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Estimating Production Costs in a Machine Shop

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Traditional methods of estimating job production costs in a bid situation have depended to a large degree on the experience and intuition of the estimator. Here's a reliable method that doesn't call for long experience and that minimizes errors —

ESTIMATING PRODUCTION COSTS IN A MACHINE SHOP

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THE ABILITY to predict production costs with a fair degree of accuracy is the keystone of intelligent management decisions. Production cost estimating in the job shop manufacturing firm is essential in the initial planning phase of the product. Cost estimates are used for sales quotes and bids. Overestimating the cost of a product to a customer is likely to cause a loss of the bid to a competitor, while underestimating the cost may lead to financial losses.

For the firm which manufactures parts for final product use, cost estimates are required for make-or-buy decisions with respect to the parts themselves and for final product pricing. Over- or under-estimating the production costs will inflate or deflate the total manufacturing cost. This, in turn, could drastically alter the selling price of the product and its market position.

Traditional method

The traditional method of machine shop cost estimating is for persons trained in the knowledge of shop methods, machine efficiencies, and the principles of time and motion study to outline from the print of the product all of the necessary steps in the manufacture of the product, to recommend proper tooling and production aids, and to attach reasonable time estimates which may be translated into costs, through application of appropriate machine-hour rates.

The resulting estimates are individualized opinions. How closely the estimator's opinion reflects true shop operating conditions is a measure of the quality of the estimator's performance. Estimators with different shop experience are likely to make different estimates on the same job. The estimator who makes the most reliable estimates is the one who best knows the equipment, working conditions, and manufacturing practices in the shop. This knowledge, however, is obtained only after considerable experience.

This machine shop cost estimating technique, which is used by most shops today, often produces only a crude approximation of the actual costs that the firm must bear in production. A great amount of educated guessing is necessary to arrive at an estimate, and seldom are the estimator's choices consistent. Most firms can tolerate reasonable variances between estimated and actual costs, but, in many instances, losses are being incurred because appropriate decisions are not made in the planning stages of a product due to unreliable cost estimates.

Some companies add so-called "fudge factors" to their cost estimates when it can be determined that estimates consistently depart from actual production costs. Other firms feel that the high estimates will offset the low estimates and the average will generally be representative of the actual overall cost. These misgivings about production cost estimating cause management to make poor pre-production decisions, which unknowingly may lead to financial losses. When decisions such as cost bidding, production loading, pricing, forecasting, make-or-buy determination, and job performance standards are based on cost estimates, it is important that each individual operation cost estimate be reliable and accurate to ensure the optimum utilization of the manufacturing facility. The ability of the estimator to predetermine the manufactured cost of products within a given acceptable range of actual cost can either make or break the company. Thus, the need for valid and reliable cost estimates is crucial.

Statistical method

As an alternative to the traditional approach, this article examines the application of a statistical method that produces an estimating formula developed from the actual costs of historical performance of an operation. Once developed, the mathematical formula may then be used by the estimator to arrive at costs for the operation by providing the values of a limited number of variables from the blueprint of the machined part.

This alternative does not remove the responsibility for estimating from the hands of the estimator and place it in the realm of a mysterious mathematical formula. The estimator must still be responsible for determining the sequence of operations that are necessary to produce the part as well as the proper method of machining the part. The statistical method is, however, a logical and an objective process which is independent of the subjectivities and the intangibles that must be incorporated into the estimating process once the correct operation and method have been determined. As such, the statistical approach is an effective complement to the judgement and intuition of the cost estimator.

The statistical approach to cost estimating has the virtues of consistency and lack of computational errors, which are unavoidable in the traditional method. Further, it has the advantage of reproducibility in that a given set of inputs will always generate the same results. The input, computational steps, and results are clearly indicated and documented. Thus, the analysis may always be resurrected after the results have been observed, and the analytical procedure can be evaluated. If testing proves the appropriateness of the analysis, the same procedure can be applied again with greater assurance that the results are appropriate. A purely subjective approach has no such permanent value. Once a subjectively determined cost is found, little knowledge has been gained about the method which was used to arrive at the cost. Each cost determination, then, is a new and unique requirement.

The reproducibility of the statistical method also yields benefits which transcend the particular people who perform the analysis. Anyone with a limited background may be taught the requirements of the statistical approach, whereas the methodology of the subjective analysis cannot be easily communicated. Any learning that results from the subjective approach accrues only to the individual who directly participates in the process.

