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SEQUENCE DEPENDENT SET-UP TIMES: A PREDICTION METHOD AND AN ASSOCIATED TECHNIQUE FOR SEQUENCING PRODUCTION

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ABSTRACT

This study develops a systematic and economical method of predicting set-up times on machine tools that considers the dependency of the set-up times on the sequence in which the products are manufactured. In addition an easy-to-use approximate technique for sequencing a closed set of jobs on a single machine so as to minimize the aggregate set-up time is presented. This technique is based upon information from the predictive model.

A general discussion of classification systems for machine tool set-ups is followed by a case study on Mono-matic lathes. In this case study a set-up classification system for Mono-matic lathes is first developed, and then used as a basis for collecting set-up data. This data is then analyzed, and a prediction equation is specified including estimates for the coefficient values. This prediction equation is then tested using a second data sample; the correlation coefficient between the values predicted by the model and the actual values for the second sample is $\rho=.8383$.

The classification system developed for the predictive model is used as a basis for an approximate technique for sequencing a closed set of jobs on a single machine so as to minimize the aggregate set-up time. The classification information is used to identify subsets of jobs, and then the relative values of the predictive model coefficients are used to select from among the subsets the one that should be next

added as a sequence is built up. The proposed method operates so as to minimize the number of those types of changes which have the larger coefficient values. The total set of jobs is successively partitioned and a partial sequence is built up step by step until all of the jobs are included and the final production sequence is established. This approximate technique is contrasted to several other approximate techniques and to a modified Branch and Bound Algorithm. This approximate technique is based upon the fundamental characteristics of the set-up operations of the machine tool. An advantage of the technique is that, unlike the other methods of sequencing the jobs, it does not require the expected set-up time matrix to be completely written out, and because it uses the relative values of those predictive model coefficients which represent sequence dependent set-up characteristics it is not as sensitive to errors in the predictive model. The method does not require much computation and is shown to be a practical method for hand solution. In addition the method allows a new job to be easily inserted into the production sequence, whereas both the Branch and Bound Algorithm and the other approximate techniques require that a new problem with a different set-up matrix be solved. For two small sample problems the technique yields production sequences which are global optima.

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TABLE OF CONTENTS

		Page
ACKNOWLEDGEMENTS		ii
LIST OF TABLES		iv
LIST OF FIGURES		v
CHAPTER		
I	Introduction and Objectives	1
II	Selection of Machine Tools as Object of Study	3
III	Prediction Methodology	13
IV	Case Study	21
V	Sequencing Technique	43
VI	Conclusions and Extensions	64
APPENDICES		
A	Data Collection Forms	69
B	Testing Model Assumptions	74
C	Listing of Mono-matic Lathe Set-up Data	77
BIBLIOGRAPHY		80

LIST OF TABLES

Table		Page
I	Distribution of Set-up Times	9
II	Distribution of Adjustment Times	10
III	Distribution of Job Times	11
IV	Average Job Times and Average Percentage of Machine Time Spent on Set-up Operations	12
V	Equivalence Between Coefficients in Model (1) and Table VI	34
VI	Results of Analysis Using Model (1) with Initial Sample	34
VII	Actual and Predicted Values for Initial Sample Using Model (1)	35
VIII	Data of Validation Sample	40
IX	Actual and Predicted Values in Validation Study	41
X	Product-Process Characteristics of Jobs for Example 1	55
XI	Product-Process Characteristics of Jobs for Example 2	59
A-I	Mono-matic Lathe Set-up Data	78

LIST OF FIGURES

Figure		Page
1	Rough Illustration of Mono-Matic Lathe Showing Relevant Features	26
2	Graph of the Errors of Prediction for Model (2) with Initial Sample	38
3	Graph of Actual and Predicted Values in Validation Study	41
4	Tree Diagram Representation of Branch and Bound Solution for Example 1	51
5	Tree Diagram Representation of Branch and Bound Solution for Example 2	62
A-1	Set-up Time Log Form	69
A-2	Set-up Classification Form	73

CHAPTER I

INTRODUCTION AND OBJECTIVES

In those production systems where a single machine is used to produce more than a single product, a change in production from one product to another product is necessarily preceded by a change in either the machine settings, the input material, or both. The times and costs associated with such conversions are referred to in the production literature as change-over or set-up times and costs.

Maxwell[23] points out that it is common practice to partition the problem of scheduling such single machine production systems into machine loading and job sequencing. Loading means to first divide time into periods, days or weeks, and then to assign specific jobs to specific time periods; that is, to make the decision of which jobs will be worked on in each time period without regard to the order in which these jobs will be completed. Sequencing is to decide on the sequential order in which the jobs assigned to each time period will be worked on; that is, the order in which the single machine will produce the jobs assigned to a time period.

On most machine tools the time to set-up for a part is dependent on both this new part and the part the machine was set-up to produce before. If the machine is being set-up for a part similar to the part just completed, the set-up time will often be shorter than if the two parts are dissimilar.

Statistics of set-up times are of increasing importance as the cost of machine down-time increases due both to the increasing ratio of indirect to direct labor costs and to growing industrial complexity and competition. Nevertheless, set-up time statistics are often not available, and, in those plants where they are, it has been observed that they often fail to include the sequence dependency of these set-up times.

The impetus for the work developed in this dissertation was the hypothesis that sequentially dependent set-up times are a crucial part of the sequencing problem on machine tools and the observation that they are not explicitly considered in either the current production literature or in actual practice.

The objective of this dissertation is to develop a practical, easy-to-use technique for sequencing a closed set of jobs on a single machine tool so as to minimize the total expected set-up time. The reasons for selecting the machine tool as the object of study are discussed in Chapter II.

A systematic and economical method for studying set-up processes on machine tools is presented which is based upon classification of set-up operations. This classification information, which can both describe and differentiate between set-ups, is used to define variables which are then used in a predictive equation for set-up times on the machine tool. This mathematical prediction technique, which explicitly considers the sequential dependency of the set-up times is presented in Chapter III. A case study is presented in Chapter IV using actual data.

This classification information on the fundamental characteristics of the set-up operations and the relative values of the coefficients of the predictive model are then used as the basis for an approximate technique

for sequencing production. This technique is developed in Chapter V and is demonstrated via two sample sequencing problems. It is contrasted to several other techniques and is shown to be a practical method for hand solution.

CHAPTER II

SELECTION OF MACHINE-TOOLS IN THE METAL-WORKING INDUSTRIES

In the early stages of the investigations for this study conversations took place with manufacturing and engineering personnel in the chemical processing, glass making, and metal working industries. These conversations confirmed the hypothesis that set-up, or change-over, considerations are frequently important in plants in these industries. Although all of these industries presented interesting and challenging set-up problems, the decision was made to concentrate on machine tools in the metal working industry.

The metal working industries tower over other manufacturing industries both in employees and in value added by manufacture. Steel[36] reports that in 1965 the metal working industries employed 42% of all employees, contrasted to 9% for the food industries and 8% for the apparel industries. In the same year the metal working industries had sales of $221,048,000,000 and their value added by manufacture was $87,645,000,000 which was 46% of the national total.

Iron Age[18] reports that in 1963 there were 2.1 million metal cutting machine tools in the United States. Steel[37] reports yearly shipments of metal cutting machine tools of $598,500,000 in 1963, $791,800,000 in 1964, and $958,600,000 in 1965 with $164,100,000 in lathe family shipments in the first nine months of 1965. Moreover, B. H. Dyson[13] recognized the importance of understanding set-up operations in metal working:

> "So often the man who can make or mar the production effort (regardless of machine tool or equipment) - the machine setter - is ignored...On a particular accurate machining job, the set-up time was five hours for a production run of fifteen hours."

Set-up personnel are skilled labor and because of the high growth rate of the metal working industries demand for them is higher than the available supply. In January of 1966 Iron Age[40] quotes O. B. Werntz, Executive Vice-President of the National Screw Machine Products Association, as saying:

> "We can't get good production men either. A true set-up man who can do his own complete set-ups without guidance from the foreman can earn $10,000 without overtime and we are a high overtime industry. But there are few men with these capabilities."

Thus we see that the machine tool metal working industry is important, that set-up operations and personnel are important, and that set-up personnel are a scarce resource. On the basis of these facts we see that the savings that would result from a better understanding of set-up operations and the ability to predict the set-up times, taking into account their sequential nature, could be very large. In addition, in several metal-working plants in close proximity to Ann Arbor, Michigan, production and engineering personnel were willing to discuss manufacturing and set-up operations.

Within the metal-working industry there are production systems where high volume allows very long production runs for a product; in these situations the total amount of time spent on set-up is often very low in comparison to the total amount of production time. In one manufacturing plant several parallel production lines each produce just a few different products with little change in production between the products on an individual line. The percentage of time spent on set-up was estimated on the basis of a work sampling study to be approximately 5%.

On the other hand situations exist in the manufacture of small production quantities where the set-up time will exceed the production time for the lot. One situation was encountered where the set-up time for a "rush order" for a customer took roughly 24 hours, the processing time for the lot was 5 hours, and the time to re-set the machine was about 20 hours. Automatic screw machines often have set-up times in excess of 10 hours, and set-up times over 40 hours are common when major changes are made. In one shop the set-up times for major change-overs on large diameter, multiple spindle, automatic screw machines ranged from 42 hours to 65 hours depending on the machine size and type.

The percentage of time spent on set-up depends on both the frequency of change-over between products, which is a function of the production lot sizes and the production rates, and on the length of time spent on the individual set-ups. Although the manufacturing engineering literature discusses set-up operations, set-up times, and production rates for various items on machine tools, very little appears in the literature on the ratio of set-up times to lot production times in actual operating situations. In conversations with manufacturing personnel this information is frequently referred to as proprietary. For this reason the following article is especially interesting as it both discusses the set-up and sequencing problem on machine tools and gives some real-world data.

In The Production Engineer W. Rodgers[29] reports three operational research studies prepared by the Industrial Operations Unit of the Department of Scientific and Industrial Research. These three studies are in the areas of inventory, sequencing, and simulation. Rodgers states:

> "The three projects now presented are actual case studies carried out in British firms. The figures shown are actual and have not been altered in order to obtain neat and tidy solutions. The problems dealt with are the same as those occurring daily in thousands of other firms."

It is interesting to note that set-up times and costs are very much a part of all three studies.

In the inventory study set-up times and costs entered into the lot quantity calculations. This study will not be discussed.

In Rodgers' sequencing study the object was to put a fixed set of jobs through a single machine tool at minimum total machine set-up time between all jobs. Rodgers stated:

> "When the machine is reset for any particular job, it is obvious that the time spent in setting-up must be influenced by the nature of the job which has just been finished. Thus if the machine has to be re-set for 1/2 inch diameter bolts 1 1/2 inch long, setting-up times are likely to be short if the previous job was on 1/2 inch diameter bolts 1 inch long, but may be considerable if the previous job was on 7/16 inch setscrews 1 1/2 inch long.
>
> The present method of scheduling jobs to the machines is to rely on the judgment and experience of a member of the Production Control Department staff, who bears the above general considerations in mind when preparing his weekly programme. For two reasons it was decided that a more systematic approach to the problem was advisable, these being:
>
> i) no one can be certain that judgment and experience will always give the optimum answer each and every week;
>
> ii) the experienced man must take holidays, and may fall sick sometimes, and it is likely that any relief pressed into service at these times will provide solutions departing still further from the ideal."

Rodgers collected his set-up data from a machine set-up man, as it was not available elsewhere. The set-up man was presented with 16 jobs to be processed on a 3/8 inch bolt-making machine in one week and asked to

fill in all of the set-up times in a 16 x 16 "to-from" set-up time matrix (16 x 16 = 256, 256 - 16 = 240 entries needed). Using a systematic method, although it is not a universal solution guaranteed to yield an optimal, Rodgers showed a specific real case where his sequence having a total set-up time of 18 3/4 hours was better by 9 1/4 hours than the sequence selected by the Production Control man which had a total set-up time of 28 hours. He commented that the time saved on this particular schedule could be used to effectively increase the production capacity of the machine with a consequent increase in financial return.

Rodgers' simulation study was to determine the optimum number of set-up men to attend a specific number of machines. Seven cold forging machines were serviced by two set-up men. If a machine needed either adjustments to the tools or fixtures or to be set-up, it remained idle until one of the two set-up men was available to service it. The kinds of data necessary for this simulation study are listed below accompanied with the source of this data.

(1) Set-up times on each machine: no set-up time records were available so estimates were made by the foreman (these will be shown below).

(2) Adjustment times on each machine: direct observation for several days

(3) Running times between adjustments on each machine: direct observation for several days

(4) Production running times to process jobs on each machine: for each machine the order quantities were known for an eight month period and the run times were extracted by dividing these known production quantities by the known production rates for the jobs.

Two points of interest for this paper are that Rodgers had to use subjective rough estimates of set-up times per machine, but no job or pair of jobs in sequence was identified. Second, the job set-up times took up a sizable portion of the machine time. Specifically, it can be seen from the data in Table I that the smallest set-up time is approximately 50 minutes and, from Table III that averaging all machines, 14.8% of the jobs have running times of 50 minutes or less.

The specific data reported by Rodgers is briefly presented below. The set-up times are very rough as only three possible values were reported. The job running times were reported in cumulative frequency form with rather large jumps in job lengths. The data is real production data without modification for publication.

On the basis of the rough set-up time data available in Table I the average set-up time is 81.6 minutes. For the seven machines, from Table III, the probabilities that the job run times are 70 minutes or less are [.288, .123, .116, .243, .271, .349, .115]. Thus, we see that the set-up times do represent a substantial portion of the total production time for the jobs.

