>192.</td>
</tr>
<tr>
<td><strong>Feed (IPR)</strong></td>
<td>0.0187</td>
<td>0.0187</td>
</tr>
<tr>
<td></td>
<td>0.0210</td>
<td>0.0210</td>
</tr>
<tr>
<td></td>
<td>0.0210</td>
<td>0.0210</td>
</tr>
<tr>
<td></td>
<td>0.0210</td>
<td>0.0210</td>
</tr>
<tr>
<td><strong>Previous Cycle Sum</strong></td>
<td>8.86</td>
<td>0.0374</td>
</tr>
<tr>
<td></td>
<td>7.52</td>
<td>0.0455</td>
</tr>
<tr>
<td></td>
<td>8.36</td>
<td>0.0381</td>
</tr>
<tr>
<td></td>
<td>8.62</td>
<td>0.0371</td>
</tr>
<tr>
<td><strong>Previous Cycle Average</strong></td>
<td>8.86</td>
<td>0.0374</td>
</tr>
<tr>
<td></td>
<td>7.52</td>
<td>0.0455</td>
</tr>
<tr>
<td></td>
<td>8.36</td>
<td>0.0381</td>
</tr>
<tr>
<td></td>
<td>8.62</td>
<td>0.0371</td>
</tr>
<tr>
<td><strong>New Observations</strong></td>
<td>8.43</td>
<td>0.0374</td>
</tr>
<tr>
<td></td>
<td>11.94</td>
<td>0.0347</td>
</tr>
<tr>
<td></td>
<td>9.44</td>
<td>0.0341</td>
</tr>
<tr>
<td></td>
<td>8.71</td>
<td>0.0403</td>
</tr>
<tr>
<td><strong>Differences</strong></td>
<td>0.43</td>
<td>-0.0000</td>
</tr>
<tr>
<td></td>
<td>-4.42</td>
<td>0.0108</td>
</tr>
<tr>
<td></td>
<td>-1.08</td>
<td>0.0040</td>
</tr>
<tr>
<td></td>
<td>-0.09</td>
<td>-0.0031</td>
</tr>
<tr>
<td><strong>New Sums</strong></td>
<td>17.30</td>
<td>0.0748</td>
</tr>
<tr>
<td></td>
<td>19.46</td>
<td>0.0801</td>
</tr>
<tr>
<td></td>
<td>17.79</td>
<td>0.0722</td>
</tr>
<tr>
<td></td>
<td>17.33</td>
<td>0.0774</td>
</tr>
<tr>
<td><strong>New Averages: Yi(t)</strong></td>
<td>8.65</td>
<td>0.0374</td>
</tr>
<tr>
<td></td>
<td>9.73</td>
<td>0.0401</td>
</tr>
<tr>
<td></td>
<td>8.90</td>
<td>0.0361</td>
</tr>
<tr>
<td></td>
<td>8.66</td>
<td>0.0387</td>
</tr>
</tbody>
</table>

#### Calculation of Standard Deviations

- Previous Average \( S \) = 0.0
- New \( S = \text{Range} \times F_{4,N} \) = 1.6479
- Range = 4.8867
- New Sum \( S \) = 3.2558
- New Average \( S = \text{New Sum} \times S/2 \) = 1.6479

#### Calculation of 2 S.E. Limits:

- For New Effects = 2.3305

---

*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 = 192.0, FEED = 0.0210
2) SPEED = 220.0, FEED = 0.0210

1) SPEED = 192.0, FEED = 0.0187
3) SPEED = 220.0, FEED = 0.0187

f.

Figure 5.3 (continued)
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:

1) SPEED = 192.  2) SPEED = 220.
   FEED = 0.0210   FEED = 0.0210

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

h.

Figure 5.3 (continued)
NEW PRODUCTION RATE ENVIRONMENT

Figure 5.3 (continued)
MULTIPLE REGRESSION ON 3 VARIABLES WITH 12 OBSERVATIONS

COST EQUATION

ANOVA

\[
\begin{array}{lllll}
\text{SOURCE} & \text{DF} & \text{SS} & \text{MS} & \text{F} \\
\hline
\text{TOTAL} & 11 & 0.16933578E 02 & & \\
\text{REGRESSION} & 3 & 0.15972290E 01 & 0.53240967E 00 & 0.27772433E 00 \\
\text{RESIDUAL} & 8 & 0.15336349E 02 & 0.19170437E 01 & \\
\end{array}
\]

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

COEFFICIENTS

\[
\begin{align*}
B_{SUB0} &= -0.72270166E 03 \\
B_{HAT(1)} &= 0.13664474E 03 \\
B_{HAT(2)} &= -0.17868708E 03 \\
B_{HAT(3)} &= 0.33366867E 02
\end{align*}
\]

T VALUES

\[
\begin{align*}
T(1) &= 0.45348996E 00 \\
T(2) &= -0.44082719E 00 \\
T(3) &= 0.43842232E 00
\end{align*}
\]

STANDARD DEV.

\[
\begin{align*}
SD(1) &= 0.30131812E 03 \\
SD(2) &= 0.40534497E 03 \\
SD(3) &= 0.76106674E 02
\end{align*}
\]

THE PREDICTION EQUATION IS

\[
\pi = -722.7017 + 136.6447*\text{LN(SPEED)} + -178.6871*\text{LN(FEED)} + 33.3669*\text{LN(SPEED)}*\text{LN(FEED)}
\]

Figure 5.3 (continued)
MULTIPLE REGRESSION ON 3 VARIABLES WITH 12 OBSERVATIONS

PRODUCTION RATE EQUATION

ANOVA

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>11</td>
<td>0.18127424E-03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REGRESSION</td>
<td>3</td>
<td>0.54460019E-04</td>
<td>0.18153340E-04</td>
<td>0.11451931E 01</td>
</tr>
<tr>
<td>RESIDUAL</td>
<td>8</td>
<td>0.12681422E-03</td>
<td>0.15851765E-04</td>
<td></td>
</tr>
</tbody>
</table>

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

COEFFICIENTS

| BSUB0      | -0.13912010E 01 |
| B(HAT(1))  | 0.28304028E 00  |
| B(HAT(2))  | -0.36929273E 00 |
| B(HAT(3))  | 0.74330508E-01  |

T VALUES

| T(1)       | 0.33243382E 00  |
| T(2)       | -0.31682760E 00 |
| T(3)       | 0.33964205E 00  |

STANDARD DEVS.

| SD(1)      | 0.86645901E 00  |
| SD(2)      | 0.11655951E 01  |
| SD(3)      | 0.21884954E 00  |

THE PREDICTION EQUATION IS

\[ PI = -1.3912 + 0.2880*\text{LN(SPEED)} + -0.3693*\text{LN(FEED)} + 0.0743*\text{LN(SPEED)}*\text{LN(FEED)} \times k. \]

Figure 5.3 (continued)
### Predicted Costs
(Predicted Production Rates)

#### Feed (IPR)

<table>
<thead>
<tr>
<th>Speed (RPM)</th>
<th>166.0</th>
<th>192.0</th>
<th>220.0</th>
<th>255.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0240</td>
<td>6.09</td>
<td>7.87</td>
<td>9.53</td>
<td>11.33</td>
</tr>
<tr>
<td></td>
<td>(0.0414)</td>
<td>(0.0433)</td>
<td>(0.0445)</td>
<td>(0.0460)</td>
</tr>
<tr>
<td>0.0210</td>
<td>7.18</td>
<td>8.30</td>
<td>9.36</td>
<td>10.50</td>
</tr>
<tr>
<td></td>
<td>(0.0401)</td>
<td>(0.0401)</td>
<td>(0.0402)</td>
<td>(0.0404)</td>
</tr>
<tr>
<td>0.0187</td>
<td>8.12</td>
<td>8.68</td>
<td>9.21</td>
<td>9.78</td>
</tr>
<tr>
<td></td>
<td>(0.0387)</td>
<td>(0.0376)</td>
<td>(0.0366)</td>
<td>(0.0354)</td>
</tr>
<tr>
<td>0.0168</td>
<td>8.99</td>
<td>9.03</td>
<td>9.07</td>
<td>9.12</td>
</tr>
<tr>
<td></td>
<td>(0.0376)</td>
<td>(0.0353)</td>
<td>(0.0332)</td>
<td>(0.0309)</td>
</tr>
<tr>
<td>0.0153</td>
<td>9.75</td>
<td>9.34</td>
<td>8.95</td>
<td>8.54</td>
</tr>
<tr>
<td></td>
<td>(0.0366)</td>
<td>(0.0333)</td>
<td>(0.0302)</td>
<td>(0.0269)</td>
</tr>
</tbody>
</table>

---

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.
Bibliography


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.
**SUMMARY TABLE**

<table>
<thead>
<tr>
<th>STEP NUMBER</th>
<th>VARIABLE ENTERED</th>
<th>VARIABLE REMOVED</th>
<th>MULTIPLE R</th>
<th>MULTIPLE RSQ</th>
<th>INCREASE IN RSQ</th>
<th>F VALUE TO ENTER OR REMOVE</th>
<th>NUMBER OF INDEPENDENT VARIABLES INCLUDED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FEEDSO</td>
<td>5</td>
<td>0.1995</td>
<td>0.0400</td>
<td>0.0400</td>
<td>0.2913</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>FEED</td>
<td>2</td>
<td>0.3584</td>
<td>0.1284</td>
<td>0.0885</td>
<td>0.6091</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>SPEED SO</td>
<td>4</td>
<td>0.4038</td>
<td>0.1630</td>
<td>0.0346</td>
<td>0.2067</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>SPEED</td>
<td>6</td>
<td>0.6074</td>
<td>0.3689</td>
<td>0.2059</td>
<td>1.3043</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>SPEED</td>
<td>1</td>
<td>0.6104</td>
<td>0.3726</td>
<td>0.0037</td>
<td>0.0176</td>
<td>5</td>
</tr>
</tbody>
</table>

**A,1 Sample Stepwise Regression Output**

**ANALYSIS OF VARIANCE**

<table>
<thead>
<tr>
<th></th>
<th>DF</th>
<th>SUM OF SQUARES</th>
<th>MEAN SQUARE</th>
<th>F RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGRESSION</td>
<td>5</td>
<td>0.001</td>
<td>0.000</td>
<td>0.356</td>
</tr>
<tr>
<td>RESIDUAL</td>
<td>3</td>
<td>0.001</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