The statistical approach to the

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estimation of manufacturing costs is based upon the fundamental hypothesis that the cost of a manufactured item is a function of its characteristics. From this premise, to which there can be little objection, one then moves on to discover, statistically, the relationships that exist between certain product characteristics and cost. In mathematical terms, cost or, initially, time, which may be easily translated to cost, is viewed as a dependent variable whose value is determined by characteristics of the product which constitute a set of independent variables. The statistical method for tracing such relationships is that of regression/correlation. That is the statistical method used herein, and it is suggested as an alternative to present more detailed procedures.

A case study

To illustrate the application of the statistical method of estimating manufacturing costs, the following test outlines the approach used in the development of statistically determined formulas to be used in connection with estimating the cycle time per piece for a turning operation on an automatic screw machine—one of several operations required in connection with the manufacture of a particular part machined. This particular example was selected since this machine is widely used and similar applications may be made in a number of different industries other than the particular one involved in this instance.

The initial step in the development of the statistical method was the collection of a sample of 21 representative parts upon which the analysis was based. Prior to the statistical analysis, each of the items that constituted the sample was re-examined to ensure that the actual times were proper and reasonable. Statistical methods require that samples be randomly selected in order that inferences and conclusions may be statistically measured in terms of levels of confidence. In this instance, however, like many other samples available in the firm, the sample consisted of whatever data one could obtain. For reasons which will be discussed later, the use of this sample, which was not random, does not invalidate the usefulness of the statistical method.

Once the available sample had been obtained, the next step was to select those product characteristics where, in the minds of those most familiar with the product, the operations and the methods should be most closely related to the cycle time. Theoretically, if one were to include all of the possible variables, appropriate results would be forthcoming. However, since there is a considerable amount of overlap among the variables, it was felt that a considerably smaller number of variables than all of those available could be used to develop the estimating formula via regression analysis. In this instance seven variables were used. These included: (1) Stock outer diameter; (2) Material (or machinability) factor; (3) Overall length of the finished part; (4) Finished outer diameter; (5) Hub outer diameter; (6) Hub length; and (7) Bore diameter. A significant fact regarding

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EXHIBIT 1

TURN COMPLETE 6 SPINDLE CONE FAMILY 30 & 31 3-12-70

CONTROL CARD 8 8 21 7 2 0.050 0.0502111 0111

TRANSFORMATION CARD 9 6 1 2 7 6 6 2 2 7 4 0 5 7 7 1 9 7 7 1 7 7 7 2 1 8 8 0
CONSTANT CARD 0.500 3.141

ORIGINAL-DATA

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
3.750	1.000	0.970	3.610	0.0	0.0	0.870	0.027
3.750	1.000	1.370	3.730	2.120	0.400	1.120	0.031
3.120	1.000	1.000	3.060	0.0	0.0	0.870	0.023
4.000	1.000	1.250	3.880	1.870	0.250	1.250	0.033
2.500	0.900	1.000	2.440	0.0	0.0	0.740	0.021
4.000	0.900	1.440	3.940	0.0	0.0	1.120	0.037
4.000	0.900	1.000	3.940	0.0	0.0	1.870	0.032
1.750	0.900	1.370	1.700	1.690	0.810	0.750	0.020
4.000	0.900	1.500	3.980	1.750	0.500	1.120	0.038
3.750	0.900	1.360	3.670	2.250	0.460	1 360	0.038
3.750	0.900	1.300	3.730	2.300	0.440	1.370	0.036
4.000	0.900	1.640	3.820	2.000	0.680	1.250	0.042
2.120	0.800	1.180	2.100	1.620	0.500	0.620	0.020
3.500	0.900	1.090	3.420	0.0	0.0	1.000	0.029
4.000	0.900	1.280	3.810	1.810	0.450	1.380	0.040
3.750	0.900	1.590	3.730	2.000	1.000	1.250	0.039
2.250	0.900	1.130	2.150	1.760	0.550	0.870	0.023
3.000	0.800	1.230	2.850	0.0	0.0	0.750	0.033
2.750	0.700	0.830	2.630	0.0	0.0	1.000	0.033
3.380	1.000	1.280	3.370	1.680	0.340	0.870	0.029
2.120	0.800	0.960	2.100	1.750	0.370	0.980	0.020

Original input data. Each row contains the variables for one of the samples. The variables are as follows:

Independent Variables:

1 — Stock outer diameter
2 — Material (machinability) factor
3 — Overall length
4 — Finished outer diameter
5 — Hub outer diameter
6 — Hub length
7 — Bore diameter

Dependent Variable:

8— Hours per piece

each of these variables is that they are readily determinable from the print of the manufactured part, thereby enabling one with substantially less training than the typical estimator to supply the inputs to the statistical estimating method. An array of the initial data which was input to a stepwise multiple regression/correlation routine on the IBM 360 is shown as Exhibit 1 above.