TABLE I

DISTRIBUTION OF SET-UP TIMES

Set-Up Times (mins.)	Frequency
46	.6
120	.2
150	.2

TABLE II

DISTRIBUTION OF ADJUSTMENT TIMES

Adjustment Times (min.)	Frequency
2	.237
4	.178
6	.131
8	.083
10	.119
12	.036
14	.048
16	.012
18	.036
20	.024
22	.012
24	.024
26	.012
28	--
30	.012
32	--
34	.024
36	.012

TABLE III

DISTRIBUTION OF JOB TIMES

Length of job (mins.)	M/c. No. 1	M/c. No. 2	M/c. No. 3	M/c. No. 4	M/c. No. 5	M/c. No. 6	M/c. No. 7
10	·039	·022	·024	·056	·065	·023	·025
30	·079	·022	·034	·032	·068	·072	·030
50	·097	·035	·034	·081	·068	·114	·020
70	·073	·044	·024	·074	·070	·140	·040
90	·084	·076	·049	·093	·084	·052	·066
110	·088	·102	·067	·081	097	·083	·056
130	·051	·054	·077	·081	·055	048	·072
150	·063	·112	067	·036	·089	·046	·045
170	·057	·079	·063	·074	·065	046	·081
190	·048	·040	·053	·056	·028	·040	·072
210	·042	·044	·063	·020	·023	·023	·040
230	·033	·070	·063	·048	·028	·020	·051
250	·027	·026	·039	·020	·025	·029	·040
270	·024	·013	·049	·028	·018	·017	·056
290	·033	·031	·029	·016	·008	·012	·051
310	·012	·018	·010	·028	·015	·014	·045
330	·024	·004	·019	·020	·023	·009	·005
350	·006	·013	·015	·016	·015	·014	·030
370	·009	·013	·049	·012	·008	—	·020
390	·006	·009	·024	·012	·010	·006	·020
410	·006	—	·019	·012	010	·026	·005
430	006	·009	·005	·012	·015	·014	·015
450	·012	·013	—	·012	·002	—	·005
470	·003	·009	·015	·004	·008	·006	·010
490	·009	·013	—	·008	008	·003	·010
510	·003	·035	·010	·012	·010	012	·005
530	·006	·004	·005	·004	·005	·003	·005
550	·003	·004	—	·008	·002	·006	—
570	—	·009	—	·004	·002	·014	—
590	—	·009	·024	—	·002	·006	·010
610	·003	·004	·005	—	·015	—	·005
630	—	·009	·005	—	·002	—	·005
650	·009	·013	—	·004	·008	·003	·020
670	—	009	005	—	002	·006	·005
690	·003	·004	·005	—	·002	·003	—
710	·006	—	·005	—	·008	·003	·005
730	·003	·004	—	—	—	·006	—
750	—	—	—	—	—	·006	—
770	—	—	·005	—	—	—	—
790	—	—	—	—	·005	003	—
810	003	—	—	004	002	·006	—
830	·003	—	005	—	—	—	—
850	—	—	—	—	·008	·006	—
870	·009	—	—	—	—	·003	·010
890	003	·004	—	—	—	—	·005
910	003	—	—	—	002	—	—
930	—	004	—	004	—	006	—
950	·003	—	—	004	008	003	—
970	—	—	—	—	—	—	—
990	—	—	—	—	002	—	005
1010	·003	—	·005	—	—	006	—
1030	—	009	—	004	—	—	—
1050	—	004	005	—	—	—	005
1070	—	—	—	—	—	003	—
1090	—	—	—	004	—	009	005
1110	—	—	—	—	002	—	—
1130	—	—	—	—	—	—	—
1150	—	—	—	—	—	—	—
1170	—	004	—	—	—	003	—
1190	—	—	—	004	—	003	—
1210	—	—	005	—	—	—	—
1230	—	—	—	—	—	003	—
1250	—	—	—	—	—	—	—
1270	—	—	—	—	—	—	—
1290	—	—	—	—	—	006	—
1310	—	—	—	—	—	003	—
1330	—	—	—	—	008	—	—
1350	—	—	005	—	—	—	—
1410	—	—	—	—	—	006	—
1490	003	—	005	004	—	—	—
1570	—	—	005	004	—	—	—
1610	—	—	005	—	—	—	—
1830	—	—	—	004	—	003	—
1990	—	—	—	—	—	003	—
2810	003	—	—	—	—	—	—

TABLE IV

AVERAGE JOB TIMES AND AVERAGE PERCENTAGE
OF MACHINE TIME SPENT ON SET-UP OPERATIONS

	Run Time	Run Time + Set-Up Time	In Set-Up
1	199.22	280.82	29.1%
2	239.36	320.96	25.4
3	268.38	349.98	23.3
4	211.98	293.58	27.8
5	206.08	287.68	28.4
6	246.92	328.52	24.8
7	248.30	329.90	24.7

Table IV contains the percentage the average set-up time is of the sum of the average set-up time plus the average job running time for each of the seven machines. Machine time and set-up man time are both scarce resources and any savings possible from reducing the total set-up time by finding advantageous sequences in which to work on any set of jobs could have a large dollar value.

In summary, the reasons for selecting machine tools in the metal working industry as the object of this study of set-up operations and set-up times are:

(1) The metal working industries represent a very large proportion of the manufacturing industries, in value added, in employees, and in value of manufacturing equipment.

(2) Several metal working plants are in close proximity to Ann Arbor, Michigan, where plant personnel were willing to discuss manufacturing operations and set-up operations.

(3) Rodgers' data is a good illustration of the fact that set-up times represent a substantial percentage of the total machine time in many plants, so we see that any savings could be of large dollar value.

CHAPTER III

PREDICTION METHODOLOGY

After the decision to study machine tool set-up operations and set-up times is made, the question of the method of study to be used remains. The goal is to choose a systematic, economical and practical prediction technique for set-up times that takes into consideration the sequential effects of set-ups on machine tools.

Hess and Pillai [16] point out that it is common in the social sciences for the researcher to face the problem of predicting an individual's position on a given numerical dependent variable when he has a knowledge about each individual's classification with respect to a number of independent characteristics or factors believed to influence the dependent variable. Frequently the researcher develops a predictive model which utilizes the method of least squares to minimize the sum of squares of the errors of prediction. The Multiple Classification Analysis model is such a model and will be presented below. It will be shown that the model is the same as a regression model using one explanatory or dummy variable for each level of each factor (such variables take the values +1 or 0 depending on whether the element belongs to the level of a factor or not).

Multiple Classification Analysis is based on the following statistical model:

$$Y_{ijk...\alpha} = \bar{Y} + a_i + b_j + c_k + \cdots + \epsilon_{ijk...\alpha}$$

The prediction starts with the overall mean of the dependent variable, and then for an element makes a set of additive adjustments, one for

each attribute, depending on the level of that attribute to which the element belongs. Thus the effect of class membership is assumed to be additive from one attribute to another. The assumptions of the model are: (1) the effects of the a_i's, b_j's, etc. are additive with no interaction and (2) the $\epsilon_{ijk...\alpha}$ have an expectation of zero, a common variance σ^2 and are independent. The model, and programs based upon it, makes it possible to use explanatory factors without arbitrary scaling of the classes; that is, without assuming linearity.

A computer program labeled the MCA program, has been developed that is available on the IBM 7090 at the University of Michigan. This program uses an iterative procedure based on the method of fitting constants first proposed by Yates (41) in 1934. The program accepts a single dependent variable and up to thirty-four predictor (independent) variables. The dependent variable must be an interval scale and each predictor may be as weak as a nominal scale and may have up to 9999 levels. It should be noted that because of limited storage all factors can not use the maximum number of levels.

This MCA program is claimed by Andrews (3) to have two main advantages over conventional multiple regression. It accepts predictor variables in as weak a form as nominal scales and it does not assume or require linearity of regression. It has the advantage over the conventional analysis of variance procedure that the program accepts unequal numbers of cases in the "cells" formed by the cross-classification of the predictors.

Andrews [3], Suits [38], [39] and Kempthorne [20] point out that the model is identical to a multiple regression model using dummy variables carried out under the constraint that the sum of the variables representing the various levels of a factor is unity. This means that the matrix of coefficients of the normal equations for a classification model considered as a regression model with dummy variables is singular, and does not have an inverse. Unique or determinate solutions for the original parameters can only be obtained by imposing conditions on the parameters.

Suits [38] in discussing regression with dummy variables illustrates the necessity of imposing constraints, to insure that the solution of the normal equations will be determinate, with several alternate forms for a specific model. He first presents the following (over-identified) model:

$$Y = aX + b_1R_1 + b_2R_2 + b_3R_3 + c + \epsilon$$

where $R_i = 0$ or 1 $(i=1,2,3)$

and $\sum_{i=1}^{3} R_i = 1$.

He then notes that there is a perfect linear multiple correlation among the R_i. Any attempt to estimate the regression parameters will fail because of the singularity in the moments matrix. He presents several possible constraints to obtain determinate estimates of these parameters including:

(1) preassign a value to one of the b_i (e.g., set $b_1 = 0$)

(2) preassign a value to c (e.g., set $c = 0$).

The point of the above discussion is that a regression model with dummy variables is equivalent to the multiple classification analysis model, but that additional constraints need to be imposed on the regression parameters to obtain determinate estimates of those parameters. It will now be shown that a stepwise procedure for solving multiple regression problems will automatically handle the problem of these necessary constraints.

Efroymson in Ralston and Wilf [28] discusses how to solve multiple regression problems by a stepwise procedure. This procedure uses intermediate results, which are not even recorded by normal calculation methods, to control the method of calculation. Essentially, without adding greatly to the number of arithmetic steps, a number of intermediate regression equations are obtained, as well as the complete multiple regression equation. These equations are obtained by adding one variable at a time and thus giving the intermediate equations:

$$Y = b_o + b_1 X_1$$

$$Y = b_o' + b_1' X_1 + b_2' X_2$$

$$Y = b_o'' + b_1'' X_1 + b_2'' X_2 + b_3'' X_3$$

.
.
.

The variable added is the one which makes the greatest improvement in "goodness of fit". The coefficients represent the best values when the equation is fitted by the specific variables included in the equation. The criteria of fit is the least sum of squared errors criteria that is commonly used in regression analysis.

A computer program written by Dallemand (9) has been modified and made available on the University of Michigan IBM 7090. This program will accept the dependent variable and up to one hundred (100) independent variables.

In classification systems the set of dummy variables is defined so that for any single element or observation the sum of the variables representing the levels of each factor is unity. It is just this functional relation that necessitates the addition of constraints to the set of normal equations. If data is gathered where the classification information for a factor is missing for some observations, two choices are possible: throw away such observations or modify the model and subsequent analysis to handle such cases. The second procedure is better as it does not destroy the representativeness of the data by discarding information.

If observations with missing classification information for some of the factors are to be admissable, one way to restore the property of all dummy variables for a factor summing to unity is to introduce an additional level for each factor to represent this missing classification information case. This method however rapidly enlarges the number of variables in the model.

With the stepwise regression program all of the variables may be entered into the predicting equation if all of the variables are independent. If the variables are highly correlated, all of them may still be entered as each may explain some of the variance of the dependent variable. However, if a subset of variables represent a set of dummy variables corresponding to a classification attribute,

and each observation is classified under each level, then they are not just highly correlated but are functionally dependent. In this case the stepwise procedure, as it is programmed in the Dallemand program, will not enter all of these dummy variables. This is because of a set of N such variables, entering N-1 will cause a reduction in the unexplained variance in the dependent variable; but, the N-th will yield no additional information. In effect this sets the coefficient corresponding to that N-th variable equal to zero and is therefore equivalent to one of the procedures discussed by Suits (38).

If a set of N variables represent all levels of an attribute with the exception of a missing classification information level, then when a data set includes any observation with missing classification information the functional relationship is destroyed. This means that entering the N-th variable, after the first N-1 are in, may very well result in a reduction of the unexplained variance.

We see now that a classification model can be analyzed using either the MCA program or the stepwise regression program on a regression model with dummy variables. The latter program has the advantage of being easier to use, and of being more widely accessible outside of the University. It has the disadvantage of not being capable of handling as large a classification model as the MCA program. Recall that the regression program will handle up to one hundred (100) independent variables while the MCA program would handle up to thirty-four factors with up to 9999 levels under each factor. When dummy variables are used the regression program will not be able to handle 15 factors with 10 levels each, while the MCA program will have no difficulty with that size model at all.

One further advantage of the regression approach is that we can use a prediction model that is not a pure classification model. It is quite possible that the researcher will have some information that is quantitative and a mixed regression and classification model might appear more natural than a pure classification model. Suits (38) considers the problem of predicting the number of pounds of sweet potatoes consumed by a family in a year (Y) given the annual income of the family (X) and the region of the nation: eastern, southern, and western (R_1, R_2, R_3). The first model proposed is:

$$Y = a X + b_1 R_1 + b_2 R_2 + b_3 R_3 + c + \epsilon$$

$$\text{where} \quad R_i = 0 \text{ or } 1 \quad (i=1,2,3)$$

$$\text{and} \quad \sum_{i=1}^{3} R_i = 1 .$$

As discussed earlier this model is then modified so determinate estimates of the parameters can be calculated. Suppose the choice is to set $b_3 = 0$, the model then becomes:

$$Y = a X + b_1' R_1 + b_2' R_2 + c' + \epsilon$$

$$\text{where} \quad R_i = 0 \text{ or } 1 \quad (i=1,2) ,$$

When using the stepwise regression program this modification need not be explicitly done. Note that this model contains both nominal and numerical independent variables.

Thus a prediction model can be used with both numerical variables (interval or ratio scale) and dummy or explanatory variables (nominal scale). Such models are applicable to predicting machine tool set-up times as both types of information are often available for

these set-ups. A specific example will be presented in Chapter IV using this regression model with numerical and dummy variables. Actual data is analyzed using the stepwise regression program.

CHAPTER IV

CASE STUDY

Background

During the course of these investigations five different metal-working plants were visited to discuss machine tool set-up operations with company personnel and to observe set-up men working on various machine tools. Machine tools of the lathe family were found in all of the plants visited; and, in four plants, the main production operation was a turning operation on a lathe type machine tool. In these same plants high demand for production was forcing overtime work and the lathe or turning operation was a bottleneck. As indicated in Chapter II lathe type machine tools often have large set-up times which are very sequence dependent; that is, the time to set-up the lathe for a different part depends on the nature of the preceding part. For these reasons a lathe type machine tool was selected for study.

In most of the plants approached the plant personnel were co-operative and willing to discuss set-up operations on their machine tools. Engineering, manufacturing, and process control personnel were interested in the study as they felt set-up operations occupied a sizeable proportion of machine time and were sequentially dependent; and also, that current planning procedures did not consider this sequence dependency. In one of these plants the initial contact was made at the plant manager level; and, it was in this plant that the data for the case study was taken. In the other plants contacts were made via technical personnel and the plant managers turned down a request to gather the necessary data.

Of the various measurement techniques considered for this study self-recording of the total set-up time by the set-up man was the only alternative both economical and applicable to the problem of measuring set-up times with the goal of detecting and explaining differences due to the sequence in which the jobs are done. Continuous time study was rejected as the set-up operations were so diverse, due to their sequential nature, that any time study would demand too many hours of expensive observation; also the man-power to undertake such a project was not available. Random sampling procedures were rejected as not applicable to the problem of measuring the duration of set-up operations when the goal is to detect and explain differences due to the sequence in which the jobs are done. Standard data techniques could not be used as the necessary data was not available.