**VARIABLES IN EQUATION**

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>COEFFICIENT</th>
<th>STD. ERROR</th>
<th>F TO REMOVE</th>
<th>(CONSTANT -0.90118)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEED</td>
<td>0.08087</td>
<td>0.60953</td>
<td>0.0176      (2)</td>
<td></td>
</tr>
<tr>
<td>FEED SO</td>
<td>0.96511</td>
<td>1.05571</td>
<td>0.7758      (2)</td>
<td></td>
</tr>
<tr>
<td>FEED SQ</td>
<td>0.63636</td>
<td>0.12451</td>
<td>0.0853      (2)</td>
<td></td>
</tr>
<tr>
<td>SPEED</td>
<td>-0.17757</td>
<td>0.27953</td>
<td>0.4050      (9)</td>
<td></td>
</tr>
<tr>
<td>SPEED SO</td>
<td>-0.12478</td>
<td>0.12969</td>
<td>0.9257      (2)</td>
<td></td>
</tr>
</tbody>
</table>

**VARIABLES NOT IN EQUATION**

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>PARTIAL CORR.</th>
<th>TOLERANCE</th>
<th>F TO ENTER</th>
</tr>
</thead>
</table>

**F-LEVEL OR TOLERANCE INSUFFICIENT FOR FURTHER COMPUTATION**
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.
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION P(30),T(J),TP(J)
DIMENSION F(30),V(J),PF(30),CU(J),PI(J)
COMMON 1NT

NPT - IS THE NUMBER OF POINTS AT WHICH THE DATA IS TO BE GENERATED
U - IS THE PERFORMANCE INDEX COEFFICIENT
INT - IS THE RANDOM SEED, A SEVEN DIGIT INTEGER

READ (5,12) NPT,Q,INT
FORMAT (110,F10.2,110)

RLO - IS THE LABOR AND OVERHEAD IN $/MIN

TLC - IS THE TOOL COST IN $/EDGE

READ (5,2U) RLO,TLC
FORMAT (2F10.4)
WRITE (6,30) RLO,TLC
FORMAT (2F10.4)

CALL SIM(J,T,J,TP,J,PDJ)
P(J) = KPT
T(J) = T(J)
TP(J) = VCT
FORMAT (2F10.4)
WRITE (6,24) "PERIND,(T,TP,CU,PR,P1),RLO,TLC,NPT)
FORMAT (20X,T,P1)
WRITE (6,25) "(T,F1,I1,T,I1,TP(I),T(I),CU(I),FR(I),P(I)),I=1,INP)
FORMAT (10X,F10.1,F10.4,F10.1,F10.1,F10.2,F12.4/
RETURN
END
FORTRAN IV G LEVEL 21

OOC1 SUBROUTINE RAND(INT,IEREAL)
OOC2 REAL*DREAL, DINT, DKEEP
OOC3 C in the subroutine
OOC4 DINT = INT
OOC5 DREAL = DINT * 16474.
OOC6 KEEP = DREAL / 2147483647.
OOC7 DKEEP = KEEP
OOC8 REAL = (INT/128) * 1073741824
OOC9 RETURN
OOC10 END

FORTRAN IV G LEVEL 21

OOC1 SUBROUTINE UNINIT, PI, PC, PL, NPT)
OOC2 IMPLICIT REAL(A-H, O-Z)
OOC3 DO 1 NPT = 1, NPT
OOC4 PI(I) = (1.4)^*P(I)/T(I)
OOC5 CU(I) = (KCU*T(I)*PLC*PI(I))/P(I)
OOC6 RETURN
OOC7 END
SIN 73361 17/31/11
OOC1
OOC2
OOC3
OOC4
OOC5
OOC6
OOC7
OOC8
OOC9
OOC10
OOC11
OOC12
OOC13
OOC14
OOC15
OOC16
OOC17
OOC18
OOC19
OOC20
OOC21
OOC22
OOC23
OOC24
OOC25
OOC26
OOC27
OOC28
OOC29
OOC30
OOC31
OOC32
OOC33
OOC34
OOC35
OOC36
OOC37
OOC38
OOC39
OOC40
OOC41
OOC42
OOC43
OOC44

FORTRAN IV  G  LEVEL  21  SIM  DATE  =  73361  17/31/11

0001 SUBROUTINE SIM(I,F,V,TK,N,TPT,TPD)
0002 IMPLICIT REAL*8 (A-H,O-Z)
0003 DIMENSION F(16),V(16)
0004 COMMON INT
0005
0006 IN THIS SUBROUTINE ALL THE PARAMETERS OF THE PRODUCTION PROCESS
0007 ARE INITIALISED RATHER THAN TO BE READ BY A READ STATEMENT
0008
0009 TAYLOR'S TOOL LIFE CONSTANTS
0010 ALP = 0.1
0011 BETA = 0.2
0012 CONST = 4.00.0
0013 XL -- LENGTH OF WORKPIECE
0014 XL = 47.5
0015 U -- DIAMETER OF WORKPIECE
0016 U = 6.5
0017 TCT -- TOOL CHANGING TIME
0018 TCT = 1.
0019 TM -- MACHINING TIME / PIECE
0020 TM = XL/(V(I)*F(I))
0021 TH -- HANDLING TIME / PIECE
0022 TH = 15.0
0023 SHIF'T -- TOTAL PRODUCTION TIME / SHIFT
0024 SHIFT = 420.0
0025 THR -- IS THE RANDOM ERROR
0026 EPR = 0.20
0027 XV = 3.1415+D(V(I))/12.
0028 SIG = (DLOG(1+XV)-BETA*ULOG(F(I))-DLOG(XV))/ALP
0029 ICONT = 0
0030 TIME = 0.
0031 PARTS = 0.
0032 WRITE (6,15) I,V(I),F(I)
0033 15 FORMAT (' 1',1X,'FOR DAY',12/10X,'SPEED',15.1,5X,'FEED',15.1,F7.4/
0034 10)
0035 WRITE (6,30) TM
0036 30 FORMAT (' 1',1X,'MACHINING TIME FOR THIS SPEED & FEED',F7.2,' MIN')
0037 ICONT = ICONT + 1
0038 Y = UNIFORM(L(4),SIG)
0039 TLIFE = DEK/SIG*Y
0040 PARTS1 = TLIFE/TH
0041 WRITE (6,20) ICONT,TLIFE,PARTS1
0042 20 FORMAT (' ',1X,'COUNT',15.1,'LIFE',15.1,'MIN',15.1,'OF PARTS=',1,F5.2/
0043 10)
0044 TIME1 = PARTS1*(TM+TH)*TCT
0045 PARTS = PARTS+PARTS1
0046 TIME = TIME+TIME1
0047 IF (TIME .LE. SHIFT) GO TO 10
0048 UNIF = TIME-SHIFT
0049 PARTMS = UNIF*(TM+TH)
0050 WRITE (6,25) PARTS,ICOUNT,SHIFT
0051 25 FORMAT (' ',15.1,'PARTS',15.1,'COUNT',15.1,'SHIFT
0052 IF FOR DAY',12/10X,'PARTS ARE PRODUCED',15.1,'1','S TOOLS ARE CHANGED DURING',10X,'MINUTES OF PRODUCTION TIME
0053 1/
0054 PARTS = PARTS + 0.25
0055 NPT = PARTS
0056 TPT = SHIFT
0057 NTG = ICONT
0058 RETURN
0059 END
SPEED = 192.0  FEED = 0.0187

MACHINING TIME FOR THIS SPEED & FEED = 13.23 MIN

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

14.3 PARTS ARE PRODUCED
15 TOOLS ARE CHANGED DURING
420.6 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

<table>
<thead>
<tr>
<th>Machine</th>
<th>Date</th>
<th>Stock Lot ID</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator</td>
<td>Shift</td>
<td>Tool Material ID</td>
<td>Feed</td>
</tr>
</tbody>
</table>

| Production | Production | Subtotals |
| Startup Time | Stop Time | (minutes) |

<table>
<thead>
<tr>
<th>Total Production Time (minutes)</th>
<th>Number of Pieces Produced</th>
<th>(Tally)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Insert Edges Used</td>
<td>(Tally)</td>
<td>Total</td>
<td></td>
</tr>
</tbody>
</table>

Comments:
- Cost/edge
- Overhead and Labor Cost

Figure C.1

87
MULTIPLE TOOL MACHINE OPTIMIZATION STUDY FORM

<table>
<thead>
<tr>
<th>Sheet No.</th>
<th>Machine</th>
<th>Speed</th>
<th>Feed</th>
<th>Operator</th>
<th>Date</th>
<th>Shift</th>
<th>Stock Lot ID</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Insert 1 ID</th>
<th>Insert 2 ID</th>
<th>Insert 3 ID</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production</th>
<th>Production</th>
<th>Subtotals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Startup Time</td>
<td>Stop Time</td>
<td>(minutes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

88
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 $L_4 = \frac{\text{number of usable speeds}}{4}$ and the distance between feeds is $M_4 = \frac{\text{number of usable feeds}}{4}$. 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 CARBOLoy MAY CAUSE TOOL FAILURE DUE TO THERMAL CRACKS. CHECK TO MAKE SURE TOOLS ARE WEARING OUT, NOT CHIPPING OR BREAKING.