In this particular instance, the capability of the particular program to accomplish certain transformations on the original input was used since it appeared that better relationships would be derived if certain logical transformations were used in lieu of the raw data. Two such transformations were made. The first transformation involved a relationship to the RPM at which the machine would operate. To accomplish this relationship the following transformation was used:

$$\text{Variable } 6 = \frac{\text{Stock outer diameter} \times \pi}{\text{material factor}}$$

The second transformation related stock removal to machinability in the following expression:

$$\text{Variable } 7 = \left[\frac{(\text{Stock O.D.} - \text{Fin. O. D.})}{2}\right] \div \text{mat factor}$$

Thus the actual regression/correlation analysis was carried out using the first five variables above, together with the transformed variables 6 and 7 as independent variables and hours per piece as the dependent variable. This arrangement of input, sorted in ascending order with respect to the dependent variable, is shown in Exhibit 2 on page 46.

The final step of the stepwise multiple regression/correlation analysis is shown as Exhibit 3* on page 47. Of initial interest is the

*Since the main purpose of this analysis is to demonstrate the use of regression/correlation in cost estimating rather than to examine the statistical method itself, there is little discussion of the statistics, which would make the discussion exceedingly long. Those interested in the statistical method itself are referred to any one of the several texts on advanced statistical methods.

EXHIBIT 2

SORTED-DATA

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.750	0.900	1.370	1.700	1.690	6.107	0.028	0.020
2.120	0.800	0.960	2.100	1.750	8.324	0.013	0.020
2.120	0.800	1.180	2.100	1.620	8.324	0.013	0.021
2.500	0.900	1.000	2.440	0.0	8.725	0.033	0.021
2.250	0.900	1.130	2.150	1.760	7.852	0.056	0.023
3.120	1.000	1.000	3.060	0.0	9.800	0.030	0.023
3.750	1.000	0.970	3.610	0.0	11.779	0.070	0.027
3.380	1.000	1.280	3.370	1.680	10.617	0.005	0.029
3.500	0.900	1.090	3.420	0.0	12.215	0.044	0.029
3.750	1.000	1.370	3.730	2.120	11.779	0.010	0.031
4.000	0.900	1.000	3.940	0.0	13.960	0.033	0.032
2.750	0.700	0.830	2.630	0.0	12.340	0.086	0.033
4.000	1.000	1.250	3.880	1.870	12.564	0.060	0.033
3.000	0.800	1.230	2.850	0.0	11.779	0.094	0.033
3.750	0.900	1.300	3.730	2.300	13.087	0.011	0.036
4.000	0.900	1.440	3.940	0.0	13.960	0.033	0.037
4.000	0.900	1.500	3.980	1.750	13.960	0.011	0.038
3.750	0.900	1.360	3.670	2.250	13.087	0.044	0.038
3.750	0.900	1.590	3.730	2.000	13.087	0.011	0.039
4.000	0.900	1.280	3.810	1.810	13.960	0.106	0.040
4.000	0.900	1.640	3.820	2.000	13.960	0.100	0.042

Input data after program transformations and sorting on variable 8, hours per piece, the dependent variable. Variables 1 through 5 appear as in Exhibit 1 except that the order is changed due to the sorting. Variables 6 through 7 are new variables, resulting from the indicated transformations.

column headed PCT ERROR, which indicates that the estimates produced by the regression equation (column headed ESTIMATE) are all within three per cent of the actual times for the operation on these jobs (column headed ACTUAL). This is well within the acceptable error level set up by management, ± 10 per cent, prior to the undertaking of the analysis.

Other information given in this last step enables the analyst to determine the estimating formula, which is as follows:

Est. Time = – 0.0968 + .0978 (variable 2) + .0086 (variable 3) – .0313 (variable 4) + .0015 (variable 5) + .0112 (transformed variable 6) – .0285 (transformed variable 7).

It should be noted that variable 1, stock outer diameter, was not used in the final form of the estimating formula. Examination of other information produced by the program indicated a high degree of relationship between it and variable 4, finished outer diameter. Thus, starting with only seven variables, duplication was uncovered by the methodology, and variable 1 was, in effect, discarded from the analysis in favor of variable 4.