The first step therefore is to develop a classification system that efficiently and effectively describes the range of set-up operations on the machine tool of interest. The basic idea is to identify all of the characteristics by which an observer can distinguish between set-ups and then for each characteristic or factor to list the several levels that could occur. For example, on a grinder with a belt drive which has two different length drive belts, the characteristic or factor "drive belt changes" could have the three levels "no change", "change from belt A to belt B", and "change from belt B to belt A".

In collecting the data necessary for using classification analysis both the total time for a set-up and its description using the classification system are recorded. The only time that needs to be measured is the total time, and no attempt is made to isolate and time the elements that make up this total time.

Once the classification analysis method is accepted the development of a set-up time predicting equation has four phases. First, the factors that might influence the set-up times are identified and a specific classification structure is developed. Next, the measurement, or data collection phase, consists of recording the total time for each of several set-ups and filling out a classification record describing each of these set-ups. Third, the data is analyzed; the model and program for this analysis were covered in Chapter III. Last, the verification or validation phase compares the predicted and actual values for a new set of data.

Measurement Procedure

Set-up men classified each of many actual set-up operations by checking the appropriate boxes on a classification form provided and filled in the requested clock times in a time log book. The set-up men were willing to fill out a classification form for the individual set-up operations, and after a brief familiarization period, were very cooperative in keeping the time logs. The time logs had time entries for start, discontinue, resume and completion time. Consequently, both the total elapsed time; that is, the time from the start until completion, and the time during this interval actually spent working on the set-up were recorded. This measurement procedure has the possibility of measurement error, but, it was felt that this was minimized by establishing good rapport with the set-up personnel. Set-up personnel are highly skilled and represent a scarce resource and they do not feel threatened by a study of this nature. Frequent visits to the shop floor over the weeks, combined with a one week sampling study verified that the set-up men were keeping accurate logs.

Classification Structures

As discussed above the purpose of a classification system is to effectively and efficiently describe the range of set-up operations on the machine tool of interest. The basic idea is to identify all of the characteristics by which an observer can distinguish between set-up operations. Such a classification structure must consider both the features and characteristics of the machine tool and the products which the machine tool is being set-up to produce. Five good sources of information for developing a classification system which can both describe and differentiate between different set-up operations are: (1) the machine tool handbook provided by the manufacturer describes the machine tool, its component parts, and its features, (2) process control texts and reference books discuss the machine tool and how it is set-up, (3) the process control engineer can discuss the machine and how set-up operations differ, (4) the manufacturing foreman, who directs the set-up men often has a valuable backlog of experience which can shed much light on the problem of describing set-up operations and how they differ, and (5) finally, the set-up man will have developed through experience a way of roughly classifying or describing set-up operations.

In developing a machine tool set-up classification structure some of the points to consider are:

(1) how many workpieces are operated on simultaneously and how are they held

(2) what is the cutting tool and how does it operate

(3) what are the moving components of the machine and how are they controlled.

(4) how are the workpieces loaded into the machine tool

(5) what automatic features of any possible loading device need to be re-set when changing between products

(6) what are the distinguishing features of the various products

(7) which of the machine tool characteristics are associated with these product features

For machine tools of the lathe family some factors for consideration are: feed gears, speed gears, main carriage cam, cross-slide cams, workpiece holders, tool holders, tool fixtures, tools, and special attachments. Each of these factors can have two or more levels; for example, the workpiece holder may have just two levels "changed" and "not changed", while the number of tools changed may have several levels; for example, 0, 1, 2, 3.

In developing a classification structure the set-up operation can be described from the point of view of the machine tool rather than from that of the product. For example, the insertion and adjustment of a single plunge-cut tool which is used in a finish turning operation is a clear statement without going into detail on the contour to be turned. In this way two parts can be differentiated not by describing their specific contours, but, rather by the fact that they have a different contour. Then, when changing from one part to the other we note that a change in the final contour tool is included in the set-up operation. As another example, it is easier to say that a gear change is necessary than it is to get into the question of differences in the diameter and the metallurgical properties of the bar stock used for the two products. In summary, set-up operations can be classified by describing the changes that need to be made on the machine tool, even though these machine tool changes are necessary because of product differences.

Case Study Classification Structure

This specific machine tool set-up operation classification structure is for an automatic, form turning, Mono-matic lathe, model number 41292-01, manufactured by the Monarch Machine Tool Company of Sidney, Ohio. This lathe has the following features and characteristics:

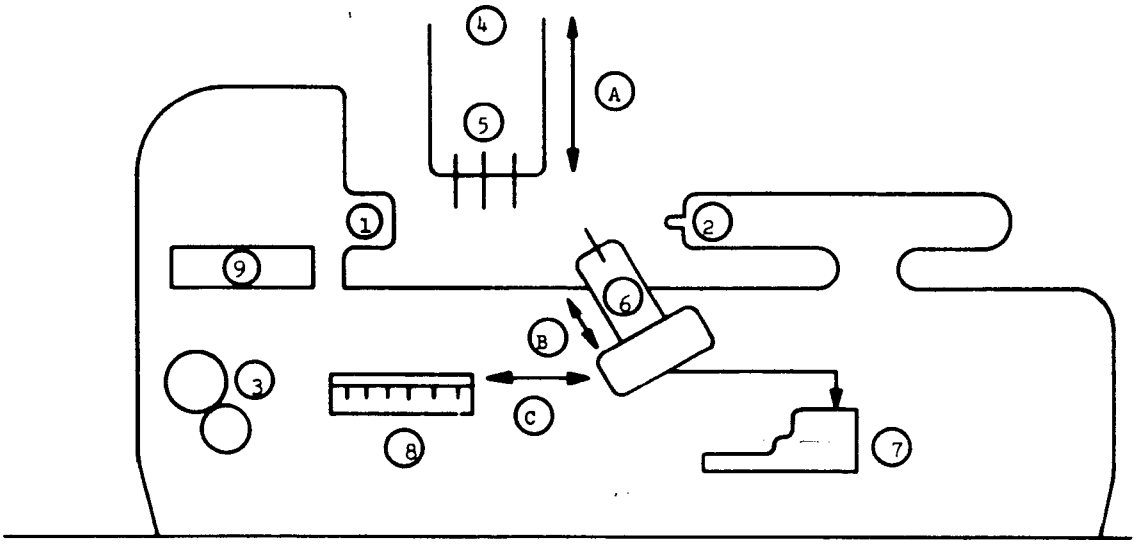


Figure 1. Rough Illustration of Mono-matic Lathe Showing Relevant Features.

The Main Features

(1) The main workpiece holding device consists of a pneumatically powered draw-bar mechanism with either a splined arbor or a withdrawing center assembly attached, depending on the nature of the piece to be machined.

(2) A secondary workpiece holding device which is used when a withdrawing center assembly is fitted to the main workpiece holder draw-bar mechanism.

(3) A set of spindle gears which govern the speed of revolution of the workpiece.

(4) A backslide which has a single degree of movement on a fixed slide track. It moves perpendicular to the turning axis as shown by the path A .

(5) The backslide has space for up to three toolholders and plunge cut tools. These tools are fixed relative to one another and all move together when the backslide moves into or retracts from the workpiece.

(6) A frontslide which holds just one tool. The frontslide has two degrees of movement; the slide moves on one track perpendicular to the axis of revolution of the workpiece as shown by path B , and the slide assembly moves on a second track parallel to the axis of revolution as shown by path C .

(7) The frontslide, and thus the front tool, moves in a continuous path under the control of a tracer unit which in turn follows a tracer element 7 . The front tool can therefore cut a curved contour.

(8) The Mono-matic lathe has a variable feed speed feature that allows the frontslide to move at any selected rate (within certain limits) in different pre-set regions of travel. This means that different portions of the contour cut by the front tool can be cut at different feed speeds. These regions of travel are set by adjusting several dogs 8 and the speeds are selected by setting dials in the control box 9 .

The machine operates in the following manner: the operator chucks up a piece in the workpiece holder (arbor or center) and actuates the pneumatically powered draw bar, the back tool slide makes a single plunge cut toward the workpiece, and the front tool slide moves along a continuous path under control of the tracer unit. For any set-up we must therefore have the following:

(1) appropriate work-holding devices

(2) correct set of speed gears

(3) correct tracer element

(4) specified tools and tool-holders in both slides

(5) tools correctly positioned and adjusted in both slides

(6) variable feed rate dogs positioned and the feed rate switches correctly set

(7) final check-out with any necessary final tool adjustments.

The specific classification form developed for the Mono-matic lathes and the directions for the set-up men describing each factor are in Appendix **A.** The items will only be briefly described as the form together with the direction sheet is self-explanatory. The items, the nature of the information requested for each item, and the range or number of possible levels for each item are:

(1) DATE: calendar date (only for identification)

(2) SHIFT: three shifts

(3) MACHINE: eight machines

(4) PREVIOUS PART: part number (only for identification)

(5) NEW PART: part number (only for identification)

(6) CUT TYPE: three cut types are identifiable

(7) WORKPIECE HOLDER: five types of workpiece holder change are identifiable

(8) GEARS: two types of spindle gear change are identifiable

(9) BACKSLIDE TOOLS:
- (a) number tools removed
- (b) number tools inserted
- (c) number tools required for new part

(10) BACKSLIDE HOLDERS:
- (a) number toolholders removed
- (b) number toolholders inserted
- (c) number toolholders required for new part

(11) FRONTSLIDE TOOL: two types of frontslide tool change are identifiable

(12) TEMPLATE SHIMMING: two levels

(13) FEED DOGS: (a) number set for previous part
(b) number set for new part

(14) GENERAL: three subjective evaluation levels

(15) COMMENTS:

Data

All of the information recorded on the classification form was not of value in the prediction model. The factors or factor levels found to be of negligible value will be discussed below. Mono-matic lathes were not set-up on the third shift as only two men were qualified to set-up these machines and one worked on the first shift and the other on the second. This means that the third level was dropped and the first two levels designate a specific man not just the shift.

The three cut types identified on the form were found to differ only in the number of back tools used in the turning; so the cut type factor was dropped as the number of back tools used was explicitly included as a different factor. The tolerances required for these different cut types were not different.

Two basically different workpiece holders could be used on these machines but of these two only one was encountered in the several months covered by this study. The only two levels under workpiece holder were therefore change or no change.

The number of backslide tools removed, inserted, and used for the new part could differ from the number of backslide holders removed, inserted, and used for the new part. In practice it was found that these

three numbers were the same for both factors, so they should be included in the analysis only once. Hence, the factors were combined into backslide tools and holders.

The front tools were disposable and the two types used differed only in rake angle. The front tool was usually changed, but the front tool change was checked off by the two set-up men only if they changed the type. This change in type was not basically different from a change within the same type; therefore, this factor was completely dropped in the analysis.

Shimming of templates was necessary when they were nicked. A metal shim was used to block over the rough spot on the tracer element. When this occurs, a new tracer element was ordered, but the old one was used for the current lot of production. Because this failure of the tracer element was not predictable this factor was not used in the prediction equation analysis.

The Mono-matic lathes have a variable feed speed feature whereby feed dogs are set and the front tool speed between two adjacent dogs along the continuous front tool path can be set to any desired value, within a certain range. This feature was not used for any of the set-ups studied. Further questioning revealed that it was very rarely used. The feed dog factor was therefore dropped.

The general evaluation by the set-up man helped make the set-up man a part of the study and elicited many valuable comments. This evaluation information was not available a'priori and was not used in the prediction equation analysis.

The time log books (see Appendix A) had three basic entries: identification of machine and part, start times, and stop times. As noted

earlier in this chapter both the total elapsed time from the start to the completion of a set-up and the amount of time in this period actually spent on the set-up were available. In addition, the set-up men checked off the reason for stopping (see time log form in Appendix A).

Classification records and set-up time measurements for eighty different set-ups were obtained for analysis for the Mono-matic lathe case study. Of these seven were classified under the ROUGH level of the GENERAL factor. Further questioning revealed that when a set-up included various minor repair activities, the set-up man would complete these repairs, rather than stop and call the machine repairman, and then check off the ROUGH level for that set-up. Otherwise they used the SMOOTH and NORMAL levels. Because such repair activities were unpredictable and the time for these repairs was included in the total set-up time, these seven data points were not used.

Of the seventy-three set-ups used in the analysis twenty-five had a recorded interruption in the set-up; that is, the set-up man had filled in a time for stopping for a reason other than completion of the set-up, later filled in a time for resuming work on the set-up, and ultimately filled in a completion time for the set-up. Of these twenty-five some had more than one such interruption. Several attempts to develop a method of predicting both the occurrance and the duration of these interruptions were made and all were unsuccessful. The reasons for the twenty-seven interruptions were: ten times the set-up man was directed by the foreman to work on another set-up, three times the set-up man called the machine repairman, two times the set-up man had to hunt for the necessary tools or holders, five times the set-up man was directed by the foreman to train

a new operator, and seven times for other reasons. These interruptions are not predictable; consequently, the times used in all of the analysis are the actual times spent on the individual set-ups.

Data Analysis

The model finally used has both dummy variables and quantitative variables:

$$\text{Model (1)} \qquad T_{ijk\ell 123m\alpha} = C + \sum_{i=1}^{8} m_i M_i + \sum_{j=1}^{2} s_j S_j + \sum_{k=1}^{2} a_k A_k + \sum_{\ell=1}^{2} g_\ell G_\ell + b_1 N_1 + b_2 N_2 + b_3 N_3 + \sum_{m=1}^{2} t_m T_m + \varepsilon_{ijk\ell 123m\alpha}.$$

The variables are defined as follows:

$T_{ijk\ell 123m\alpha}$ - the set-up time for the α-th set-up belonging to the cross-classification identified by the subscripts

$M_1 \ldots M_8$: $M_i = 1$ if set-up is on machine i

$M_i = 0$ otherwise and $\sum_{i=1}^{8} M_i = 1$

S_1, S_2 : $S_j = 1$ if set-up on j-th shift

$S_j = 0$ otherwise and $\sum_{j=1}^{2} S_j = 1$

A_1, A_2 : $A_1 = 1$ if workpiece holder (arbor) is not changed

$A_1 = 0$ if workpiece holder (arbor) is changed and $\sum_{k=1}^{2} A_k = 1$

G_1, G_2 : $G_1 = 1$ if set of spindle gears is changed

$G_1 = 0$ if set of spindle gears is not changed and $\sum_{\ell=1}^{2} G_\ell = 1$

N_1, N_2, N_3 : N_1 = the number of backslide tools/holders removed

N_2 = the number of backslide tools/holders inserted

N_3 = the number of backslide tools/holders required for turning the part being set-up

T_1, T_2 : $T_1 = 1$ if the tracer control element (template) is changed

$T_1 = 0$ if template not changed and $\sum_{m=1}^{2} T_m = 1$

$\varepsilon_{ijk\ell 123m\alpha}$ = the error of prediction for the α-th element in the cross-classification identified by the subscripts.