<table>
<thead>
<tr>
<th>IDENTIFICATION</th>
<th>AISI 4140</th>
</tr>
</thead>
<tbody>
<tr>
<td>STARTING SURFACE CONDITION</td>
<td>HTR</td>
</tr>
<tr>
<td>FINAL SURFACE FINISH</td>
<td>250 MU. IN. 'AA'</td>
</tr>
<tr>
<td>BRINELL HARDNESS</td>
<td>252</td>
</tr>
<tr>
<td>PART TOLERANCE</td>
<td>.015 IN.</td>
</tr>
<tr>
<td>COOLANT</td>
<td>EMU</td>
</tr>
<tr>
<td>MACHINE TOOL TYPE</td>
<td>LATHE</td>
</tr>
<tr>
<td>OPERATION</td>
<td>AXIAL TURV</td>
</tr>
<tr>
<td>MOTOR HORSEPOWER</td>
<td>50</td>
</tr>
<tr>
<td>SPINDLE SPEED LIMIT</td>
<td>380</td>
</tr>
<tr>
<td>C U T T I N G T O O L</td>
<td></td>
</tr>
<tr>
<td>TOOL MATERIAL</td>
<td>CARBOLoy</td>
</tr>
<tr>
<td>GRADE</td>
<td>350</td>
</tr>
<tr>
<td>2ND. CHOICE GRADE</td>
<td>78</td>
</tr>
<tr>
<td>SIDE CUTTING EDGE ANGLE</td>
<td>30 DEG.</td>
</tr>
<tr>
<td>NOSE RADIUS</td>
<td>0.047 IN.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUTPUT DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SET UP</td>
</tr>
<tr>
<td>STARTING DIA.</td>
</tr>
<tr>
<td>FEED</td>
</tr>
<tr>
<td>DEPTH OF CUT</td>
</tr>
<tr>
<td>SPEED MIN. COST</td>
</tr>
<tr>
<td>SPEED-MAX. PR0D.</td>
</tr>
<tr>
<td>TECHNICAL</td>
</tr>
<tr>
<td>WEAR LAND</td>
</tr>
<tr>
<td>TOOL LIFE-MIN. COST</td>
</tr>
<tr>
<td>SPEED-MIN. COST</td>
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<tr>
<td>H.P.-MIN. COST</td>
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<tr>
<td>TOOL LIFE-MAX. PR0D.</td>
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<tr>
<td>SPEED-MAX. PR0D.</td>
</tr>
<tr>
<td>H.P.-MAX. PR0D.</td>
</tr>
</tbody>
</table>

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

Figure E.1 Sample Carboloy Computerized Machinability Program Output
THE MACHOP PROGRAM UTILIZES EVOLUTIONARY OPERATION (EVP) AND REGRESSION ANALYSIS TO EXAMINE THE RESPONSE SURFACE OF MACHINING OPERATIONS TO DETERMINE THE OPTIMUM FEED-SPEED COMBINATIONS. TWO PERFORMANCE INDICES, COST/PIECE AND PRODUCTION RATE ARE CONSIDERED AS RESPONSES. FIRST THE PROGRAM PERFORMS AN EVP ANALYSIS AND RECOMMENDS TWO SETS OF OPERATING CONDITIONS. NEXT THE REGRESSION COEFFICIENTS FOR THE FOLLOWING EQUATION (OR A REDUCED FORM OF IT) ARE ESTIMATED:

\[ P = R_0 + R_1 \ln(\text{SPEED}) + R_2 \ln(\text{FEED}) + R_3 \ln(\text{SPEED})^2 + R_4 \ln(\text{FEED})^2 + R_5 \ln(\text{SPEED} \cdot \text{FEED}) \]

USING THESE RESULTS, THE PERFORMANCE INDICES ARE PREDICTED FOR FEED - SPEED COMBINATIONS ADJACENT TO THOSE OBSERVED. THE PROGRAM IS APPLICABLE TO SINGLE-OPERATION AND MULTIPLE-OPERATION (NUMERICALLY CONTROLLED) MACHINING PROCESSES.

REFERENCES ARE:


DRAPER, N. & SMITH, H., APPLIED REGRESSION ANALYSIS, JOHN WILEY & SONS, NEW YORK, 1968.
*IPH,JIPCY,ICP,IMAX,NTLC,FLO,AVES(1,1),AVES(2,1),BSP,BFD
0011 IF(IPH.GT.0)GO TO 6C1
0012 WRITE(6,6G02)IPH
0013 IER=2
0014 GO TO 6C2
0015 601 WRITE(6,6G02)IPH
0016 602 IF(ICYC.GT.0)GO TO 6D3
0017 WRITE(6,6G03)ICYC
0018 IER=2
0019 GO TO 6D4
0020 603 WRITE(6,6G04)ICYC
0021 604 IF(IPH.GT.0)AND.1CP.LT.4)GO TO 6D5
0022 WRITE(6,6G05)IOP
0023 IER=2
0024 605 GU TO (G6,3607,6O8),ICP
0025 606 WRITE(6,6G06)IOP
0026 GU TO G6C7
0027 607 WRITE(6,6G07)IOP
0028 GU TO 6C9
0029 608 WRITE(6,6G08)IOP
0030 609 IF(IMAX.GE.1)GU TC 61C
0031 WRITE(6,6G09)
0032 GU TO 611
0033 610 WRITE(6,6G10)
0034 611 WRITE(6,6G11)ILOC
0035 IF(AVES(1,1).LE.0.0)GU TO 612
0036 WRITE(6,6G12)AVES(1,1)
0037 GU TO 613
0038 612 WRITE(6,6G13)
0039 613 IF(AVES(2,1).LE.0.0)GC TO 6112
0040 WRITE(6,6G14)AVES(2,1)
0041 GU TO 6C14
0042 614 IF(IPH.GE.3)GO TO 628
0043 IF(IPH.LE.0.0)AND.1CP.LT.0)GO TO 615
0044 WRITE(6,6G11)BSP,BFD
0045 GU TO 6D8
0046 615 WRITE(6,6G15)
0047 IER=2
0048 616 IF(INTC.LT.0)JNTLC=1
0049 IF(INTC.LT.0.0)HTLC.GT.20)GO TO 747
0050 WRITE(6,6G22)JNTLC
0051 WRITE(6,6G23)JNTLC
0052 READ(5,503)ENU*6G09,EK=9010)TLC(I1,1=1,NTLC)
0053 GO 2276 I=1nTLC
0054 IF(TLC(I1,LT.0)GO TO 2277
0055 CONTINUE
0056 WRITE(6,6G29)TLC(I1,1=1,NTLC)
0057 GU TO 614
0058 2277 IER=2
0059 WRITE(6,6G26)
0060 GO TO 614
0061 747 IER=2
0062 WRITE(6,6G25)JNTLC
0063 614 GU TO (616,6G17),IER

93
0064 617 WRITE(6,6016)  
0065 CALL EXIT 
C  
C    INPUT SPEED ENVIRONMENT 
C  
0066 616 READ(5,5012;END=96903;ERR=9307)NSPD  
0067 IF(FSPD.LE.0.;OR,NSPD;GT.100.)GO TO 618  
0066 WRITE(6,6018)NSPD  
0069 GO TO 619  
0070 618 WRITE(6,6019)NSPD  
0071 GO TO 617  
0072 619 READ(5,5033;END=9003;ERR=9004) (SPEED(I),I=1,NSPD)  
0073 UO 62C I=1,NSPD  
0074 IF(SPEED(I).LE.0.)GO TO 621  
0075 620 CONTINUE  
0076 GO TO 622  
0077 621 WRITE(6,6020)  
0078 GO TO 617  
C  
C    INPUT FEED ENVIRONMENT 
C  
0079 622 READ(5,5022;END=9005;ERR=9006)NFD  
0080 IF(FNFD.LE.0.;OR,NFD;GT.50.)GO TO 623  
0080 WRITE(6,5023)NFD  
0082 GO TO 624  
0083 623 WRITE(6,5021)NFD  
0084 GO TO 617  
0085 624 READ(5,5033;END=9005;ERR=9006) (FEED(I),I=1,NFD)  
0087 IF(FEED(I).LE.0.)GO TO 626  
0088 625 CONTINUE  
0089 GO TO 627  
0090 626 WRITE(6,6023)  
0091 GO TO 617  
C  
C    INPUT LIMITS FOR SPEED AND FEED 
C  
0092 627 IF(1*MAX,EQ.1)READ(5,5033;END=9007;ERR=9008)SMAX,SMIN,FMAX,FMIN  
0093 IF(1*SPAX,EQ.0.)IF(1*SPAX=SPEED(NSPU))  
0094 IF(1*MINS,EQ.0.)IF(1*MINS=FEED(NFD))  
0095 IF(1*MAX,EQ.0.)IF(1*MAX=FEED(FND))  
0096 IF(1*MIN,EQ.0.)IF(1*MIN=FEED(FND))  
C  
C    INSURE INPUT SPEEDS AND FEEDS ARE WITHIN DEFINED LIMITS 
C  
0097 DO 7 J=1,NSPD  
0098 IF (SPEED(J).LT.SMINSPEED)GO TO 7  
0099 IF(SPEED(J).LT.0.)GO TO 8  
0100 NP0=NBS0-P+1  
0101 DO 15 K=1,NSPD  
0102 SPEED(K)=SPEED(J)  
0103 J=J+1  
0104 GO TO 8  
0105 7 CONTINUE
FURTRAN IV  G  LEVEL  21  MAIN

0126  8  DO  J=1,NSPD
0127  9  IF(SPEED(J).GT.SMAX)GO TO 10
0128  10  ND=J
0129  11  DO  I=1,NFD
0130  12  IF (FEED(I).LT.FMIN)GO TO 14
0131  13  IF(I.EQ.1)GO TO 12
0132  14  CONTINUE
0133  15  IF (FEND(I).GT.FMAX)GO TO 17
0134  16  IF(I.EQ.1)GO TO 12
0135  17  NFD=1

PREPARE FOR E V O P ANALYSIS

0136  64  CALL NLCYCL
0137  65  IDENTIFY INPUT SPEED
0138  66  GO TO 33
0139  67  IDENTIFY INPUT FEED
0140  68  GO TO 35
0141  69  PERFORM THE E V O P ANALYSIS
0142  70  CALL EVOP
0143  71  PERFORM THE REGRESSION ANALYSIS