Since the original sample was not a random sample, various of the other measures provided in the analysis could not be properly used in tests of confidence. In any instance, the acceptance of the statistical alternative in this application demands that the method produce results within a given range for all members of the universe with no averaging or cancelling of high and low errors to be tolerated. In view of the success of the statistical method in this sample, the formula has been subjected to extensive testing using many other parts and is producing times that are well within the acceptable range of error.

Conclusions

The use of a statistical alternative to present estimating methods in job machine shop operation is a single example of extensive use of the method by the authors in the development of a computerized system of preparing quotations or bids. The statistical method has been successfully used in a number of instances involving other operations on other machines.

Compared to present manual methods, the statistical method of cost estimating offers the following advantages:

1. *Ease of use.* Use of the statistical method involves the mere substitution of the appropriate variable into the estimating equation and the calculation of the estimated time. Since the input variables are typically readily obtainable from the blueprint, the estimate can be obtained by those who have considerably less experience than the typical estimator. To avoid errors in calculation, the equation could be computer-stored and the estimate automatically calculated.

2. *Consistency.* Given the same set of input variables, the statistical method will produce identical results. This benefit is unlike the present situation, where two differ-

EXHIBIT 3

STEP NUMBER 6 ENTER VARIABLE 7

STANDARD ERROR OF ESTIMATE= 0.001
MULTIPLE CORRELATION COEFFICIENT= 0.997
GOODNESS OF FIT,F (6, 14)=339.9080

CONSTANT TERM= —0.0968

VAR	COEFF	STD DEV COEFF	T VALUE	BETA COEFF
2	0.0978	0.0190	5.1406	1.0554
3	0.0086	0.0010	8.1895	0.2629
4	—0.0313	0.0055	—5.6734	—3.2347
5	0.0015	0.0002	6.3123	0.2001
6	0.0112	0.0016	7.1630	3.7437
7	—0.0285	0.0123	—2.3064	—0.1281

OBS	ACTUAL	ESTIMATE	RESIDUAL	PCT ERROR
1	0.020	0.020	—0.000	—1.068
2	0.020	0.020	0.000	0.708
3	0.021	0.022	—0.001	—2.599
4	0.021	0.021	0.000	1.689
5	0.023	0.023	—0.000	—0.098
6	0.023	0.023	—0.000	—0.968
7	0.027	0.027	0.000	0.450
8	0.029	0.028	0.001	2.274
9	0.029	0.030	—0.001	—2.399
10	0.031	0.031	—0.000	—1.417
11	0.032	0.033	—0.001	—1.882
12	0.033	0.033	0.000	0.515
13	0.033	0.033	0.000	0.752
14	0.033	0.033	0.000	1.142
15	0.036	0.036	—0.000	—0.026
16	0.037	0.036	0.001	1.709
17	0.038	0.039	—0.001	—2.338
18	0.038	0.037	0.001	1.647
19	0.039	0.038	0.001	2.459
20	0.040	0.040	0.000	0.698
21	0.042	0.043	—0.001	—2.219

Final stage of stepwise regression/correlation output from the computer. Items relevant to this study are cited in the text. Standard symbols and terminology are used for the other items, and their significance may be examined in any of several standard texts in advanced statistical methods.

ent estimators may be quite some distance apart on an identical job.

3. *Rapid cost determination.* The statistical method is faster than present manual methods, which should enable the firm to reduce backlogs and improve turnaround times in the estimating department.

4. *Cost savings.* Since the statistical method may be used with persons having less training than the typical estimator and since it is accomplished more rapidly than by manual methods, there will be cost savings.

In addition to the above analysis, which relates to a machine-shop-type operation, the authors have made preliminary studies which indicate that the statistical method may offer considerable cost savings in the estimating activity in a wide variety of job shop operations, including those of heat and air conditioning contractors, electrical contractors, and forging shops. From these promising results, it is reasonable to expect that the approach could also benefit job shop printers and several other kinds of job shop operations.

A final observation concerning the statistical approach to cost estimating in a machine shop is that the cost of exploring the feasibility or appropriateness of the method is relatively small as compared to other quantitative approaches to business problems. Stepwise regression programs are readily obtainable at computing installations if one is not readily available. Given the computing capability, then, which does not require any investment in programing, all that is required is the collection of sample data for the operation. In firms where production data have been collected, little effort is required. Thus, only a small outlay is required to get the initial evidence as to whether or not the statistical method may work in any given situation.