The results of analyzing the initial sample of seventy-three set-ups are shown below. Table V shows the correspondence between the variables as listed in the computer output shown in Table VI and the variables as they appear in the Model (1). Table VI lists the coefficient estimates, the coefficient of determination, and the multiple correlation coefficient when Model (1) is used with the seventy-three set-ups. Table VII lists the actual set-up times, the predicted set-up times, the difference or deviation of the predicted value from the actual value, and the magnitude of the deviation as a percent of the actual value.

TABLE V

EQUIVALENCE BETWEEN COEFFICIENTS
IN MODEL (1) AND TABLE VI

$X_1 \sim m_1$	$X_{11} \sim a_1$
$X_2 \sim m_2$	$X_{12} \sim a_2$
$X_3 \sim m_3$	
$X_4 \sim m_4$	$X_{13} \sim g_1$
$X_5 \sim m_5$	$X_{14} \sim g_2$
$X_6 \sim m_6$	
$X_7 \sim m_7$	$X_{15} \sim b_1$
$X_8 \sim m_8$	$X_{16} \sim b_2$
	$X_{17} \sim b_3$
$X_9 \sim s_1$	
$X_{10} \sim s_2$	$X_{18} \sim t_1$
	$X_{19} \sim t_2$

TABLE VI

RESULTS OF ANALYSIS USING MODEL (1) WITH INITIAL SAMPLE

COEFF OF DETERMINATION = .57330896E 00
MULTIPLE CORLTN COEFF = .75717168E 00

CONSTANT TERM = .21860375E 02

VARIABLE NO.	COEFFICIENT	STD ERR OF COEFF
X- 1	.20481612E 01	.12864146E 02
X- 2	-.44990700E 01	.12931894E 02
X- 3	.24926094E 02	.13402723E 02
X- 4	.13179393E 02	.12962960E 02
X- 6	.98528396E 00	.12119159E 02
X- 7	.43850184E 00	.14631710E 02
X- 8	.65283772E 01	.11906348E 02
X- 10	.89568225E 01	.63308653E 01
X- 12	.15315964E 02	.62256809E 01
X- 13	.35009210E 01	.64870170E 01
X- 15	-.56864889E 00	.37879677E 01
X- 16	.69543247E 01	.56739695E 01
X- 17	.10803024E 02	.49350596E 01
X- 18	.31252756E 02	.12261848E 02

TABLE VII

ACTUAL AND PREDICTED VALUES FOR INITIAL SAMPLE USING MODEL (1)

OBSN NO.	PREDICTED VS ACTUAL RESULTS ACTUAL	PREDICTED	DEVIATION	PERCENT
4	.8[illegible]E 02	.9[illegible]644E 02	-.10644E 02	-13.31
5	.9[illegible]E 02	.9[illegible]237E 02	-.23710E 00	-.26
6	.7[illegible]E 02	.73596E 02	-.35957E 01	-5.14
7	.95[illegible]E 02	.80143E 02	.14857E 02	15.64
8	.1[illegible]E 03	.95344E 02	.96562E 01	9.20
9	.1[illegible]E 03	.10709E 03	.29095E 01	2.65
10	.1[illegible]E 03	.93498E 02	.21502E 02	18.70
11	.1[illegible]E 03	.10524E 03	-.24427E 00	-.23
12	.5[illegible]E 02	.55173E 02	-.51729E 01	-10.35
13	.9[illegible]E 02	.89100E 02	.90220E 00	1.00
14	.9[illegible]E 02	.98354E 02	-.83538E 01	-9.28
15	.9[illegible]E 02	.82553E 02	.12447E 02	13.10
16	.6[illegible]E 02	.87899E 02	-.27899E 02	-46.50
17	.95[illegible]E 02	.99645E 02	-.46453E 01	-4.89
18	.7[illegible]E 02	.89980E 02	-.19980E 02	-28.54
19	.7[illegible]E 02	.96527E 02	-.21527E 02	-28.70
20	.12[illegible]E 03	.11325E 03	.12750E 02	10.20
21	.5[illegible]E 02	.32663E 02	.17337E 02	34.67
22	.3[illegible]E 02	.33102E 02	-.31019E 01	-10.34
23	.6[illegible]E 02	.71736E 02	-.11736E 02	-19.56
24	.1[illegible]E 03	.87490E 02	.22510E 02	20.46
25	.1[illegible]E 03	.10786E 03	-.28613E 01	-2.73
26	.1[illegible]E 03	.10359E 03	.11412E 02	9.92
27	.8[illegible]E 02	.12370E 03	-.38704E 02	-45.53
28	.9[illegible]E 02	.12414E 03	-.29142E 02	-30.68
29	.5[illegible]E 02	.55865E 02	-.58649E 01	-11.73
30	.6[illegible]E 02	.73784E 02	-.87838E 01	-13.51
31	.1[illegible]E 03	.90237E 02	.19763E 02	17.97
32	.9[illegible]E 02	.67531E 02	.22469E 02	24.97
33	.7[illegible]E 02	.61918E 02	.80821E 01	11.55
34	.1[illegible]E 03	.11913E 03	.38874E 02	20.58
35	.1[illegible]E 03	.13437E 03	.56267E 01	4.02
36	.9[illegible]E 02	.10080E 03	-.57997E 01	-6.10
37	.1[illegible]E 03	.11117E 03	-.11747E 01	-1.17
38	.1[illegible]E 03	.11913E 03	.30874E 02	20.58
39	.15500E 03	.13783E 03	.17173E 02	11.08
40	.80000E 02	.79827E 02	.17270E 00	.22
41	.90000E 02	.80266E 02	.97342E 01	10.82
42	.45000E 02	.87485E 02	-.42485E 02	-94.41
43	.45000E 02	.81303E 02	-.36303E 02	-80.67
44	.80000E 02	.10430E 03	-.24301E 02	-30.38
45	.75000E 02	.61918E 02	.13082E 02	17.44
46	.85000E 02	.87485E 02	-.24852E 01	-2.92

TABLE VII (Continued)

RUN NO.	PREDICTED VS ACTUAL RESULTS ACTUAL	PREDICTED	DEVIATION	PERCENT
44	.10322E 03	.92675E 02	.12325E 02	11.74
45	.13000E 03	.11054E 03	.19458E 02	14.97
46	.12520E 03	.97275E 02	.79253E 01	6.59
47	.2[illegible]	.28459E 02	-.84588E 01	-42.29
48	.4[illegible]	.4[illegible]3E 02	-.6[illegible]1E 0[illegible]	-1.51
49	.55[illegible]0E 02	.71[illegible]2E 2	-.16032E 02	-29.15
50	.65[illegible]0E 02	.76701E 02	-.11791E 02	-18.14
51	.12500E 03	.[illegible]5481E 02	.31519E 02	25.22
52	.13[illegible]0E 03	.1[illegible]03E 03	.29972E 02	23.06
53	.6[illegible]E 2	.83984E 02	-.23984E 02	-39.97
54	.6[illegible]E 02	.77803E 02	-.17803E 02	-29.67
55	.4[illegible]E 02	.5586[illegible]E 02	-.10865E 02	-24.14
56	.7[illegible]0E 02	.73744E 02	-.37838E 01	-5.41
57	.8[illegible]E 02	.99645E 02	-.19645E 02	-24.56
58	.9[illegible]E 02	.11655E 03	-.26555E 02	-29.51
59	.13[illegible]E 03	.88272E 02	.16728E 02	15.93
60	.8[illegible]E 02	.82659[illegible] 02	.23412E 01	2.75
61	.45[illegible]E 02	.7389[illegible]E 02	-.28890E 02	-64.20
62	.6[illegible]E 02	.[illegible]8277[illegible] 02	-.82771E 01	-13.8[illegible]
63	.1[illegible]E 03	.7[illegible]27[illegible] 02	.29973E 02	28.55
64	.11[illegible]E 03	.[illegible]8217[illegible] 02	.34783E 02	30.25
65	.7[illegible]E 2	.8757[illegible]E 02	-.12570E 2	-16.76
66	.7[illegible]E 02	.81[illegible]23E 02	-.11[illegible]23E 02	-15.75
67	.11[illegible]E 03	.8[illegible]53E 02	.23947E 02	21.77
68	.1[illegible]E 03	.[illegible]E 02	.73993E 01	7.4[illegible]
69	.95[illegible]E 02	.67531E 02	.27469E 02	28.91
70	.13500E 03	.12575E 03	.92482E 01	6.85
71	.65[illegible]E 02	.83690E 02	-.18690E 02	-28.75
72	.55[illegible]E 02	.90237E 02	-.35237E 02	-64.07
73	.95[illegible]E 02	.62[illegible]E 02	.32930E 02	34.66

Machine Effect

Initially the machine effect term was not included in the set-up time prediction model as no significant difference between the eight machines was noted during the data collection. One model initially used was:

$$\text{Model (2)} \quad T_{jk\ell 123m\alpha} = C + \sum_{j=1}^{2} s_j S_j + \sum_{k=1}^{2} a_k A_k + \sum_{\ell=1}^{2} g_\ell G_\ell + b_1 N_1 + b_2 N_2 + b_3 N_3 + \sum_{m=1}^{2} t_m T_m + \varepsilon_{jk\ell 123m\alpha}$$

with the variables and coefficients defined the same as for model (1). However, the errors of prediction resulting from the analysis using model (2) indicated that such a machine difference might exist (see Figure 2). Inspection of the data yielded no explanation for this difference between machines other than a difference in mechanical condition. When the model (1) was used the multiple correlation coefficient increased to .7572 from the value of .7112 which was calculated when model (2) was used.

Six of the machine terms listed in Table VII are close to zero while the remaining two are significantly different from zero. Of the seven observations discarded because the recorded set-up time included some repair time, four were on these two machines. This reinforces the coefficient estimate evidence that these two machines were in poorer mechanical condition.

Test for Equality of Error Variances

The assumption of equality of variances was tested for the errors of prediction. The sample was separated into the eight sub-samples formed by the cross-classification of the three factors: T_m, A_k, and G_ℓ ;

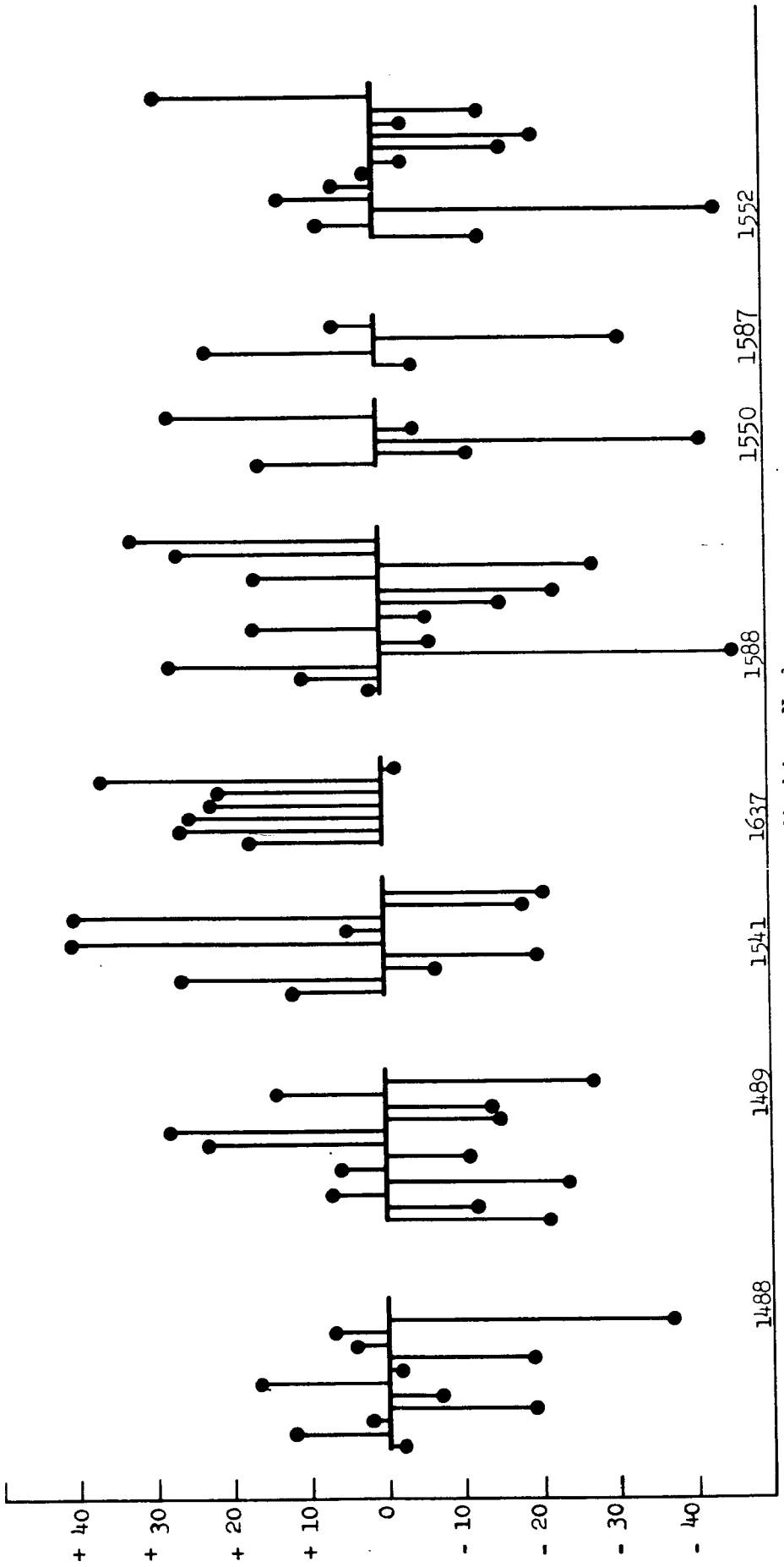


Figure 2. Graph of the Errors of Prediction for Model (2) with Initial Sample.

each of these three factors has two levels. Of these eight sub-samples only five contained observations. The test for equality of variances was made on these five sub-classes.

Most common tests for equality of several variances assume that all of the populations from which samples have been obtained are normal. Consequently, the errors of prediction for these five sub-samples were tested for normality using the Kolmogorov-Smirnov one sample test; see Appendix B. The hypothesis of normality was accepted in all five tests. Bartlett's test was then used to test for the equality of the five variances; see Appendix B. The hypothesis of equality of variances was accepted.

Test for Independence

The assumption of the independence of the error terms was next tested. A Kolmogorov-Smirnov one sample test was run on the cumulative frequency distribution of the lengths of the sign runs of the prediction error terms for the seventy-three set-ups. The hypothesis of independence of the error terms was accepted; see Appendix B.