CENTER
```
C C PRINT PREDICTION EQUATION AND RESPONSE SURFACE PREDICTION
C
C GO TO (1,2,3,4,5),IREG
C
C WRITE(6,911)N0,B(1),B(2)
C GO TO 6
C
C WRITE(6,912)N0,B(1),B(2),B(3),B(4)
C GO TO 6
C
C WRITE(6,913)N0,B(1),B(2),B(3),B(4)
C GO TO 6
C
C WRITE(6,914)N0,B(1),B(2),B(3)
C CONTINUE
C
C WRITE(6,920)IC0=80
C WRITE(6,921)IC0=IREG
C DU 505 1=1,5
C
C 595 CONTINUE
C
C CALL REGLPLT(B00,BP,IND,IRR)
C
C ERROR ANALYSIS
C
C 9001 WRITE(6,9017)
C 9002 WRITE(6,9018)
C GO TO 9033
C 9004 WRITE(6,9020)
C GO TO 9033
C 9006 WRITE(6,9022)
C GO TO 9033
C 9008 WRITE(6,9024)
C GO TO 9033
C
C 9009 WRITE(6,9027)
C 9011 WRITE(6,9029)
C 9013 WRITE(6,9031)
C 9015 WRITE(6,9033)
C 9017 WRITE(6,9035)
C GO TO 9033
C```

FORTRAN IV G LEVEL 21

0197 48 FOR.MAT(1) *** ERROR *** UNABLE TO DISTINGUISH SPEEDED/FEED *.
     *COMBINATIONS*!
0198 51 FOR.MAT(1)//1*TIO, THE PREDICTION EQUATION IS /*0 PI = //FIO.4,
     * + *FLJ.4*LN(SPEEDED) + /*FIO.4*MNFEED()!.
0199 56 FOR.41//(1*TIO, THE PREDICTION EQUATION IS /*0 PI = //FIO.4,
     * + *FLJ.4*LN(SPEEDED) + /*FIO.4*MNFEED()!.
0200 53 FOR.MAT(1)//1*TIO, THE PREDICTION EQUATION IS /*0 PI = //FIO.4,
     * + *FLJ.4*LN(SPEEDED) + /*FIO.4*MNFEED()!.
0201 54 FOR.MAT(1)//1*TIO, THE PREDICTION EQUATION IS /*0 PI = //FIO.4,
     * + *FLJ.4*LN(SPEEDED) + /*FIO.4*MNFEED()!.
0202 55 FOR.MAT(1)//1*TIO, THE PREDICTION EQUATION IS /*0 PI = //FIO.4,
     * + *FLJ.4*LN(SPEEDED) + /*FIO.4*MNFEED()!.
0203 5U01 FOR.MAT(1,S21,5F10.4)
0204 5U02 FORMAT(S1)
0205 5U03 FOR.MAT(1,BF1.4)
0206 5U04 FOR.MAT(2,4A4)
0207 5V99 FOR.MAT(1,T01,'A C H D P')
0208 6000 FOR.MAT(1001,0,20/4A)
0209 6001 FOR.MAT(10*,T20,0,20/4A)
0210 6002 FOR.MAT(10*,T20,0,20/4A)
0211 6003 FOR.MAT(10*,T20,0,20/4A)
0212 6004 FOR.MAT(10*,T20,0,20/4A)
0213 6005 FOR.MAT(10*,T20,0,20/4A)
0214 6006 FOR.MAT(10*,T20,0,20/4A)
0215 6007 FOR.MAT(10*,T20,0,20/4A)
0216 6008 FOR.MAT(10*,T20,0,20/4A)
0217 6009 FOR.MAT(10*,T20,0,20/4A)
0218 6010 FOR.MAT(10*,T20,0,20/4A)
0219 6011 FOR.MAT(10*,T20,0,20/4A)
0220 6012 FOR.MAT(10*,T20,0,20/4A)
0221 6013 FOR.MAT(10*,T20,0,20/4A)
0222 6014 FOR.MAT(10*,T20,0,20/4A)
0223 6015 FOR.MAT(10*,T20,0,20/4A)
0224 6016 FOR.MAT(10*,T20,0,20/4A)
0225 6017 FOR.MAT(10*,T20,0,20/4A)
0226 6018 FOR.MAT(10*,T20,0,20/4A)
0227 6019 FOR.MAT(10*,T20,0,20/4A)
0228 6020 FOR.MAT(10*,T20,0,20/4A)
0229 6021 FOR.MAT(10*,T20,0,20/4A)
0230 6022 FOR.MAT(10*,T20,0,20/4A)
0231 6023 FOR.MAT(10*,T20,0,20/4A)

DATE = 73361 15/21/16

MAIN 2710
MAIN 2720
MAIN 2730
MAIN 2740
MAIN 2750
MAIN 2760
MAIN 2770
MAIN 2780
MAIN 2790
MAIN 2795
MAIN 2800
MAIN 2810
MAIN 2820
MAIN 2830
MAIN 2840
MAIN 2850
MAIN 2860
MAIN 2870
MAIN 2880
MAIN 2890
MAIN 2900
MAIN 2910
MAIN 2920
MAIN 2930
MAIN 2940
MAIN 2950
MAIN 2960
MAIN 2970
MAIN 2980
MAIN 2990
MAIN 3000
MAIN 3010
MAIN 3020
MAIN 3030
MAIN 3040
MAIN 3050
MAIN 3060
MAIN 3070
MAIN 3080
MAIN 3090
MAIN 3100
MAIN 3110
MAIN 3120
MAIN 3130
MAIN 3140
MAIN 3150
MAIN 3160
MAIN 3170
MAIN 3180
MAIN 3190
MAIN 3200
MAIN 3210
MAIN 3220
MAIN 3230
MAIN 3240
FORTRAN IV G LEVEL 21       MAIN         DATE = 73361  15/21/16

0231  6024 FORMAT(*'**',T10,'NUMBER OF TCCLS IS ',T5,110)     MAIN3250
0232  6025 FORMAT(*'**',T10,'NUMBER OF TOOLS IS ',T5,110,' ERROR **') MAIN3260
0233  6026 FORMAT(*'**',T10,'SPECIFIED TCCL COST NEGATIVE ERROR **') MAIN3270
0234  6027 FORMAT(*'**',T10,'COST MISSING')
0235  6028 FORMAT(*'**',T10,'EXPECTED TERMINATION OF DATA */D') MAIN3280
0236  6029 FORMAT(*'**',T10,'TITLE CARD MISSING')
0237  6030 FORMAT(*'**',T10,'UNEXPECTED TERMINATION OF DATA */D') MAIN3290
0238  6031 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3300
0239  6032 FORMAT(*'**',T10,'TITLE CARD')
0240  6033 FORMAT(*'**',T10,'PRECEEDING')
0241  6034 FORMAT(*'**',T10,'MAIN PROBLEM CARD MISSING')
0242  6035 FORMAT(*'**',T10,'INVALID CHARACTER ENCOUNTERED */D') MAIN3310
0243  6036 FORMAT(*'**',T10,'MAIN PROBLEM CARD')
0244  6037 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3320
0245  6038 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3330
0246  6039 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3340
0247  6040 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3350
0248  6041 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3360
0249  6042 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3370
0250  6043 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3380
0251  6044 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3390
0252  6045 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3400
0253  6046 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3410
0254  6047 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3420
0255  6048 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3430
0256  6049 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3440
0257  6050 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3450
0258  6051 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3460
0259  6052 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3470
0260  6053 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3480
0261  6054 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3490
0262  6055 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3500
0263  6056 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3510
0264  6057 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3520
0265  6058 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3530
0266  6059 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3540
0267  6060 FORMAT(*'**',T10,'ERROR INVALID CHARACTER ENCOUNTERED */D') MAIN3550

END
SUBROUTINE NUCYCL

SUBROUTINE NUCYCL IS USED FOR PROCESSING ALL PHASE/ CYCLE COMBINATIONS. NUCYCL PREPARES THE INPUT DATA FOR BOTH THE EVAP AND REGRESSION PROCESSES.

DIMENSION TEMP(4,24)

COMMON /CI02/ I, MCYC, SCYCLE, RLC, X(24,100), Y(12,100), NUBS, NOBS
* 10P, RSP, BUC4, NTIC, TIC (20)

COMMON /CI03/DIFF(2,4), SUM(2,4), AVE(2,4), SUM3(2,4), AVE3(2,2)

COMMON /CI07/ID(O4), SMAX, SMIN, FMAX, FMIN

DO 9 I=1,2

NUCY 10
NUCY 20
NUCY 30
NUCY 40
NUCY 50
NUCY 60
NUCY 70
NUCY 80
NUCY 90

C
C     INPUT NEW OBSERVATIONS
C
C 0011 NUBS=1
C 0012 NUB=NUBS+1
C 0013 NOB=NGUS+3
C 0014 REAC(5,532,END=9017,ERP=9016) (X1 J, NOBS, J, 1, NTIC CP)
C 0015 IF (X1, NOBS) EQ .0 .123451) GO TO 701
C 0016 D = 66 J = VIAM, N0H4
C 0017 66 REAC(5,532, END=9015, ERP=9016) (X1 J, 1, NTIC CP)
C 0018 NOB=NUHS+4
C 0019 GO TO 703
C
C
C     INPUT THE DATA FROM THE PREVIOUS CYCLE
C
C 0020 REAC(S,532,END=9011, ERP=9012)
C 0021 IF (AVE(S,1,2),NE,0.) AVE(S,1,2) = AVE(S,1,2) + AVE(S,1,2)
C 0022 IF (AVE(S,2,2),NE,0.) AVE(S,2,2) = AVE(S,2,2)
C
C
C     SCRT POINTS INTO CORRECT SEQUENCE
C
C 0023 NUB = NUB + 1
C 0024 NUH = NUH + 3
C 0025 DU 45 I = 1
C 0026 DU 45 J = 1, NTIC CP
C 0027 45 TEMP(I,J)=X1(NUMB, J, 1)+1
C 0028 SPMK= TEMP(I,J)
C 0029 SPK=M TEM P(I,J)
C 0030 FEMF= TEMP(I,J)
C 0031 FEMK=F TEM P(I,J)
C 0032 DO 10 1=1,2
C 0033 IF (TEMP(I,J),LE,SPMK) SPK=TEMP(I,J)
C 0034 IF (TEMP(I,J),LE,SPMK) SPK=TEMP(I,J)
C 0035 IF (TEMP(I,J),LE,SPMK) SPK=TEMP(I,J)

99
IF (TEMP(1,2).GE.FCMP) FDMA = TEMP(1,2) CONTINUE
DO 11 I = 1,4
J=0
IF (TEMP(1,1).EQ.SPPA.AND.TEMP(1,2).EQ.FDMA) J=1
IF (TEMP(1,1).EQ.SPPA.AND.TEMP(1,2).EQ.FDMA) J=2
IF (TEMP(1,1).EQ.SPPA.AND.TEMP(1,2).EQ.FDMA) J=3
IF (TEMP(1,1).EQ.SPPA.AND.TEMP(1,2).EQ.FDMA) J=4
IF (J.EQ.3) GO TO 15

C CALCULATE THE RESPONSE VARIABLES
DO 11 K=1,NTLCP
X(K,J+1,J-1)*TEMP(1,K)
CONTINUE
DO 40 I=1,NOBS
Y(2,I)=X(3,I)/X(4,I)
Y(1,I)=X(2,I)/X(4,I)
DO 47 J=5,NTLCP
47 Y(1,I)=Y(1,I)*X(J,I)*TLC(J-4)
46 Y(1,I)=Y(1,I)/X(3,I)
PLOT THE INPUT POINTS
CALL ORGPTS(SPM1,SPPA,FDM1,FCMA,3)
PRINT THE INPUT DATA AND RESPONSES.
WRITE(6,/)C02
J=1,NOBS
HKJ T(JO,JK)(X(I,J),I-1,NTLCP)
WKL T(6,/Y(K,J),K=1,2)
TABULATE THE RESPONSES
CALL PLOTPHMJU81
IF (ICYC.EQ.1) GO TO 12
RETURN

C PREPARE THE DATA FOR E V O P
DO 14 I=1,4
UO 14 J=1,2
SUM(J,1)=0.0
AVE(J,1)=0.0
RETURN
WRITE(6,/)9027
GU TO 9033
WRITE(6,/)9028
GU TO 9033
WRITE(6,/)9030
GU TO 9033
WRITE(6,/)9031
GU TO 9033
WRITE(6,/)9032
GU TO 9033
WRITE(6,/)9033
GU TO 9033
WRITE(6,/)9034
GU TO 9033
WRITE(6,/)9035
GU TO 9033
WRITE(6,/)9036
GU TO 9033
WRITE(6,/)9037
GU TO 9033
WRITE(6,/)9038
GU TO 9033
WRITE(6,/)9039
GU TO 9033
WRITE(6,/)9040
GU TO 9033
WRITE(6,/)9041
GU TO 9033
WRITE(6,/)9042
GU TO 9033
WRITE(6,/)9043
GU TO 9033
WRITE(6,/)9044
GU TO 9033
WRITE(6,/)9045
GU TO 9033
WRITE(6,/)9046
GU TO 9033
WRITE(6,/)9047
GU TO 9033
WRITE(6,/)9048
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GU TO 9033
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WRITE(6,/)9100
GU TO 9033
WRITE(6,/)9101
GU TO 9033
WRITE(6,/)9102
GU TO 9033
WRITE(6,/)9103
GU TO 9033
WRITE(6,/)9104
GU TO 9033
WRITE(6,/)9105
GU TO 9033
WRITE(6,/)9106
GU TO 9033
WRITE(6,/)9107
GU TO 9033
WRITE(6,/)9108
GU TO 9033

100
FORTRAN IV G LEVEL 21

NUCYCL DATE = 73361 15/21/16

0075 9015 WRITE(6,9031)
0076 GO TO 9033
0077 9016 WRITE(6,9032)
0078 9033 CALL EXIT
0079 15 IF TEMP(I,1),NE.SPML,AND,TEMP(I,1),NE.SPMA)JK=3
0080 15 IF TEMP(I,2),NE.FDML,AND,TEMP(I,2),NE.FDMA)JK=JK+1
0081 GO TO (15/17,10,18,19),JK
0082 17 WRITE(6,9034)
0083 GO TO 9034
0084 GO TO 9033
0085 18 WRITE(6,9035)
0086 GO TO 9033
0087 19 WRITE(6,9036)
0088 GO TO 9033
C
C FORMATS
0089 5311 FORMT(6E13.8/6E13.8/6E13.8/2E13.8,412)
0090 5312 FORMT(13F10.4)
0091 6021 FORMAT(11',T20,31X,') INPUT VALUES AND COMPUTED RESPONSES''/''
0092 *0',''SPEED FEED PARTS TIME,T51,20X,
0093 *T3L-EDGES,T105,' CJST PROD RATE'',T51,
0094 * (1) (3) (4) (5) (6) (7) (8)',NUCY1310
0095 * (9) (10),T105, ' (3/PIECE) (PIECES/MIN)'
0097 (19) (20)
0098 FORMATT(13F10.0)
0099 FORMATT(13F10.2)
0100 FORMATT(13F10.4)
0101 FORMATT(13F10.6)
0102 FORMATT(13F10.8)
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0158 END
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FORTAN IV G LEVEL 21  EVOP  DATE = 73361  15/21/16

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102
GO TO 45
0035 44 DO 467 I=1,2
0036 467 $NEW(I)=J+0
0037 467 $SUM(I)+$SUM(I)
0038 467 $SAVE(I)+$AVE(I)
C C
C CALCULATE 2 STANDARD ERROR ESTIMATES
C C
0039 45 DO 468 I=1,2
0040 468 $SAVE(I)=2./$SUM(SCYCLE)*$SAVE(I)
0041 468 $MEAN(I)=1./$SUM(SCYCLE)*$SAVE(I)
0042 468 $IF $SAVE(I)+$AVE(I)=1./$SUM(SCYCLE)*$SAVE(I)
0043 468 CONTINUE
C C
C COMPUTE SUMS AND AVERAGES
C
0044 47 DO 11 I=1,4
0045 11 J=1,2
0046 11 SUM(J,I)=SUM(J,I)+Y(J,NUR*1+I-1)
0047 11 $AVE(J,I)=SUM(J,I)/$CYCLE
C C
C FINISH PRINTING THE EVOP TABLE
C
0048 56 WRITE(60603)((Y(J,I),I=1,4,J=1,4),J=1,2)
0049 60603 WRITE(60604)((DIFF(J,I),I=1,4,J=1,2)
0050 60604 WRITE(60605)((SLP(J,I),I=1,4,J=1,2)
0051 60605 WRITE(60606)((AVE(J,I),I=1,4,J=1,2)
0052 60606 WRITE(60607)
C C
C SAVE COMPUTED VALUES FOR FUTURE CYCLES
C
0053 60621 WRITE(60621)SUMS(1),SUMS(2)
0054 60621 WRITE(60621)SAVE(1),SAVE(2)
0055 60621 WRITE(60621)MEAN(1),MEAN(2)
0056 60621 WRITE(60621)RANGE(1),RANGE(2)
0057 60621 WRITE(60621)SAVE(1),SAVE(2)
0058 60621 WRITE(60621)
C C
C ANALYZE THE EFFECTS
C
0059 60700 WRITE(7,7100)!
0060 7100 !((SUM(J,I),I=1,4),$SUM(J), (AVE(J,I),I=1,4),$SAVE(J),J=1,2),!
0061 7100 !((INCl(I),I=1,4)
C C
C ANALYZE THE EFFECTS
C
0062 144 AVE(2,1)=AVE(2,1)
0063 144 $IG=1
0064 144 ISP=1
0065 144 IF0=1
0066 145 GO TO (146,147,148)
0067 146 $GO TO 149
0068 147 WRITE(6,150)
0069 150 IF $SAVE(1),EQ.0.0)GO TO 999

103
C CALCULATE THE EFFECTS OF THE VARIABLES
C
C EFFA=(AVE(I0G,2)+AVE(I0G,3)-AVE(I0G,1)-AVE(I0G,4))/2.
C EFFB=(AVE(I0G,2)+AVE(I0G,4)-AVE(I0G,3)-AVE(I0G,1))/2.
C EFFC=(AVE(I0G,1)+AVE(I0G,2)-AVE(I0G,3)-AVE(I0G,4))/2.
C IA=C
C IF(ABS(EFFA)-AVE(I0G))/30,31,31
C THE EFFECT OF SPEED IS NOT SIGNIFICANT
C
C 0075 WRITE(6,6611)EFFA
C 0076 GO TO 32
C THE EFFECT OF SPEED IS SIGNIFICANT
C
C 0077 IA=IA+1
C 0078 WRITE(6,6611)EFFB
C 0079 IF(ABS(EFFB)-AVE(I0G))/33,34,34
C THE EFFECT OF FEED IS NOT SIGNIFICANT
C
C 0080 WRITE(6,6614)EFFB
C 0081 GO TO 39
C THE EFFECT OF FEED IS SIGNIFICANT
C
C 0082 IA=IA+2
C 0083 WRITE(6,6613)EFFB
C 0084 IF(ABS(EFFB)-AVE(I0G))/36,37,37
C THE EFFECT OF THE INTERACTION IS NOT SIGNIFICANT
C
C 0085 WRITE(6,6614)EFFAB
C 0086 GO TO 38
C THE EFFECT OF THE INTERACTION IS SIGNIFICANT
C
C 0087 IA=IA+3
C 0088 WRITE(6,6615)EFFAB
C 0089 IA=IA+1
C RECOMMEND THE NEW OPERATING CONDITIONS
C THE BASE POINT FOR SHIFTING OPERATIONS IS TAKEN TO BE THE
C LOWER LEFT POINT. ALL OTHER POINTS ARE DETERMINED AS