Validation Phase

In addition to the original sample of eighty set-ups, seventy-three of which were used for the analysis, another sample of sixteen set-ups was taken. In this new sample three observations were dropped for the same reason the seven were dropped from the original sample. The prediction equation was then checked using this new sample of thirteen set-ups.

The relevant classification information for these thirteen observations in the validation sample is shown in Table VIII. Comments on three of these observations are germane: the set-ups numbered 1 and 2

were noted by the set-up man as having gone smoothly, and the set-up numbered 6 was split with sixty minutes on each shift.

The actual and predicted set-up times for these thirteen set-ups are shown in Table IX. The predicted values were computed using the set-up time prediction model (1) and the coefficient estimate values shown in Table VI.

TABLE VIII

DATA OF VALIDATION SAMPLE

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	S_1	S_2	A_1	A_2	G_1	G_2	T_1	T_2	N_1	N_2	N_3	Actual Set-up
1								1		1		1	1		1		1			60
2						1				1		1	1		1		1			50
3		1								1		1		1	1		2			85
4	1									1		1		1	1		1		1	100
5				1					1		1			1	1		1	1	1	90
6			1						1		1			1	1		1	1	1	120
7								1	1		1			1		1		1	1	45
8						1			1		1			1		1		1	1	55
9			1						1		1			1		1	1	1	1	60
10						1			1		1			1		1			2	45
11								1	1		1			1		1			2	45
12		1							1			1		1	1			1	3	105
13	1								1			1		1		1		2	3	120

TABLE IX

ACTUAL AND PREDICTED VALUES IN VALIDATION STUDY

	Actual	Predicted	Deviation	Percent
1	60	87.1	-27.1	-45.1
2	50	81.5	-31.5	-63.0
3	85	72.0	13.0	15.3
4	100	89.8	10.2	10.2
5	90	83.6	6.4	7.1
6	120	95.4	24.6	20.5
7	45	46.3	-1.3	-2.9
8	55	40.7	14.3	26.0
9	60	64.1	-4.1	-6.8
10	45	44.5	.5	-1.1
11	45	50.1	-5.1	-11.3
12	105	103.8	1.2	1.1
13	120	116.9	3.1	2.6

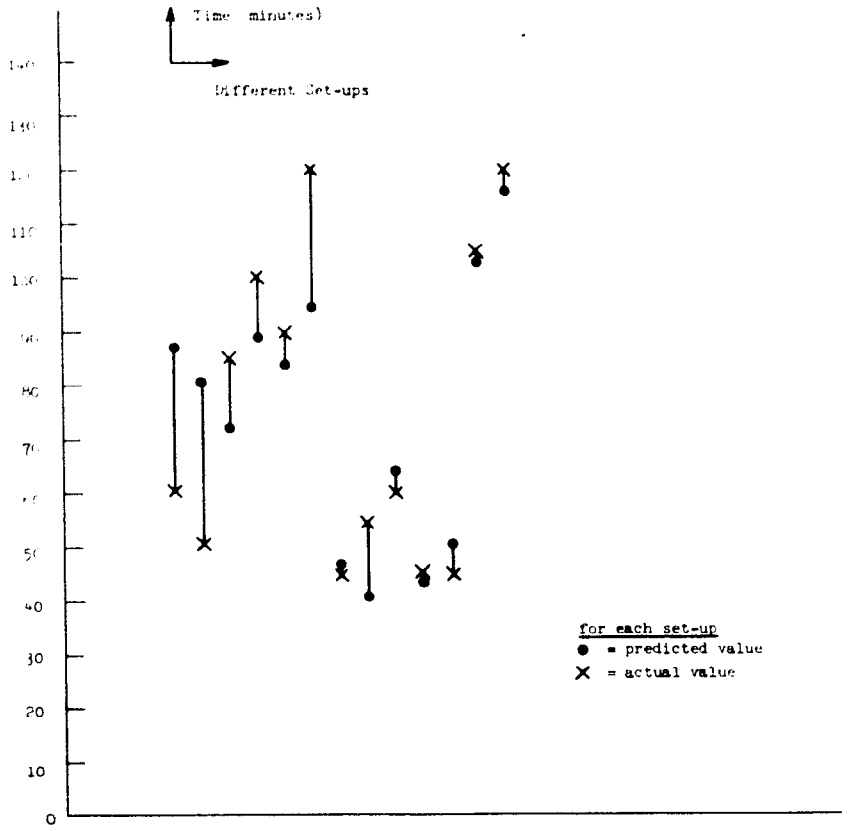


Figure 3. Graph of Actual and Predicted Values for Validation Sample.

Conclusions

Set-up operations on most machine tools are complex and require highly skilled and experienced set-up men. Set-up operations, unlike most production tasks, include many adjustments and re-adjustments, giving rise to a large variation in the time required for their completion. However, another very large source of variation in the time to set-up a machine tool for any particular part is the dependence of the set-up time on the nature of the previous part set-up on that machine tool.

A set-up time prediction method has been developed which considers the sequential nature of machine tool set-up times. It has been demonstrated via a case study on Mono-matic lathes. The correlation coefficient of the prediction equation for the initial sample of seventy-three set-ups was $\rho = .7572$ and for the validation sample of thirteen set-ups was $\rho = .8383$.

In addition to building a set-up time prediction equation this method also yields information about the underlying characteristics of the set-up operations which can be valuable in sequencing production so as to take advantage of the sequence dependency of the set-up times. This second point will be developed further in Chapter V.

CHAPTER V

SEQUENCING TECHNIQUE

Sequencing

The separation of the problem of scheduling production on a single machine into machine loading and job sequencing was presented in Chapter I. Sequencing is to decide on the sequential order in which the jobs assigned to each time period will be worked on. Sisson (33) discusses sequencing models and the assumptions behind the various models presented in the literature. None of the research work summarized in his discussion relaxes the assumption that the time intervals for processing are independent of the order in which the operations are performed. However, it has been shown that for a job done on a machine tool the processing time, which can be separated into the time for set-up and the time to actually produce the job after the set-up is complete, is not independent of the order in which the jobs are performed. The work in this chapter will explicitly consider the sequence dependency of the set-up times and will not make the assumption that the processing times are independent of the job sequence.

Three basic approaches or models for the single machine sequencing problem have appeared in the literature. Two of these have ignored the sequence dependency of the processing times. In effect they assume the set-up time as well as the actual production time for each job is independent of the sequence in which the jobs are produced. Two objectives have been: (1) to minimize the total

amount of waiting time in the queue for all of the jobs, and (2) to associate a due date to each job and consider objective functions which are measures of the tardiness of the individual jobs. (The tardiness of a job is the amount of time by which its completion time exceeds its due date). Papers considering these two objectives are Jackson[19], Smith[32], Conway[6], McNaughton[29], and Schild and Fredman[30].

The third approach, which has received little attention compared to the others, is to recognize the sequence dependency of the set-up portion of the processing time for an individual job and to attempt to find a sequence which minimizes the total amount of set-up time. It is this third approach which is being considered in this dissertation.

The sequencing model being considered here has the following assumptions:

(1) a single machine

(2) a known set of jobs to be processed with no future arrivals

(3) the time to process a job can be separated into a time for set-up and a time for actual processing.

(4) the time for set-up is dependent on the order in which the jobs are produced and will be labeled S_{ij}

(5) the time for actual production once a job has been set-up is independent of the order in which the jobs are produced and will be labeled P_j

(6) the expected times for set-up S_{ij} and the expected times for production P_j are known

(7) the first job in the sequence is known as the machine is currently set-up for that job

The objective is to find the sequence in which to produce this set of jobs so that the total amount of set-up time is minimized. For the single machine problem this same sequence will also minimize the total elapsed time from the start of the first job until the completion of the last job; this total elapsed time is called the "makespan" in Sisson's articles (33),(34). This is true because the total elapsed time is the sum of the total set-up time and the total production time for the set of jobs. The latter is a fixed quantity independent of the sequence in which the jobs are produced.

This sequencing problem, with the first job in the sequence fixed, can be phrased as a variation of the traveling salesman problem. The traveling salesman problem in its classic form requires that a salesman starting in one city visit each of n - 1 other cities once and only once and return to the start in such an order that the total travel distance (or time) is minimized. The single machine sequencing problem is essentially the same problem without the requirement of returning to the initial job. These two problems will be referred to as the "closed" problem, requiring a return to the origin; and the "open" problem, not requiring a return to the origin. Either the "closed" problem or the "open" problem can be formulated as an integer linear programming problem. One possible formulation of the former is given by Dantzig (11) as:

(1) let $x_{i,j,t}$ = 0 or 1 according to whether the t^{th} directed arc on the route is from node i to node j

(2) set $x_{i,j,n+1} = x_{i,j,1}$ for all i and all j

$$(3)\quad \sum_{i=1}^{n} x_{i,j,t} = \sum_{k=1}^{n} x_{j,k,t+1} \qquad (j = 1\ldots n)(t = 1\ldots n)$$

$$(4)\quad \sum_{t=1}^{n} \sum_{j=1}^{n} x_{i,j,t} = 1 \qquad (i = 1\ldots n)$$

$$Z_c = \sum_{t=1}^{n} \sum_{j=1}^{n} \sum_{i=1}^{n} s_{i,j}\, x_{i,j,t}$$

and minimize Z_c subject to (1) through (4). Flood (14) has shown that an integer solution to this system is a closed tour. One possible integer programming formulation of the "open" problem is to minimize Z_o subject to (5) through (8) where:

(5) let $x_{i,j,n} =$ for all i and all j

(6) let $x_{i,1,t} =$ for all i and all t

$$(7)\quad \sum_{i=1}^{n} x_{i,j,t} = \sum_{k=1}^{n} x_{j,k,t+1} \qquad (j = 2\ldots n)(t = 1\ldots n-2)$$

$$(8)\quad \sum_{t=1}^{n-1} \sum_{i=1}^{n} x_{i,j,t} = 1 \qquad (j = 2\ldots n)$$

$$Z_o = \sum_{t=1}^{n-1} \sum_{j=2}^{n} \sum_{i=1}^{n} s_{i,j}\, x_{i,j,t}$$

The point of importance is that either problem can be phrased as an integer linear programming problem. The importance of this will be seen in the next section discussing the use of expected values for the s_{ij} set-up times.

Using Expected Values

Set-up times s_{ij} are task times and as such are subject to some variability. If we recognize that this uncertainty is present and that the s_{ij} is really a random variable, then we need to consider the method of finding the optimum value of the optimization criterion carefully. Dantzig[11] in his chapter on programming under uncertainty discusses the problem.

The problem can be written as:

$$A^T X \geq B \qquad \begin{matrix} A : (n \times m) \\ X : (n \times 1) \\ B : (m \times 1) \\ P : (n \times 1) \end{matrix}$$

$$X \geq 0 \quad [x_j = 0 \text{ or } 1]$$

$$\text{minimize} \quad C = P^T X = \sum_{j=1}^{n} p_j x_j$$

where the uncertainty is in the price vector P and so for the X which is selected before the prices P are known the cost C is a random variable.

Let the expected value of any variable, say U, be written $\epsilon(U)$. Accordingly the expected cost E of such a problem is clearly

$$E = \epsilon(C) = [\epsilon(P)]^T X$$

because Dantzig[11] gives us the following theorem:

> "If the unit costs p_j in $C = \sum_{j=1}^{n} p_j x_j$ are randomly distributed independently of the x_j, then the minimum expected total cost solution is obtained by finding $x_j \geq 0$ satisfying $A^T X \geq B$ and minimizing C with p_j replaced by $\epsilon(p_j)$."

If we recognize that the s_{ij} are random variables, we can substitute the expected values $\epsilon(s_{ij})$ into the deterministic statement of the problem and proceed as before. Accordingly we shall use $\tilde{s}_{ij} = \epsilon(s_{ij})$ from now on.

Solving the "Open" Problem by Branch and Bound

The "open" problem can be solved by breaking it into $(n - 1)$ modified "closed" problem formulations where each new $\tilde{s}_{ij}$ matrix has one row and one column deleted and one $\tilde{s}_{ij}$ value set to infinity. The

minimum cost solution to the "open" problem is then the solution corresponding to the lowest of the (n - 1) values found for the sub-problems. This method may not be the most efficient possible but it is effective.

Once the "open" problem has been divided into (n - 1) separate modified "closed" type problems we may use the Branch and Bound Algorithm of Little[22] which guarantees an optimal solution. The basic method of the algorithm is to break up the set of all tours into smaller and smaller subsets and to calculate a lower bound for each of them on the cost (length) of the best tour therein. The bounds guide the partitioning of the subsets and eventually identify an optimal tour. When a subset is found that contains a single tour whose cost is less than or equal to the lower bounds for all other subsets, that tour is optimal.

The partitioning of the "open" tour problem into (n - 1) separate modified "closed" tour type sub-problems is the initial step in a modified Branch and Bound Algorithm. The (n - 1) separate sub-problems are differentiated by having different jobs specified as the last job in the sequence. The set-up matrix $\| \tilde{s}_{ij} \|$ is modified for each sub-problem as follows: when job $i(i = 2,3,\ldots n)$ is specified as the last job in the sequence, set $\tilde{s}_{1i} = \infty$, delete row i, and delete column 1. The Branch and Bound Algorithm is then used operating on these (n - 1) new matrices. The solution sequence for each of these sub-problems will be an "open" sequence because of the non-equivalence of the row indices and column indices for each of these new matrices.

The logic of this process will be demonstrated via an example. Recall that job 1 will be the first job in any solution sequence as it is

the job currently set-up on the machine. For the example let

$\| \tilde{S}_{ij} \| =$

	1	2	3	4	5	6
1	--	65	83	103	36	65
2	85	--	99	62	85	43
3	63	67	--	99	65	42
4	83	22	99	--	83	47
5	36	65	83	103	--	65
6	85	43	82	87	85	--

The tree diagram (Figure 4) represents the branching of the set of all "open" tours starting with job 1 (job 1 is the job which is currently set-up on the machine) into disjoint subsets. The first branching is into the (n - 1), here 5, subsets defined by specifying the last job in the sequence or tour.

The notation will be further defined with specific reference to the branching under the node specifying job 5 last. The value of 275 associated with the node specifying job 5 last is a lower bound on the total cost of any sequence which starts with job 1 and ends with job 5. The node (4, 2) represents the subset of sequences which start with job 1, end with job 5, and in which job 2 immediately follows job 4. The lower bound associated with this subset of sequences is 300. The node $(\overline{4,2})$ represents the subset of all sequences with job 1 first, job 5 last, and job 2 not immediately following job 4. The lower bound associated with this subset is 300.

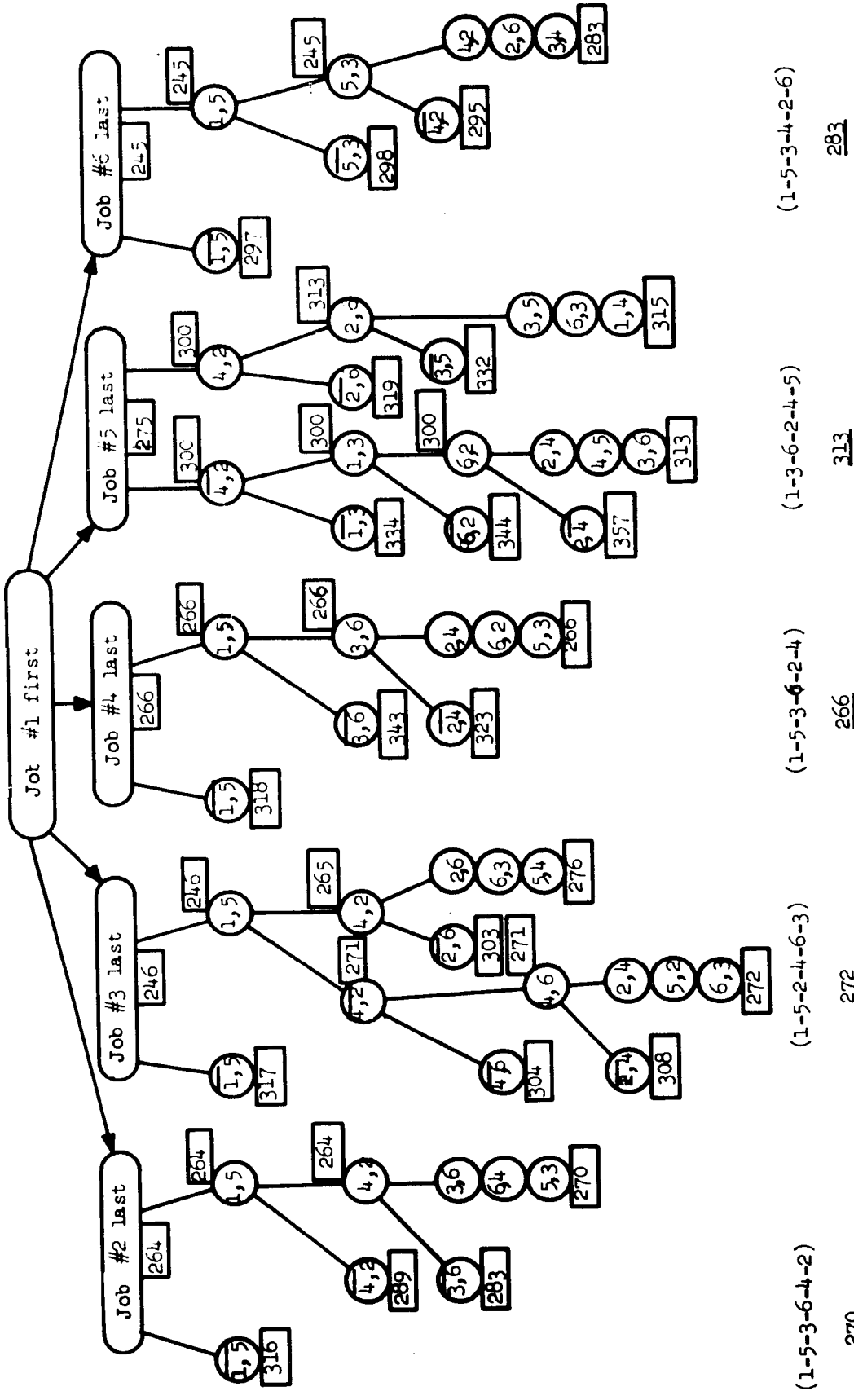
The branching from node (4,2) is into nodes $(\overline{2,6})$ and (2,6). The node (2,6) represents all sequences with job 1 first, job 5 last, job 2 immediately following job 4, and job 6 immediately following job 2. The lower bound associated with this subset of sequences is 313. Node $(\overline{2,6})$ represents all sequences with job 1 first, job 5 last, job 2 immediately following job 4, and job 6 not immediately following job 2. The lower bound associated with this subset of sequences is 319.

In general, for any node we can trace the path back to the initial node and determine which pairs of jobs are committed to or prohibited from following in sequence in the subset of sequences that node defines. When this branching process is carried far enough a single sequence or "open" tour will be defined by some node. Thus, the node (1,4) defines the sequence $\{1,4,2,6,3,5\}$ and the cost of this sequence is 315.

This process of branching and calculating lower bounds is continued until a node is reached which defines a unique sequence and which has a lower bound that is not greater than the lower bound for all other sets. That node represents an optimal "open" tour or equivalently a sequence of minimum total cost.

The branching of the five main subsets is shown in Figure 4. All of the branching, which is shown for illustration, would not be required if the subset specifying job 4 last was not done last.

The optimal "open" tour, or the sequence of minimum total set-up cost, as shown in Figure 4, is $\{1,5,3,6,2,4\}$ with a cost of 266.



Tree Diagram Representation of Branch and Bound Solution for Example 1

Figure 4

Heuristic Methods of Gavett

In Volume 11, Number 8 of Management Science, Gavett[15] presents his paper "Three Heuristic Rules for Sequencing Jobs to a Single Production Facility". These three heuristics will be briefly described and then used on the sample problem of the preceding section.

RULE 1 "NEXT BEST"

Starting with job 1 (the current job) always select as the next job the unassigned job with the least set-up time relative to the job just completed.

RULE 2 "NEXT BEST WITH VARIABLE ORIGIN"

Apply Rule 1 in at least (n - 1) different ways. Each sequence starts out with a different job following the initial status, job 1. The number of possible sequences using this rule will be greater than n - 1 when multiple choices are possible because of equal matrix times.

RULE 3 "NEXT BEST AFTER COLUMN DEDUCTIONS"

Apply Rule 1 after subtracting the minimum value in each column of the set-up time matrix from all other values in the column.

$\| \tilde{S}_{ij} \| =$

	1	2	3	4	5	6
1	--	65	83	103	36	65
2	85	--	99	62	85	43
3	63	67	--	99	65	42
4	83	22	99	--	83	47
5	36	65	83	103	--	65
6	85	43	82	87	85	--

Column Deductions Yields →

$\| \tilde{S}_{ij} \| - \| C_{ij} \| =$

	1	2	3	4	5	6
1	--	43	1	41	0	23
2	49	--	17	0	49	1
3	27	45	--	37	29	0
4	47	0	17	--	47	5
5	0	43	1	41	--	23
6	49	21	0	25	49	--

where $c_{ij} = 0, \; i = j$

$c_{ij} = c_j, \quad i \neq j$

$c_j = \max_i \{\tilde{s}_{ij}\}$, all j

Rule 1*

1-5-2-6-3-4 cost = 36 + 65 + 43 + 82 + 99 = 325

1-5-6-2-4-3 cost = 36 + 65 + 43 + 62 + 99 = 305

Rule 2

1-2-6-3-5-4 cost = 358

1-3-6-2-4-5 cost = 313

1-4-2-6-3-5 cost = 315

1-5-2-6-3-4 cost = 325

1-5-6-2-4-3 cost = 305

1-6-2-4-5-3 cost = 336

Rule 3

1-5-3-6-2-4 cost = 266

Gavett's first heuristic rule is an easy and practical one for production sequencers to use. However, it does not use much of the information available in the set-up matrix and consequently will often yield non-optimal sequences. His second heuristic rule is similar to the first but it looks at a larger set of possible sequences; it also neglects much of the available information. It is somewhat more complex for use by production sequencers but still is manageable. His third, in essence, looks at the relative costs of reaching the various jobs. Subtraction for the matrix column deduction step could be a source of error. It is a manageable method for hand computation but the possibility of error increases

with n, as the number of entries, and hence the number of subtractions, increases as the square of n. All three of Gavett's heuristic rules require that the specific set-up matrix be available with just the jobs under consideration as rows and columns.

Heuristic Based on the Sequence Dependency Information From the Set-up Predictions

The heuristic method being proposed is a path-building technique that looks not at the complete set-up matrix but rather at the underlying structure or classification information and the coefficient value estimates of the sequence dependent factors obtained in the set-up time prediction phase. It might be best to introduce this technique in terms of a specific example.

Consider a machine-tool product-mix situation where the product process characteristics are: workpiece holders needed, set of spindle gears needed, and the number of tools used for that job. This set of characteristics is simple but it reflects differences in product dimensions (holders and tools), product materials (gears), and product shape (tools) as well as process differences (gears for speeds).

Consider a set of six jobs to put through this single machine with the objectives of minimizing the total set-up time over the set of all jobs, or alternatively minimizing the total make-span for the set of jobs.

Let the six jobs have product-process characteristics as shown in Table X.

TABLE X

PRODUCT-PROCESS CHARACTERISTICS OF
JOBS FOR EXAMPLE 1

Job Number	Work piece Holder needed	Gear set needed	Number of tools used
1	I	A	2
2	II	C	1
3	I	B	3
4	II	C	3
5	I	A	2
6	II	B	1

Further assume that the classification, measurement, and data analysis phases yielded the following prediction model for the expected set-up times and the coefficient values listed below.

$$\tilde{s}_{ij} = \sum_{k=1}^{2} h_k H_k + \sum_{\ell=1}^{2} g_\ell G_\ell + t_1 T_1 + t_2 T_2 + t_3 T_3$$

where

H_1 = 1 if workpiece holder not changed, 0 otherwise

H_2 = 1 if workpiece holder is changed, 0 otherwise

G_1 = 1 if gear set not changed, 0 otherwise

G_2 = 1 if gear set is changed, 0 otherwise

T_1 = number of tools removed

T_2 = number of tools inserted

T_3 = number of tools used for new part

and

$h_1 = 0 \quad g_1 = 0 \quad t_1 = 2$

$h_2 = 20 \quad g_2 = 25 \quad t_2 = 4$

$t_3 = 18$

Hence, we see for example:

$$\tilde{s}_{14} = 20 + 25 + 0 + 4 + 54$$
$$= 103$$
$$\tilde{s}_{42} = 0 + 0 + 4 + 0 + 18$$
$$= 22$$

Continuing in a similar fashion all of the possible $\tilde{s}_{ij}$ entries can be generated and the matrix of expected set-up times can be developed. This matrix has the following values:

$\|\tilde{s}_{ij}\| =$

	1	2	3	4	5	6
1	--	65	83	103	36	65
2	85	--	99	62	85	43
3	63	67	--	99	65	42
4	83	22	99	--	83	47
5	36	65	83	103	--	65
6	85	43	82	87	85	--

When both the underlying structure and estimates of the associated times are available, the sequencing problem can be seen in much better perspective. Both the modified traveling salesman algorithm solution method and the set of heuristic solution rules proposed by Gavett need the n x n matrix of estimated set-up values. When the set of n jobs is a small set from a large population, it is no minor task to find the $\tilde{s}_{ij}$ matrix. It can be obtained either by generating the (n-1)(n) values using the prediction method, or by looking up the required values in a large exhaustive master $\tilde{s}_{ij}$ matrix.

Although the modified Branch and Bound Algorithm guarantees optimality it is not a practical method for a production sequencer to use. Time estimates for solution times increase at least exponentially with the number of cities[22]. Little[22] reports that a thirteen city "closed" tour problem required 3 1/2 hours to solve by hand using the Branch and Bound Algorithm. The associated "open" tour problem would take much more time as n - 1 separate modified "closed" problems must be investigated to find the optimal solution for the n city "open" problem.

As indicated earlier none of Gavett's heuristic rules guarantee optimality. It is also true that working just with the n x n set-up matrix as they do, they give little insight into the sequencing problem.

The method being proposed is based on information about the underlying structure of the set-up tasks. Some aspects or factors of the set-up times are sequence dependent and of this set some will be more important than others in the sense of having larger coefficient values. In this example, the workpiece holder change value of 25 is larger than the gear set change value of 20, and both are clearly larger than the values for inserting or removing tools. The value of 18 associated with each tool required for processing any new job does not enter in, as it is not dependent on the sequence in which the jobs are processed.

The heuristic method being proposed operates so as to minimize the number of those types of changes which have the larger coefficient values. The total set of jobs is successively partitioned with the stipulation that once a subset is identified no job outside of that subset will be processed until all jobs in the subset are completed. After all of the jobs in each subset are completed the first job to follow will be selected

from the set of remaining jobs using the underlying structural information and coefficient values. Then on the basis of the characteristics of the job selected a new subset will be identified and partitioned from the set of unsequenced jobs. This process of alternately identifying subsets of jobs and searching for the first job to follow the jobs in each such subset, after those jobs are ordered, is continued until all of the jobs are sequenced. Because the structure and the coefficients are based directly on the real-world properties of the set-ups the production sequencer can directly and objectively use his experience as he develops the sequence.

Example 1 (Table X) Using Proposed Heuristic Method

(1) Job 1 -- already on the machine (initial status), and it uses gear set A (the gear set value of 25 is largest). The subset of jobs with gear set A is (1,5) so we put Job 5 next.

(2) Job 5 -- on the machine and it uses gear set A but that subset is empty (Jobs 1 and 5) so we look at the next most important characteristic, workpiece holder 1 and that subset is (1,3,5) so we put Job 3 next.

(3) Job 3 on machine and it uses gear set B, the subset using B is (3,6) so we put Job 6 on next.

(4) Job 6 uses gear set B but that subset is empty (Jobs 3 and 6) so look at work-piece holder II, that subset is (2,4,6). Jobs 2 and 4 are both candidates to be next, we select Job 2 as it uses the same number of tools as Job 6.

(5) Job 2 uses gear set C, that subset is (2,4) so we do Job 4 next.

(6) Job 4; all jobs now sequenced.

Sequence = 1 - 5 - 3 - 6 - 2 - 4

Cost = 266

The solution found is equal to the optimal solution found earlier using the modified Branch and Bound Algorithm (see Figure 4).

As a second example we shall consider a set of six jobs to be processed on one of the Mono-matics using the underlying set-up structure or factors, the set-up time prediction equation, and the coefficient estimates discussed in Chapter IV. Let these six jobs have product-process characteristics as shown in Table XI.