C DISPLACEMENTS FROM THIS POINT. SHIFTS TO A NEW SET OF
C OBSERVATIONS ARE DETERMINED BY SHIFTING THE BASE POINT
C AND REComputING THE OTHER THREE POINTS FROM THE NEW BASE.
C
C 0095 GO TO (999,1001,1002,1012,1013,1023,1123),IA
C NONE OF THE EFFECTS ARE SIGNIFICANT
C
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105
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<th>EVOP</th>
<th>DATE = 73361</th>
<th>15/21/16</th>
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<td>IFD=IFD-1</td>
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<td>0125</td>
<td>GO TO 1030</td>
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<td>IFU=IFD+1</td>
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<td>GO TO 1000</td>
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<td>2011 ISP=ISP+1</td>
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<td>GO TO 1000</td>
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<td>GO TO 2015</td>
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<td>SPEED AND THE INTERACTION ARE SIGNIFICANT</td>
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FORTRAN IV LEVEL

DATE = 7/346L

15/2/16

EV012700
EV022700
EV032700
EV042700
EV052700
EV062700

EV072700

EV082700
EV092700
EV102700
EV112700
EV122700

EV132700
EV142700
EV152700
EV162700
EV172700
EV182700

EV192700

EV202700
EV212700
EV222700
EV232700
EV242700

EV252700

EV262700
EV272700
EV282700
EV292700
EV302700

EV312700
EV322700
EV332700
EV342700
EV352700
EV362700

EV372700

EV382700
EV392700
EV402700
EV412700
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EV432700

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EV452700
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EV492700

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EV522700
EV532700
EV542700

EV552700

EV562700
EV572700
EV582700
EV592700
EV602700

EV612700
EV622700
EV632700
EV642700
EV652700
EV662700

EV672700

EV682700
EV692700
EV702700
EV712700
EV722700

EV732700

EV742700
EV752700
EV762700
EV772700
EV782700
PARAMETERS

M E S I G N I F I C A N T

THE PREVIOUS SETTING

CALCULATION OF STANDARD DEVIATIONS

F V A R I A N C E S

S T A N D A R D D E V I A T I O N S

F O R M A T ( I , 1 2 3 4 )
FOIFAN IV G LEVEL 21 ORG P5 S DATE = 73361 15/21/16

0001 C SUBROUTINE ORGPTS (SF1,SP2,FL1,FD2,IG0)
0002 C SUBROUTINE ORGPTS SELECT EACH DEFINED FEED-SPEED COMBINATION
0003 C AS a '1' ON A GRAPh AND INDICATES THE FOUR POINTS OF PARTICULAR
0004 C INTEREST WITH IN *!

0005 COMMON / :LOJ,SPD(100),FEED(100),NSPD(100),NSP(100)
0006 COMMON /C1,JSP(1),PT2,PT3,NAME(i),CHART(100),SG

0007 C READ IN THE FUNCTION FD(50)
0008 C IF SR. 1 = 1,3,6,9,10
0009 C FD(1) = 0.0
0010 C IF NS = 10C/NSPD
0011 C NF = 50/NSPD
0012 C NS1 = NS*NSPD
0013 C NF1 = NF*NSPD
0014 C ISP1 = 1
0015 C ISP2 = 1
0016 C NF01 = 1
0017 IF (ISP1.EQ.0.AND.ISP2.EQ.0) CONTINUE
0018 C IF (JS = 1,4,7) CONTINUE
0019 C IF (JS = 1,4,7) CONTINUE
0020 C IF (JS = 1,4,7) CONTINUE
0021 C IF (JS = 1,4,7) CONTINUE
0022 C IF (JS = 1,4,7) CONTINUE
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0038 C IF (JS = 1,4,7) CONTINUE
0039 C IF (JS = 1,4,7) CONTINUE
0040 C IF (JS = 1,4,7) CONTINUE
0041 C IF (JS = 1,4,7) CONTINUE
0042 C IF (JS = 1,4,7) CONTINUE
0043 C IF (JS = 1,4,7) CONTINUE
0044 C IF (JS = 1,4,7) CONTINUE
0045 C IF (JS = 1,4,7) CONTINUE
0046 C IF (JS = 1,4,7) CONTINUE
0047 C IF (JS = 1,4,7) CONTINUE

109
FORTRAN IV G LEVEL 21  ORGPTS  DATE = 74045  14/04/47

0048  11  SPNE(IJ)=SPEED(I)
0049  00  WRITE(6,70)
0050  *WRITE(6,71)(SPNE(I),I=1,NSPD)
0051  00  WRITE(6,72)
0052  00  CHART(ISP,1,AFD11)=PT3
0053  00  CHART(ISP,2,AFD21)=PT3
0054  00  CHART(ISP,2,AFD21)=PT3
0055  00  RETURN
0056  C
C         FORMATS
C
0057  64  FORMAT(’1’,’T54’,’NEW CEST ENVIRONMENT’)
0058  65  FORMAT(’1’,’T55’,’NEW PRODUCTION RATE ENVIRONMENT’)
0059  66  FORMAT(’1’,’T56’,’SPECIFIED ENVIRONMENT’)
0060  67  FORMAT(’ ’,1A1,’ ’,10X,’ ’,2X, ’1’,’2X,’100A1)
0061  68  FORMAT(’ ’,1A1,’ ’,12X,’1’,2X,’100A1)
0062  70  FORMAT(’ ’,4X,’I’)
0063  71  FORMAT(’ ’,7X,’10F10.0’)
0064  72  FORMAT(’ ’,7X,’S P E E D (R P M)’)
0065  END
FORTAN IV G LEVEL 21  FLOTPM  DATE = 73361  15/21/16

0061  SUBROUTINE FLOTPM(II)  PLOT 10
     C  PLOT 20
     C  PLOT 30
     C  AND SPEEDS.
     C  PLOT 40
     C  PLOT 50
     C
0062  CALL /C12/IF,ICY,SCYCLE,RLO,X(24,100),Y(2,100),NOBS,NUBL
     *  IUP,NSP,BFD,NILC,TLC(20)
0063     12+II+1  PLOT 60
0064     I3+II+2  PLOT 70
0065     14*II+3  PLOT 80
0066     I5+II+4  PLOT 90
0067     WRITE(6,72)  PLOT 100
0068     END  PLOT 110
0069     RETURN  PLOT 120
0070     PLOT 130
0071     RETURN  PLOT 140
0072     PLOT 150
0073     PLOT 160
0074     FORMAT(10,D0X,F16.4)  PLOT 170
0075     COST = 'F10.2,16X,'  COST = 'F10.2
0076     *'F10.2
0077    assel(F10.4,F10.4,'PRCO FI = ',F10.4//  PLOT 180
0078     *'F10.4
0079     '*F10.2
0080     assel(F10.4,F10.4,'PRCO FI = ',F10.4//  PLOT 190
0081     *'F10.2
0082     '*F10.4
0083     assel(F10.4,F10.4,'PRCO FI = ',F10.4//  PLOT 200
0084     *'F10.2
0085     '*F10.4
0086     assel(F10.4,F10.4,'PRCO FI = ',F10.4//  PLOT 210
0087     *'F10.2
0088     '*F10.4
0089     assel(F10.4,F10.4,'PRCO FI = ',F10.4//  PLOT 220
0090     *'F10.2
0091     '*F10.4
0092     assel(F10.4,F10.4,'PRCO FI = ',F10.4//  PLOT 230
0093     *'F10.2
0094     '*F10.4
0095     assel(F10.4,F10.4,'PRCO FI = ',F10.4//  PLOT 240
0096     *'F10.2
0097     '*F10.4
0098     END  PLOT 250

111
113
FORTRAN IV LEVEL 21     REGRES     DATE = 73361     15/21/16

OUC1
C SUBROUTINE REGRES (X,Y,N,IREG,RSUM,PHAT,IDEP)
C C SUBRATINE REGRES COMPUTES A MULTIPLE LINEAR REGRESSION ON
C M VARIABLES WITH N OBSERVATIONS. EQUATIONS USED ARE:
C PI = A0 + A1 LN(SPEED) + A2 LN(FEED)
C PI = B0 + B1 LN(SPEED) + B2 LN(FEED) + B3 LN(SPEED)*LN(FEED)
C + B4 LN(SPEED)**2 + B5 LN(FEED)**2
C PI = B0 + B1 LN(SPEED) + B2 LN(FEED) + B3 LN(SPEED)*LN(FEED)
C + B4 LN(FeED)**2 + B5 LN(FeED)**2
C C DIMENSION IND(5),YBAR(2)
D DIMEN5I X(N5,105), Y(210OJ), DJML(5.5), XPHI(5.6)
O0C4 C DIMEN5I XBAR(5), RADI(5), S(51,7(51),THAT(100),
C #11F I(51,5), #5Y(25), SST(2)