TABLE XI

PRODUCT-PROCESS CHARACTERISTICS
OF JOBS FOR EXAMPLE 2

Job Number	Template Element Required	Workpiece Holder (Arbor) Required	Spindle Gear Set Required	Number of Backslide Tools and Holders Required
1	1	I	A	2
2	2	II	C	1
3	1	I	B	3
4	1	II	C	3
5	2	I	A	2
6	1	II	B	1

The prediction equation (i) for the expected set-up times on the Mono-matics is:

$$(i)\quad \tilde{T}_{ijk\ell m123} = C + \sum_{i=1}^{8} m_i M_i + \sum_{j=1}^{2} s_j S_j + \sum_{k=1}^{2} a_k A_k + \sum_{\ell=1}^{2} g_\ell G_\ell + \sum_{m=1}^{2} t_m T_m + b_1 x_1 + b_2 x_2 + b_3 x_3$$

When the set-up times and the underlying set-up characteristics are to be used in sequencing production on one of these Mono-matics the prediction equation can be rewritten as

$$\text{(ii)}\quad \tilde{S}_{k\ell m123} = \sum_{k=1}^{2} a_k A_k + \sum_{\ell=1}^{2} g_\ell G_\ell + \sum_{m=1}^{2} t_m T_m + b_1 x_1 + b_2 x_2 + b_3 x_3 + \{c + M + s\}$$

where the terms in brackets are the constant terms, the machine effect term, and the shift effect term. The machine is known so the machine effect term can be added to the constant term, together they increase each set-up time by an amount independent of the sequence. For purposes of production sequencing they can be dropped. The shift (man) effect can be considered only by considering a complex time-phasing problem, and therefore shall not be included here. When using the expected set-up time prediction equation for production sequencing the terms in the brackets will therefore be dropped. The prediction equation and the coefficient estimates of interest in building up a production sequence are as follows:

$$\text{(iii)}\quad \tilde{S}_{k\ell m123} = \sum_{k=1}^{2} a_k A_k + \sum_{\ell=1}^{2} g_\ell G_\ell + \Sigma\, t_m T_m + b_1 x_1 + b_2 x_2 + b_3 x_3$$

coefficient estimates (rounded for convenience)

$a_1 = 0$ $\qquad$ $t_1 = 31$

$a_2 = 15$ $\qquad$ $t_2 = 0$

$g_1 = 4$ $\qquad$ $b_1 = 0$

$g_2 = 0$ $\qquad$ $b_2 = 7$

$\qquad\qquad$ $b_3 = 11$

Example 2 (Table XI) Using Proposed Heuristic Method

(1) Job 1, the initial job on the machine uses template 1. The template change value of 31 is largest. The subset of jobs using template 1 is $\{1,3,4,6\}$.

(2) The next largest value 15 is for arbor change from this subset $\{3,4,6\}$ only Job 3 uses the same arbor as Job 1. Job 3 is therefore the job selected to immediately follow Job 1.

(3) Job 3 on the machine and the partitioned subset still contains Jobs $\{4,6\}$. Jobs 4 and 6 both use a different arbor than Job 3 and Job 4 uses the same number of backslide tools. Job 4 is therefore the job selected to immediately follow Job 3.

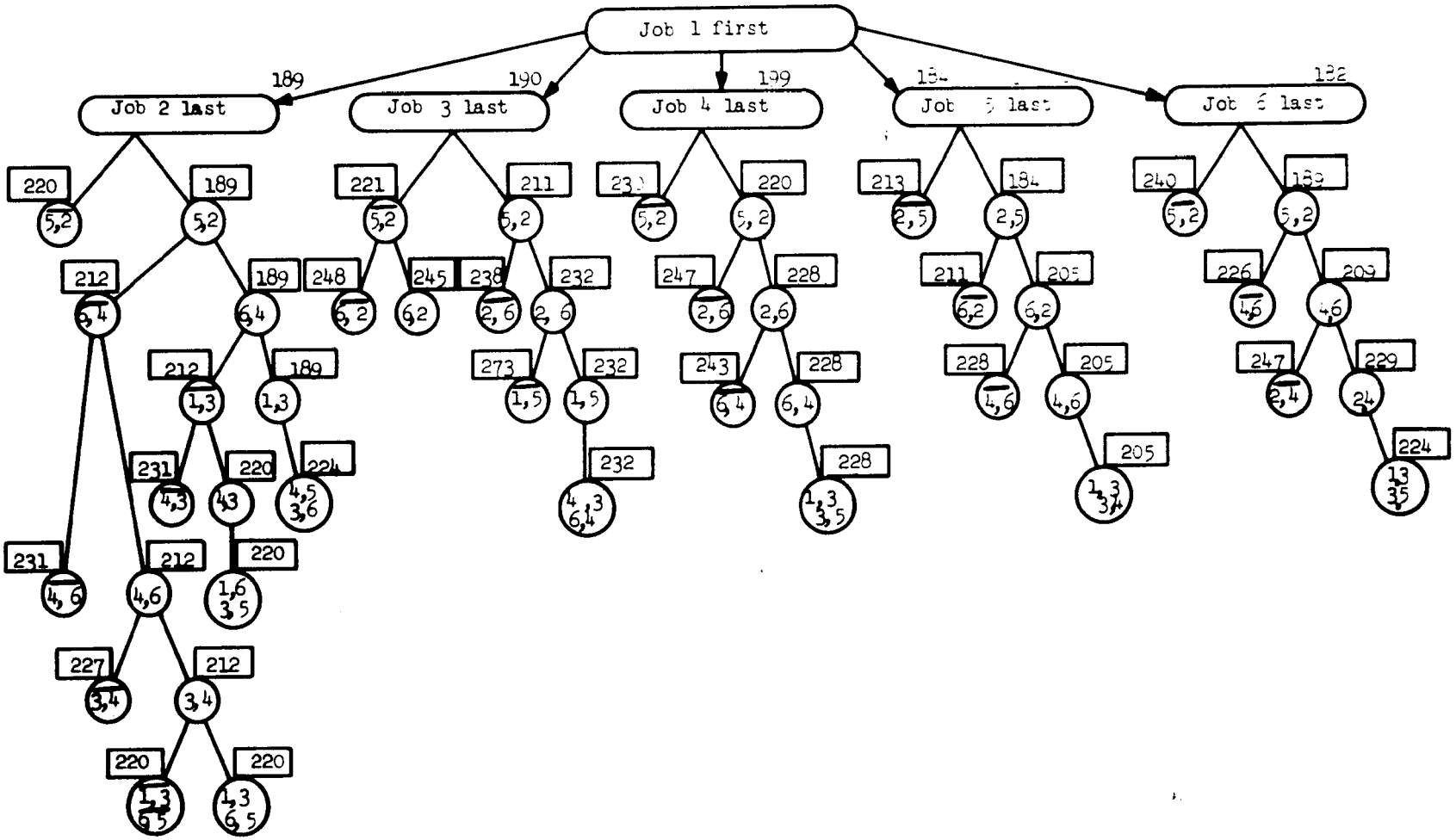
(4) Job 4 on the machine, Job 6 will be the next job as it is the last job in the partitioned subset $\{1,3,4,6\}$ not yet added to the sequence.

(5) Job 6 on the machine, the subset which uses template 1 is now exhausted, Jobs 2 and 5 remain and both use template 2. Job 6 uses arbor II and the subset of remaining jobs using arbor II is $\{2\}$ so Job 2 immediately follows Job 6.

(6) Job 2 on the machine. The subset of remaining jobs is $\{5\}$ so Job 5 immediately follows Job 2.

The sequence thus formed or built up is $\{1,3,4,6,5,2\}$ with a cost of 205.

The tree diagram resulting from the application of the Branch and Bound Algorithm is shown in Figure 5. The optimal solution is $\{1,3,4,6,2,5\}$ with a cost of 205. The optimal solutions using Gavett's three rules are: (1) $\{1,6,2,5,3,4\}$ with a cost of 251, (2) $\{1,5,2,6,4,3\}$ with a cost of 232, and (3) $\{1,3,4,6,2,5\}$ with a cost of 205.



1-6-4-3-5-2 = 220
1-3-4-6-5-2 = 220

220

1-5-2-6-4-3 = 232

232

1-3-5-2-6-4 = 228

228

1-3-4-6-2-5 = 205

205

minimum total cost

1-3-5-2-4-6 = 224

224

Figure 5. Tree Diagram Representation of Branch and Bound Solution for Example 2.

Conclusions

Advantages of this heuristic technique for sequencing production are that it is easy to understand, easy to use, and it gives insight into the production sequencing problem because it is based directly on the basic characteristics of set-up operations of the machine on which the production is being sequenced. Unlike the other methods of sequencing the jobs, it does not require the expected set-up time matrix to be completely written out, and because it uses the relative values of those predictive model coefficients which represent sequence dependent set-up characteristics it is not as sensitive to errors in the predictive model. The method does not require much computation and is shown to be a practical method for hand solution. In addition the method allows a new job to be easily inserted into the production sequence, whereas both the Branch and Bound Algorithm and the other approximate techniques require that a new problem with a different set-up matrix be solved when a new job is added to the job set. For two small sample problems the technique yields production sequences which are global optima.

CHAPTER VI

CONCLUSIONS AND EXTENSIONS

The objectives of this investigation have been twofold: (1) to develop a systematic and economical method for predicting set-up times on machine tools considering the sequential dependency of these set-up times, and (2) to develop a practical, easy-to-use method of solving the single machine sequencing problem using the information available from the prediction method which is developed.

The concept of using classification structures for describing the range of possible set-ups on a machine tool and then using this classification information to build a set-up time prediction equation has been developed both in general and in detail via a case example. The ranges of those machine tool features that must be changed or modified during a set-up were looked at. These changes or modifications in the machine tool set-up were necessitated by differences in the properties of the products being manufactured. However, it was easier to look at the machine than at the products, as the number of features by which the products can differ was larger and many of these features did not influence the set-up operations on the machine tool.

The case study in Chapter IV was important in two respects: (1) the set-up time prediction model based on classification of set-ups in terms of the underlying characteristics of the set-up operations had correlation coefficients of $\rho=.7572$ and $\rho=.8383$ for the two samples, and (2) the basic logic of the heuristic method for sequencing

production on a single machine, discussed in Chapter V, was developed while considering these underlying characteristics and their effect on the set-up times.

The single machine sequencing problem is to arrange in sequence a known set of jobs, all of which must be processed on that machine, so as to optimize a specified criterion. The processing time of each job can be separated into the set-up time and the actual production time. The actual production time is assumed to be independent of the sequence in which the jobs are processed but the set-up times are recognized as being dependent on the sequence. The criterion considered in this dissertation is minimizing the total set-up time. The total elapsed time until the last job is completed, called the "makespan", is the sum of the total set-up time and the total of the individual production times. Since the latter term is independent of the sequential order in which the jobs are processed, the sequence which minimizes the total set-up time will also minimize the "makespan".

A heuristic method of building up a job sequence for the single machine sequencing problem was discussed in Chapter V. This method is based on the information in the classification structure developed for that machine and uses the coefficient estimates of the sequentially dependent factors in building up the job sequence. The method is as follows: select a first sub-set of jobs, arrange those jobs in a sequence, select a second sub-set of jobs. From this second subset select the first job to follow the partial sequence already established and then add each of the jobs in the second subset to the partial sequence until that second sub-set is exhausted.

This procedure of selecting new subsets of jobs to add to the partial sequence continues with the rule that all of the jobs in each sub-set that is selected will be added to the partial sequence that is being built up before any of the remaining jobs not in that sub-set. This procedure of constructing a job sequence continues until all jobs are included and the final sequence is reached. The classification information is used to define the sub-sets and the relative values of the coefficient estimates are used in choosing which sub-set will be added at each step in the procedure. The results of this method are compared with the results obtained using (1) an algorithm which is a modification of the Branch and Bound Algorithm of Little, et al[22], and (2) a group of three heuristic rules proposed by Gavett [15].

The algorithm based upon a modification of the Branch and Bound Algorithm guarantees an optimal sequence, but it requires a great deal of computation since the solution of the N node "open" problem requires that N - 1 separate modified "closed" problems be investigated. The three heuristic rules of Gavett require less computational effort. All of these techniques require that the matrix containing all of the set-up times for the set of jobs under consideration be available.

The heuristic method developed in this dissertation allows the production sequencer to use directly the information on set-up operations and set-up times available from the classification analysis of these set-ups and requires little computation. The amount of time and effort for solution does not increase exponentially for this method as it does for the modified Branch and Bound Algorithm.

A thirteen job sequencing problem was solved in twenty minutes using this technique while Little[22] reports that 3 1/2 hours were required to solve a thirteen city "closed" tour problem.

Further, it is not difficult to insert a new job into the production sequence, whereas both the Branch and Bound Algorithm and the set of heuristic rules proposed by Gavett require that a new problem with a different set-up matrix be solved.

The work reported here can be extended in five directions:

(1) The sequencing technique which is introduced should be more extensively investigated both in general and for actual sequencing problems. The predictive model would then be employed to investigate the set-up processes on the machine under consideration and then the classification information, and the associated coefficient values, would be used in building up the production sequence. The sensitivity of the sequencing technique to errors in the coefficient estimates could then be investigated for these real situations.

(2) Set-up times occupy a substantial percentage of the available production time on the manufacturing equipment in many industries and are often dependent on the sequence in which the jobs are produced. The method reported here is an effective and inexpensive way to investigate set-up operations and develop set-up time prediction equations which reflect this sequence dependency. The case study reported is a first step in investigating such sequence dependent set-up times and further work in other manufacturing industries should be done.

(3) The manufacturers of machine tools should investigate the underlying characteristics of set-up operations on the machine tools they produce and provide a list of possible factors and levels

for these factors to their customers. The customer could then gather data in his own shop to determine if the list is adequate, and, if it is what the coefficient values are for his shop.

(4) Production standards are maintained in most companies both for control and for planning; however, standards on set-up or change-over operations are rare. The information from the set-up time phase of this study was used only in the planning sense to build up the sequence in which to process jobs over a machine. Using this prediction method to develop set-up standards for control purposes might very well reduce the amount of variance of the set-up times.

(5) The proposed heuristic method uses the information on set-up operations and set-up times to construct a job sequence for the single machine sequencing problem where the sequence dependency of the set-up times is recognized. When several parallel machines are available and each job in the known set can be processed on any machine, perhaps with different set-up times and production times on the various machines, the sequencing problem is much more complex. It is conjectured that the proposed heuristic, which uses fundamental information about the set-up operations and times, could be extended to cover such problems. The extension would have to include a method of viewing both the set-up times and the production times.

APPENDIX A

DATA COLLECTION FORMS

I. Set-Up Time Log

1. One of these log sheets is to be filled out for each set-up.
2. Set-up activities are sometimes interrupted. Start times refer to both the initial starting of a set-up and the resumption of a set-up started before. Stop times refer to either the completion time or to a stop due to some other reason besides completion. When a stop time is filled in, the reason for stopping is to be filled in by checking the appropriate box.
3. The time entries should be made when the job is started (or resumed) or stopped, not at a later time. The set-up man is to fill out the log for the job.