O0C5 C #11E I(51) #5X(55), #5Y(25)
O0C6 C NP = N
O0C7 C EPS = 1.0E-05
O0C8 C 50 N = 5
O0C9 C XN = N
O0C0 C MP = M+1
O0C1 C IF(IDEP,EQ,1) GO TO TC 30
O0C2 C DJ 10 J = 1,5
O0C3 C DJ 10 J = 1,5
O0C4 C 10 #X(1+J) = DJML(I+J)
O0C5 C UD II IM = 1,5
O0C6 C 11 #X(1+J) = #X(2+J)
O0C7 C GO TO 139
C C COMPUTE THE MEANS
C C 50 DJ 40 J = 1,NP
O0C8 C AI(1+J) = ALOG10(#X(1+J))
O0C9 C X(2+J) = ALOG10(#X(2+J))
O0C10 C X(3+J) = #X(1+J) #X(2+J)
O0C11 C A(4+J) = #X(1+J) * #X(2+J)
O0C12 C #X(5+J) = #X(2+J) #X(2+J)
O0C13 C 40 CONTINUE
O0C14 C DO 60 J = 1,2
O0C15 C YBAR(J) = 0.0
O0C16 C D0 60 I = 1,N
O0C17 C 60 YBAR(J) = YBAR(J) + Y(I)/XN
O0C18 C DO 30 J = 1,N
O0C19 C XBAR(J) = 0.0
O0C20 C DO 7C I = 1,N
O0C21 C 70 XBAR(J) = XBAR(J) + X(I,J)/XN
O0C22 C REG 10
O0C23 C REG 20
O0C24 C REG 30
O0C25 C REG 40
O0C26 C REG 50
O0C27 C REG 70
O0C28 C REG 90
O0C29 C REG 100
O0C30 C REG 110
O0C31 C REG 120
O0C32 C REG 130
O0C33 C REG 140
O0C34 C REG 150
O0C35 C REG 160
O0C36 C REG 170
O0C37 C REG 180
O0C38 C REG 190
O0C39 C REG 200
O0C40 C REG 210
O0C41 C REG 220
O0C42 C REG 230
O0C43 C REG 240
O0C44 C REG 250
O0C45 C REG 260
O0C46 C REG 270
O0C47 C REG 280
O0C48 C REG 290
O0C49 C REG 300
O0C50 C REG 310
O0C51 C REG 320
O0C52 C REG 330
O0C53 C REG 340
O0C54 C REG 350
O0C55 C REG 360
O0C56 C REG 370
O0C57 C REG 380
O0C58 C REG 390
O0C59 C REG 400
O0C60 C REG 410
O0C61 C REG 420
O0C62 C REG 430
O0C63 C REG 440
O0C64 C REG 450
O0C65 C REG 460
O0C66 C REG 470
O0C67 C REG 480
O0C68 C REG 490
O0C69 C REG 500
O0C70 C REG 510
O0C71 C REG 520
O0C72 C REG 530
O0C73 C REG 540
FORTAN IV G LEVEL 21  REGRES  DATE = 73361  15/21/16

0033  80  CONTINUE
     C     COMPUTE THE SUMS OF SQUARES
     C
0034   DU 50  I=1,2
0035   SST(I)=0.0
0036   DU 50  J=1,N
0037   90  SST(I)=SST(I)+Y(I,J)-YBAR(J)*Y(I,J)-YBAR(J)
0038   DO 110  J=1,M
0039   DO 110  I=1,M
0040   APX(J,J) = 0.0
0041   DO 100  K=1,A
0042    100  APX(J,J)=XPX(J,J)+(X(J,K)-YBAR(J))*(X(J,K)-YBAR(J))
0043   CONTINUE
0044
0045   DU 13C  K=1,2
0046   DU 130  J=1,M
0047   APY(K,J) = 0.0
0048   DU 120  J=1,M
0049   APY(J,K) = 0.0
0050    12C  APY(K,J)*APY(K,J)*(X(J,J)-YBAR(J))*(Y(K,J)-YBAR(K))
0051   CONTINUE
0052   DO 14C  I=1,M
0053   140  APX(I,0) = APX(I,0) + APX(I,0)*APX(I,0)
0054   DO 135  I=1,M
0055   DO 135  J=1,N
0056   DUM(I,J) = APX(I,J)
0057   CONTINUE
     C     DETERMINIE THE FORM OF THE REGRESSION EQUATION AND
     C     INVERT THE X*P MATRIX
     C
0058   136  GU TC (1,1,1,1,1), IREG
0059   142  DU 144  I=1,3
0060   144  XPX(4,1)*XPX(5,1)
0061   144  XPX(1,4)*XPX(1,5)
0062   144  XPX(4,4)*XPX(5,5)
0063   143  M=6
0064   DO 141  I=1,M
0065    141  APX(I,5) = APX(I,6)
0066   CALL CICGWN(APX,EPS,D,1)
0067   LF (125(1),GE, EPS) GO TO 145
0068   GU TC 143
0069   151  M = 2
0070   151  XPA(I,3) = XPA(I,6)
0071   XPA(2,3) = XPA(2,6)
0072   GU TO 154
0073   CALL CICGWN(APX,EPS,D,1)
0074   LF (125(1),GE, EPS) GO TO 145
0075   IREG = 5
0076   DO 149  I=1,3
0077   DO 149  J=1,3
0078    149  APX(I,J)=DUM(I,J)
0079    149  M = 3

115
FORTPAN IV  G  LEVEL  21  REGRES DATE  =  73361  15/21/16

0060 DD  L47  I=1,3
0061 147 XPX(I,M) = XPX(I,1) - XPX(1,M)
0062 154 CALL DIMECN(XPX,M,EPS,0,1)
C C COMPUTE THE REGRESSION PARAMETERS
C C
0063 145 DD LSC I = 1,M
0064 150 BMT (I) = XPX(I,1)*BMT(1)
0065 0 = 0.0
0066 0086 SSR = 0.0
0067 0067 DD L6C I=1,M
0068 W = M + BMT(I)*XBAR(I)
0069 0085 BSUBU = YBAR(I*DEP) - W
0060 0060 C SUBMIT I = 1, M
0061 0056 SA = SSR*A + BMT(I) + BPV(I*DEP, I)
0062 0051 XM = M
0063 0052 XMSE = SSR/M:
0064 0053 SSE = SST(I*DEP) - SSR
0065 0054 XE = N-M-1
0066 0055 A = XE
0067 0056 XMSE = SSE/XE
0068 F = X*XMSE
0069 0048 UD L7C I=1,M
0070 0049 XM = XMSE + MSE/MD
0071 004C Sdad(I) = 2 YAT(I)
0072 010C T(I) = BMT(I)*ST(I)
0073 010D 170 CONTINUE
0074 0101 UD LVO I=1,M
0075 0104 YMAT(I) = BSUUM
0076 0105 UD LBU J=1,M
0077 0106 180 YAT(I) = YAT(I) + BMT(J)*X(I,J)
0078 0107 DUDD(I) = Y(I*DEP, I)- YAT(I)
0108 0108 190 CONTINUE
0109 0109 WRITE (6,503) M,N
C C OUTPUT THE REGRESSION RESULTS
C C
0110   0110 IF OUTPUT OF THE X'X, X'Y, (X'X)^-1 & RESIDUALS IS DESIRED, +1
C C THE FOLLOWING COMMENT CARDS SHOULD BE ACTIVATED BY
C C REMOVING THE C'S
C C
0111 0111 0110 GO TO (521,522),IDEP
0112 0112 521 WRITE(6,521)
0113 0113 522 GO TO 523
0114 0114 523 WRITE(6,524)
0115 0115 524 WS0 = SS0/SST(I*DEP)
C C WRITE (6,505)
0116 0116 525 WRITE(6,505)
C C WS0 = SST(I*DEP)
0117 0117 DD L200 J=1,M
C C WRITE (6,510) I,(XPCI(I,J),J=1,M)
0118 0118 WRITE(6,510)
C C WRITE (6,515)
0119 0119 DD L210 I=1,M
C C WRITE (6,510) I,XPY(I*DEP, I)
0120 0120 WRITE(6,510)
C C WRITE (6,507)
FOK1FAN I V G LEVEL 21  REGRES  DATE = 73361  15/21/16

C DO 260 1=1,N
C220 WRITE (6,501) I,(XP(X(1,J),J=1,M)
0115 N1 = N - 1
0116 WRITE (6,502) N1,(SST(1:DEP),4,S0R,3X,MR,6,S0E,5X,K,5X,SSE,5X,PS)
0117 WRITE (6,510) 0SUEC
0118 DO 260 1=1,N
0119 WRITE (6,511) I, (T(I),I=1,STD(I)
C WRITE (6,512)
C DO 240 1=1,N
C240 WRITE (6,513) I, (Y(I,DEP,1),YMAT(I),DIFF(I)
C KEYVAR
C FORMATS
C
0121 503 FORMAT (11,(2,6X,22H MULTIPLE REGRESSION ON, I3, 15H VARIABLES WITH REGRES))
C 15,15H OBSERVATIONALS //)
C504 FORMAT (11,2,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C505 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C506 FORMAT (11,2,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C507 FORMAT (11,2,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C508 FORMAT (11,2,6X,45X,13,1X,6F19.8/(12X,6E18.0))
0122 509 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C510 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C511 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C512 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C513 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C514 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C515 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
C516 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
0125 523 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
0126 524 FORMAT (11,4,6X,45X,13,1X,6F19.8/(12X,6E18.0))
0127 END

117
SUBROUTINE DIMEQN(A,N,EP,S,DET,NSOLUT)

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

118
Riemann 