Machine Number_____

SET-UP RECORD LOG

NEW PART NUMBER	START TIME	STOP TIME	END OF SHIFT	OTHER SET-UP	REPAIR CALLED	OTHER	SET-UP DONE	ADJUST DONE	FIND TOOLS

YOUR COOPERATION ON THIS RESEARCH PROJECT IS GREATLY APPRECIATED. PLEASE FILL OUT BOTH THE SET-UP RECORD LOG AND THE SET-UP CHANGE RECORD.

Figure A-1. Set-up Time Log Form.

II. Step-Up Record Directions

1. One of these set-up record sheets is to be filled out for each set-up. If both machines of a pair are being set-up at the same time, then both sides of a record sheet should be filled out. If just one machine is being set-up, then the record sheet will have only one side filled out when it is turned in.
2. All of the items on the set-up record sheet are to be filled out by the set-up man who actually does the set-up. If the set-up overlaps several shifts, then the record sheet should be passed on from one set-up man to the next.
3. The items on the set-up record sheet will each be discussed below to avoid any possible confusion on how the record is filled out. The items are mainly concerned with what the set-up man must do to change the machine over.
4. It is recognized that sometimes a set-up goes smoothly and other times the same set-up might be difficult. Space is provided both for recording the general smoothness of the set-up and for remarks the set-up man (or men) might have regarding that particular set-up. These remarks are welcomed.

Items

DATE SET-UP STARTED: Please fill in the date of the day on which the set-up was started using the calendar month and day.

SHIFT SET-UP STARTED: Please check the box corresponding to the shift during which the set-up was started.

MACHINE NUMBER: Please fill in the number of the machine that is being set-up.

PREVIOUS PART NUMBER: Please fill in the number of the part that the machine was set-up for just before this set-up was started. If for any reason the machine was not set-up for a part, please put "none" on the line.

NEW PART NUMBER: Please fill in the number of the part that is now being set-up on the machine.

TYPE OF CUT: Please check the box corresponding to the type of cut that is to be made on this machine; i.e., rough, semi-finish, finish, when this set-up is completed.

ARBOR: Either the arbor is left the same and not changed or else the arbor (or center) is changed and a different arbor (or center) is put in. If there is no change, please check that box and go on to the next item. If there is a change, please check the type of change in one of the four squares provided.

SPINDLE GEARS: Please check the correct box noting either a change in the spindle gears or no change.

BACKSLIDE TOOLS AND HOLDERS: In a set-up the backslide tools are usually adjusted and sometimes new tools or even new tool holders need to be added. On each of the three lines please check the box of the number that corresponds to this set-up (realizing that at other times because of the part on the machine before these numbers might be different). The lines are for the tools and the holders and the information wanted is (1) how many tools/holders are

taken out, (2) how many tools/holders are put in, (3) the number of tools that are used in the backslide for the new part. The number of tools/holders taken out and the number put in may be different. Please fill out carefully.

FRONTSLIDE TOOLS: Sometimes the front tool is changed and other times it is not; please check whether the frontslide tool is changed or not changed.

TEMPLATE CONDITION: Sometimes the templates are in poor condition and shimming is necessary. Please check the appropriate box after looking at the definitions:

no shimming = the template was in acceptable condition and no shimming was needed.

shimming = the template needed shimming.

FEED DOGS: Please check the box corresponding to the number of speed change dogs that were set for the old job, and the number of speed dogs that need to be set for the new job.

GENERAL: Here we are attempting to recognize that identical set-ups may differ in general smoothness for reasons other than those given above. Please check one of the three boxes. Also please write in any comments regarding this set-up that you feel made it different from the usual set-up.

MACHINE NUMBER _____
PREVIOUS PART NUMBER _____
NEW PART NUMBER _____
DATE SET-UP STARTED _____

SHIFT SET-UP STARTED 1 ☐ 2 ☐ 3 ☐

TYPE OF CUT (NEW PART) ROUGH ☐ SEMI FINISH ☐ FINISH ☐

ARBOR: NO CHANGE ☐
CHANGE → FROM

	TO ARBOR	TO CENTER
FROM ARBOR		
FROM CENTER		

SPINDLE GEARS: CHANGED ☐ NOT CHANGED ☐
FRONT SLIDE TOOL: CHANGED ☐ NOT CHANGED ☐

BACK SLIDE TOOL:

	TOOLS 0	1	2	3	HOLDERS 0	1	2	3
NUMBER TAKEN OUT								
NUMBER PUT IN								
NUMBER FINALLY USED								

TEMPLATE CONDITION: NO SHIMMING ☐ SHIMMING ☐

FEED DOGS:

	0	1	2	3	4	5
NUMBER USED BEFORE						
NUMBER NOW USED						

GENERAL: SMOOTH ☐ NORMAL ☐ ROUGH ☐

1) GENERALLY THE SET-UP WAS
2) PLEASE WRITE IN YOUR COMMENTS ON THIS PARTICULAR SET-UP (UNUSUAL PROBLEMS, ETC...)

MACHINE NUMBER _____
PREVIOUS PART NUMBER _____
NEW PART NUMBER _____
DATE SET-UP STARTED _____

SHIFT SET-UP STARTED 1 ☐ 2 ☐ 3 ☐

TYPE OF CUT (NEW PART) ROUGH ☐ SEMI FINISH ☐ FINISH ☐

ARBOR: NO CHANGE ☐
CHANGE → FROM

	TO ARBOR	TO CENTER
FROM ARBOR		
FROM CENTER		

SPINDLE GEARS: CHANGED ☐ NOT CHANGED ☐
FRONT SLIDE TOOL: CHANGED ☐ NOT CHANGED ☐

BACK SLIDE TOOL:

	TOOLS 0	1	2	3	HOLDERS 0	1	2	3
NUMBER TAKEN OUT								
NUMBER PUT IN								
NUMBER FINALLY USED								

TEMPLATE CONDITION: NO SHIMMING ☐ SHIMMING ☐

FEED DOGS:

	0	1	2	3	4	5
NUMBER USED BEFORE						
NUMBER NOW USED						

GENERAL: SMOOTH ☐ NORMAL ☐ ROUGH ☐

1) GENERALLY THE SET-UP WAS
2) PLEASE WRITE IN YOUR COMMENTS ON THIS PARTICULAR SET-UP (UNUSUAL PROBLEMS, ETC...)

Figure A-2. Set-up Classification Form.

APPENDIX B

TESTING MODEL ASSUMPTIONS

I. Kolmogrov-Smirnov Tests for Normality on the Five Sub-Classes [17][31]

The Kolmogorov-Smirnov one sample test is a test of goodness of fit. That is, it is concerned with the degree of agreement between the distribution of a set of sample values (observed values) and some specified theoretical distribution. Briefly, the test involves specifying the cumulative frequency distribution which would occur under the theoretical distribution and comparing that with the observed cumulative frequency distribution. The theoretical distribution represents what would be expected under H_o. The point at which these two distributions, theoretical and observed, show the greatest divergence is determined. Reference to the sampling distribution indicates whether such a large divergence is likely on the basis of chance.

let $F_o(X)$ = a completely specified cumulative frequency distribution, the theoretical cumulative distribution under H_o. Thus, for any value of X, the value of $F_o(X)$ is the proportion of cases expected to have values equal to or less than X.

let $S_n(X)$ = the observed cumulative frequency distribution of a random sample of N observations. Where X is any possible score, $S_n(X) = k/n$, where k is the number of observations equal to or less than X.

$D = \text{maximum } |F_o(X) - S_n(X)|$

The sampling distribution of D under H_o is known. Tables can be found in Siegel (31) and in Hoel (17).

The procedure here is to hypothesize that the subclass population is normal, estimate the mean and variance, develop both $F_o(X)$ and $S_n(X)$ and then calculate D. If the calculated D is larger than the table value for the correct N and the selected α value the normal hypothesis is rejected, otherwise it is accepted.

The calculated values and the critical values (for two α levels) for the five populations are shown below:

POPULATION	SAMPLE SIZE	CALCULATED D	CRITICAL D α=.05	α=.20	H_o: POPULATION NORMAL
$T_1A_1G_1$	5	.3157	.56	.45	Accept
$T_1A_1G_2$	21	.1466	.294	.210	Accept
$T_1A_2G_1$	13	.1544	.34	.27	Accept
$T_1A_2G_2$	29	.0839	.24	.19	Accept
$T_2A_1G_2$	5	.3239	.56	.45	Accept

II. Bartlett Test for Homogeneity of the Five Variances (4) (12)

We shall now test the equality of a set of variances ($\sigma 1^2 = \sigma 2^2 \ldots = \sigma k^2$) on the basis of the sample variances S_1^2, S_2^2,... S_k^2 based on $\gamma 1$, $\gamma 2$,...γk degrees of freedom, respectively. Bartletts' test, which assumes normality of the populations, will be used.

$$B = \frac{1}{C} \left(\gamma \ln S^2 - \sum_{i=1}^{k} \gamma_i \ln S_i^2 \right)$$

where $$C = 1 + \frac{\sum_{i=1}^{k} (1/\gamma i) - 1/\gamma}{3(k-1)}$$

$$\gamma = \sum_{i=1}^{k} \gamma_i$$

$$S^2 = \sum_{i=1}^{k} \gamma_i S_i^2 / \gamma$$

For values of γ_i of 5 or more the distribution of B is satisfactorily approximated by the χ^2 distribution with (k-1) degrees of freedom. Hence we would reject the hypothesis $\sigma 1^2=\sigma 2^2=\ldots=\sigma k^2$, if the value of B were greater than $\chi^2_{k-1,\alpha}$ where α is the chosen significance level.

Calculated B = 6.957

Critical Value (α=.05) = 9.488

$\therefore$ Accept Hypothesis $\sigma 1^2=\sigma 2^2=\sigma 3^2=\sigma 4^2=\sigma 5^2$

III. Test for Independence

Run test on the sign of the deviations using the Kolmogorov-Smirnov one sample test.

RUN LENGTH	FREQUENCY		CUMULATIVE	CUMULATIVE THEORETICAL	|T-A|
1	9	.297	.297	.500	.203
2	10	.333	.630	.750	.120
3	3	.099	.729	.875	.146
4	6	.198	.927	.938	.011
5	1	.033	.960	.969	.009
6	1	.033	.993	.984	.009
7	0				
8	0				
	30				

Calculated D = .203

Critical $D_{\alpha=.05}$ = .56

Critical $D_{\alpha=.20}$ = .23

$\therefore$ Accept Hypothesis of Independence

APPENDIX C

LISTING OF MONO-MATIC LATHE SET-UP DATA:

Card Column	Item Identification
1-2	Identification number (not chronological order)
3	Number of interruptions recorded
4-7	Machine identification number
8-9	Shift (first, second)
10-12	Cut type (rough, semi-finish, finish)
13-14	Arbor (not changed, changed)
15-16	Spindle gears (changed, not changed)
17-18	Template element (changed, not changed)
19	Number backslide tools/holders removed
20	Number backslide tools/holders inserted
21	Number backslide tools/holders required for new part
22-23	Template shimming required (yes, no)
24-26	General evaluation
29-31	Measured total set-up time

TABLE A-I

MONO-MATIC LATHE SET-UP DATA

MONO-MATIC LATHE SET-UP DATA (ORIGINAL SAMPLE)

```
011148901001010110011010101  080
020148801001010110001010101  090
030148910001010110201011000  070
040148810001010110201011000  095
051154110001011C1010101100   105
061163710001011010101011010  110
071154101001011010100010101  115
080163701001011010100010101  105
092154101001011010011010011  170
100163701001011010011010011  170
111154110001101010012100101  090
121163710001101010012100011  150
131154110001100110002011000  060
140163710001100110002011000  095
151148901001100110003010100  070
160148801001100110003010100  075
170148901001010110013010101  125
181155010001100101001010100  050
190158710001100101001010100  030
202155001001100110201010100  060
213158701001010110201010100  110
220155210001011010122010100  105
231158810001010110012100100  115
240155001001010110023011000  085
250158701001010110023010100  095
260148901100100110300011000  050
271148801001100110201100100  065
280148801001010110001010100  110
290158801100100110200010100  090
300155201100100110200010100  070
311154101001010110012010100  150
320163701001011010012010100  140
331154101001010110101100100  095
340163701010010110200010100  100
350154101001010110012010100  150
360163701001010110022010100  155
370155001010100110011010100  080
380158701001100110011010100  090
390158801100011010000010100  045
400155201100011010100010100  045
410154101010011010101010100  080
420163701001100110002010011  110
430158801100011010000010100  085
441155201001011010001010100  105
451158810001010110022010100  130
460155210001010110012010100  105
470158810010100101000101000  020
480155210001100101011100100  040
490158801100101010200011000  055
500155201001101010101010100  065
```

TABLE A-I (CONT'D)

MONO-MATIC LATHE SET-UP DATA

5	1114890100110101000301010	125
5	2014880100110101000301010	130
5	3015880110001011000010100	060
5	4015520101000101101001010C	060
5	5014890110010011030001010	045
5	6014880100110011020110010	070
5	7016371000110011000201010	080
5	8115411000101011012210010	090
5	9015881000110011001201010	105
6	0015521000110011C01201C10	085
6	1115881010000101102000101O	045
6	2015521000101011020001010	060
6	3115881010001011000010010	105
6	4015521000101011000110010	115
6	5014891000110011000310010	075
6	6114881000110011000310010	070
6	7014890100101101020101010	110
6	8114880100101101020101010	100
6	9015880100101101010201001	180
7	0015520100101101010210001	200
7	1014890100101011000101010	065
7	2014880100101011000101010	055
7	3015500100110011000001010	095
7	4114880100101011002301010	135
7	5015880110010011020001010	095
7	6015520101010011020001010	075
7	7014890100101011020101010	095
7	8014880100101011020101010	090
7	9115880101010010101110010	050
8	0015520100110010101101001	150

MONO-MATIC LATHE SET-UP DATA (VALIDATION SAMPLE)

0	1015880110001101010001100	060
0	2015520110001101010001100	050
0	3114890110001011020010010	085
0	4114880100101011010101010	100
0	5015411000110011011101010	090
0	6116371000110011011101010	120
0	7015881000110010101110010	045
0	8015521000110010101110010	055
0	9115411000110010111101001	105
1	0016371000110010111101010	060
1	1015521000110010100201010	045
1	2015881000110010100210010	045
1	3314891000101011001210001	180
1	4014880100101011001210001	130
1	5114891000101011001301010	105
1	6114881000101010102301010	120

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