```
0045 A(LLL,L4) = A(LLL,L4) - AJCK*A(IR,L4) 
0046 104 CONTINUE 
0047 1C0 CONTINUE 
0048 DO 105 I=1,N 
0049 IR = IP1V(I,1) 
0050 ICJ(IR) = JC 
0051 105 CONTINUE 
0052 ICT = U 
0053 NM1 = N-1 
0054 DO 106 I=1,NM1 
0055 IP1 = 1+1 
0056 DO 106 J = IP1,N 
0057 IF((ICJ(J).GE.ICJ(1))) GO TO 106 
0058 ITEMP = (ICJ(J)) 
0059 ICJ(J) = ICJ(1) 
0060 ICJ(J) = ITEMP 
0061 ICT = ICT + 1 
0062 106 CONTINUE 
0063 IF( (ICT/2)*2.NE.ICT) DET = DET 
0064 DO 107 J=1,N 
0065 JC = IP1V(J,1) 
0066 ICJ(J) = A(IR,J) 
0067 108 Y(JC) = A(IR,J) 
0068 DO 109 K=1,N 
0069 A(K,J) = Y(K) 
0070 UJ(J) = 1
0071 DO 110 K=1,N 
0072 UU(J) = 1
0073 IR = IP1V(J,J) 
0074 JC = IP1V(J,J) 
0075 111 Y(IR) = A(IR,J) 
0076 DO 110 K=1,N 
0077 A(I,K) = Y(K) 
0078 200 RETURN 
0079 END 
```
FOOTMAN IV G LEVEL 21

BLK DATA

DATE = 73361

15/21/16

0011  BLOCK DATA
0012  C
0013  C  DEFlNITION OF CCNSTANTS
0014  C
0015  C04MK /C104/F4N11C1
0016  C04MK /C105/PT1,FT2,PT3,NAME(50),CHART(100,50)
0017  C04MK /C105/INDU(4),SMAX,SMIN,FMAX,FMIN
0018  DATA F11/0.1,34,40,42,43,44,45,46,47,48
0019  DATA PT1,PT2,PT3/4,5,6,7,8,9,10
0020  DATA NAME/50*1
0021  DATA NAME(16),NAME(17),NAME(18),NAME(19),NAME(20)/*-17,'F','F,'F,'F'
0022  BLCK 110
0023  *11*1*1*1
0024  DATA NAME(21),NAME(24),NAME(26),NAME(28)/*-17,'F','F','F','F'
0025  BLCK 130
0026  DATA CPA1/5J00t1
0027  DATA 1ND/100,0,15,0/C
0028  DATA SMAX,SMIN,FMAX,FMIN/0,0,0,0,0,0
0029  BLCK 160
0030  END
0031  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

Start

Input Controls & Environment

Yes

Initial Cycle

No

Input Old EVOP Table

Input Old & New Observations

Order New Observations

Compute New EVOP Table

Output EVOP Table

Determine Significant Effects

Compute Regression Equation

Predict P.I. Values

Output Results

End

122
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

/*
PUNCHED OUTPUT FROM PREVIOUS CYCLE
NEW OBSERVATIONS (4)
OLD OBSERVATIONS
LIMITS FOR SPEEDS & FEEDS
DEFINED FEEDS
# OF FEEDS
DEFINED SPEEDS
# OF SPEEDS
TOOLING COSTS
MAIN PROBLEM CARD
TITLE CARD
//GO.SYSIN DD *
/*
BLOCK DATA
DIMEQN
REGRES
REGPLT
PLOTPM
ORGPTS
EVOP
NUCYCL
MAIN
//FORT.SYSIN DD *
// EXEC FORTRAN
// JOB

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 (513, T21, 5F10.4) (Required)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPH</td>
<td>Current Phase Number (Right justified)</td>
</tr>
<tr>
<td>ICYC</td>
<td>Current Cycle Number (Right justified)</td>
</tr>
<tr>
<td>IOP</td>
<td>Operation Type: IOP= 1: single operation (Right justified) 2: multiple operation 3: numerically controlled operation (N/C)</td>
</tr>
<tr>
<td>IMAX</td>
<td>1: If limits for speed and feed are specified (Right justified) 0: Otherwise</td>
</tr>
<tr>
<td>NTLC</td>
<td>Number of different tools (Right justified)</td>
</tr>
<tr>
<td>RLO</td>
<td>Rate for labor and overhead</td>
</tr>
<tr>
<td>AVES(COST)</td>
<td>Preliminary estimate of the standard deviation of the cost observations</td>
</tr>
<tr>
<td>AVES(P/R)</td>
<td>Preliminary estimate of the standard deviation of the production rate observations</td>
</tr>
<tr>
<td>BSP</td>
<td>Base speed for N/C operations (Must be present when IOP=3, cc 7-9)</td>
</tr>
<tr>
<td>BFD</td>
<td>Base feed for N/C operations (Must be present when IOP=3, cc 7-9)</td>
</tr>
</tbody>
</table>
3. Tool Cost Card (Required)

<table>
<thead>
<tr>
<th>cc</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>TLC(1)</td>
<td>Cost of a tool edge for tool no. 1</td>
</tr>
<tr>
<td>11-20</td>
<td>TLC(2)</td>
<td>Cost of a tool edge for tool no. 2</td>
</tr>
<tr>
<td>21-30</td>
<td>TLC(3)</td>
<td>...</td>
</tr>
</tbody>
</table>

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 (NSPD = 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 (NFD = 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 IMAX = 1, cc. 10-12 M.P.C.

<table>
<thead>
<tr>
<th>cc</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>SMAX</td>
<td>Maximum speed allowed for this operation</td>
</tr>
<tr>
<td>11-20</td>
<td>SMIN</td>
<td>Minimum speed allowed for this operation</td>
</tr>
<tr>
<td>21-30</td>
<td>FMAX</td>
<td>Maximum feed allowed for this operation</td>
</tr>
<tr>
<td>31-40</td>
<td>FMIN</td>
<td>Minimum feed allowed for this operation</td>
</tr>
</tbody>
</table>

*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)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1,i)</td>
<td>Observed speed setting (rpm)</td>
</tr>
<tr>
<td>X(2,i)</td>
<td>Observed feed setting (ipr)</td>
</tr>
<tr>
<td>X(3,i)</td>
<td>Number of parts produced</td>
</tr>
<tr>
<td>X(4,i)</td>
<td>Time (in minutes) expended on this</td>
</tr>
<tr>
<td></td>
<td>operation</td>
</tr>
<tr>
<td>X(5,i)</td>
<td>Number of tool edges for tool #1</td>
</tr>
<tr>
<td>X(6,i)</td>
<td>Number of tool edges for tool #2</td>
</tr>
<tr>
<td>X(7,i)</td>
<td>...</td>
</tr>
</tbody>
</table>

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.

- P/O FROM PREVIOUS CYCLE
- NEW OBSERVATIONS (4)
- OLD OBSERVATIONS
- S/F LIMITS
- FEEDS DEFINED
  - # FEEDS
- SPEEDS DEFINED
  - # SPEEDS
- TOOL COSTS
- MAIN PROBLEM CARD
- TITLE CARD

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.
<table>
<thead>
<tr>
<th>Title Card</th>
<th>Identification of the Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Prob Card</td>
<td>IPH</td>
</tr>
<tr>
<td>Tool Cost Card</td>
<td>Tool Change</td>
</tr>
<tr>
<td>Speed</td>
<td>NSPD</td>
</tr>
<tr>
<td>Environment</td>
<td>Speed #1</td>
</tr>
<tr>
<td>Feed</td>
<td>NFC</td>
</tr>
<tr>
<td>Environment</td>
<td>Feed #1</td>
</tr>
<tr>
<td>Speed &amp; Feed Limits</td>
<td>MAX Speed</td>
</tr>
<tr>
<td>Observation</td>
<td>Speed</td>
</tr>
</tbody>
</table>

Figure G.1 MACHOP Input Formats
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 $X'y$.  

132
G.3 Systems Material

G.3.1 Flow Chart

**MAIN PROGRAM**
- Start
- Input Control Information
- Input Correct?
  - Yes
  - Redefine Speeds & Feeds to Within Limits
  - Input Observations
    - Determine ISP = Speed Index
    - Determine IFD = Feed Index
    - Compute EVOP Parameters
    - Compute Regression Parameters
    - Plot Results
  - End
  - Output Errors
  - NUCYCL
- End

**SUBROUTINE NUCYCL**
- Input Old & New Observations
- Initial Phase & Cycle
  - Yes
  - Input EVOP Table
    - Order Observations
      - Cost = (RLO*TIME + TLC*TLCH) / PARTS
      - PR = PARTS/TIME
    - Plot the Points
    - Print Input Data, Cost, & PR
    - Plot Observations
    - PLOTPM
  - No
- New Phase
  - Yes
    - Sum = 0
    - Ave = 0
    - Return
  - No

SUBROUTINE EVOP

EVOP
  Print EVOP Table
  Print Std. Error Estimates
  Do to End for Cost & P.R.
  Compute Effects
  IA = 0

  9

  [Diff = Ave - Y]
  [Range = YMAX - YMIN]
  [NEW S = RANGE/N - T4, NEW]
  [New Sum S = New S + Sum S]
  [New Ave S = New Sum S/2]

  [S.E. Ave =]
  [-2/\pi*New Ave S]

  Do to End for Cost & P.R.

  IA = IA + 3
SUBROUTINE PLOTPM

PLOTPM

Print Costs & PR for Defined Pts

Return

SUBROUTINE ORGPTS

ORGPTS

Convert Indices From NSPD & NTD to Chart (50, 100)

Sets Points of Interest

Print Chart

Compute the Speed Scale

Print Speed Scale

Return

SUBROUTINE REGPLT

REGPLT

Compute: Regression Equation

Print Estimates P.I.

End

SUBROUTINE REGRES

REGRES

Compute Means

Compute Sums of Squares

Calculate $X'X$ for $3 \times 3$ Equation

Invert $X'X$ Matrix

$X'X$ Singular

Yes

No

Compute Regression Coefficients

Compute ANOVA Table

Output Results

Return
### G.3.2 Glossary of Important Variables

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANS</td>
<td>Vector of regression results returned from REGRES subroutine</td>
</tr>
<tr>
<td>AVE</td>
<td>Vector of the averages in the EVOP routine</td>
</tr>
<tr>
<td>AVES</td>
<td>Estimate of the standard error in the EVOP table</td>
</tr>
<tr>
<td>B</td>
<td>Vector of estimates of the b-coefficients in the regression equation</td>
</tr>
<tr>
<td>CHART</td>
<td>100 x 50 matrix containing the plot output in the ORGPTS routine</td>
</tr>
<tr>
<td>DIFF</td>
<td>Vector of the differences between the average cost at a given point and the newly observed cost</td>
</tr>
<tr>
<td>FEED</td>
<td>Vector containing all defined feed settings in ascending sequence</td>
</tr>
<tr>
<td>F4N</td>
<td>Vector of the values of $f_{4,n}$ as defined in Box and Draper [3]</td>
</tr>
<tr>
<td>ICYC</td>
<td>Cycle number</td>
</tr>
<tr>
<td>IFD</td>
<td>Index containing the current feed setting</td>
</tr>
<tr>
<td>IPH</td>
<td>Phase number</td>
</tr>
<tr>
<td>ISP</td>
<td>Index containing the current speed setting</td>
</tr>
<tr>
<td>NFD</td>
<td>Number of feed settings defined in the environment of this operation</td>
</tr>
<tr>
<td>NOBS</td>
<td>Number of observations in the current cycle</td>
</tr>
<tr>
<td>NSPD</td>
<td>Number of speed settings defined in the environment of this operation</td>
</tr>
<tr>
<td>RLO</td>
<td>Labor and overhead rate as reported on the main problem card</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>SPEED</td>
<td>Vector of all defined speed settings in ascending sequence</td>
</tr>
<tr>
<td>SUM</td>
<td>Vector of the sums of the observations</td>
</tr>
<tr>
<td>SUMS</td>
<td>Sum of the estimates of the standard error of the observations</td>
</tr>
<tr>
<td>TLC</td>
<td>Tool edge cost</td>
</tr>
<tr>
<td>TLCH</td>
<td>Observed number of tool edges used</td>
</tr>
<tr>
<td>X</td>
<td>Matrix (5xn) of the input observations, both old and new. For observation n, &lt;br&gt;  X(1,n) = speed (rpm), &lt;br&gt;  X(2,n) = feed (ipr), &lt;br&gt;  X(3,n) = number of parts produced, &lt;br&gt;  X(4,n) = production time in minutes, and &lt;br&gt;  X(5,n) = number of tool edges used.</td>
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<tr>
<td>Y</td>
<td>Matrix (2xn) of the performance indices, both old and new. For observation n, &lt;br&gt;  Y(1,n) = cost (dollars/piece), and &lt;br&gt;  Y(2,n) = production rate (pieces/minute).</td>
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