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Using Computers in the Development of Statistically Based Acceptance Plans

James L. Burati, Jr., and Jack H. Willenbrock

This paper presents a number of ways in which a computer can be used to assist in the development of statistically based acceptance plans. These techniques include statistical analysis of preliminary data to determine the appropriate parameters to use in the development of the acceptance plan. Data collected from 13 bituminous airport pavement construction projects were used to develop a proposed acceptance plan for asphaltic concrete density. A computer algorithm was used to calculate the probabilities necessary to determine the operating characteristics (OC) curves for the plan. Another computer program was used to estimate the integral necessary to determine the expected payment curve associated with a continuous price adjustment schedule. The continuous price adjustment schedule eliminates the problem of having relatively large differences in payment associated with small differences in quality. This situation is encountered frequently in the discrete price adjustment schedules typically used in pavement construction. A computer simulation program used to determine the OC curves for the proposed density acceptance plan is presented. The OC curves from the simulation agree very closely with OC curves that were calculated by theoretical means. The simulation program provides an advantage over the theoretical solution in that it provides OC curves in terms of means and standard deviations that can be related easily to the contractor's process capabilities. The simulation program presented can be used to develop OCs for properties that require either one-sided or two-sided specification limits.

In 1978, for the first time, the Federal Aviation Administration (FAA) Eastern Region incorporated statistically based concepts into its bituminous surface course specification (Item P-401). This specification included price adjustment factors for mat density. In order to expand the scope of its statistical specification to include additional acceptance characteristics and price adjustment factors, FAA contracted with Pennsylvania State University through the Pennsylvania Transportation Institute to investigate the Eastern Region's P-401 specification.

Data for the study were collected by FAA on 13 projects from the 1978 construction season. These projects represented over 180 000 Mg (200 000 tons) of asphaltic concrete. These data were analyzed by using standard statistical computer packages (1, 2) to determine the statistical parameters representative of existing acceptable construction. These parameters were then used in the development of proposed acceptance plans for asphaltic concrete.

The objective of this paper is to present the original mat-density acceptance plan and the modifications recommended for it as a result of the research study. The acceptance plan originally developed by FAA will first be presented and discussed. Recommended modifications to this plan will then be presented. The role of the computer, which made possible in seconds tedious and laborious calculations that would have required many hours if done by hand, will be discussed in detail.

ORIGINAL ACCEPTANCE PLAN

The original acceptance plan based acceptance for mat density on a lot-by-lot basis, with a lot defined as one day's production. The method of acceptance was based on the percentage of the material in the lot that was above the lower specification limit of 96.7 percent, as estimated from the test results for the lot. The percentage of material within limits (PWL) was estimated by the range method discussed below. The acceptance plan allowed material to be accepted at full payment, to be accepted at an adjusted price, or to be rejected and replaced.

The price adjustment schedule from the FAA plan is presented in the following table:

Percentage Above Lower Tolerance Limit	Percentage of Contract Price to Be Paid
90-100	100
85-89	98
80-84	95
75-79	90
70-74	80
65-69	70

It can be seen that 90 percent of the material must be within the specification limits (referred to as 90 PWL) for the material to be accepted at full payment. For material that is less than 90 PWL, the material is accepted but at a reduced payment. The incremental payment reductions increase as the level of quality, as measured by PWL, decreases. Because the price reductions become more severe as the quality of the material decreases, the contractor is encouraged to produce acceptable material rather than to produce inferior material at a reduced price.

The operating characteristics (OC) curves for the FAA plan are shown in Figure 1. The OC curves graphically represent the relation between the actual quality of a lot and its probability of acceptance. For the FAA plan, a set of OC curves is required in order to show the probability of a lot's being accepted at any of the possible payment levels. The curves shown in Figure 1 are for a sample size of four.

Another useful relation for examining the reasonableness of an acceptance plan is quality of the material, as measured by PWL, versus expected payment. This relation is plotted in Figure 2 for the FAA plan. Expected payment can be thought of as the average payment over the long run. To arrive at the curve shown in Figure 2, it is necessary to make certain assumptions concerning the probability of receiving 50 percent payment when the material has an estimated PWL less than 65. When the material has less than 65 PWL, it can either be removed and replaced or it can be accepted as it is at a payment level of 50 percent. In arriving at the expected payment curve, the following assumptions were made in the case when the estimated PWL is below 65:

1. When the actual PWL is between 50 and 80, the material is accepted at 50 percent payment 75 percent of the time.
2. When the actual PWL is equal to 80, the material is accepted at 50 percent payment 90 percent of the time.
3. When the actual PWL is above 80, the material is accepted at 50 percent payment 100 percent of the time.

These assumptions were made by the FAA Eastern Region (3) and have been used by the researchers be-

Figure 1. Set of operating characteristics curves for FAA density acceptance.

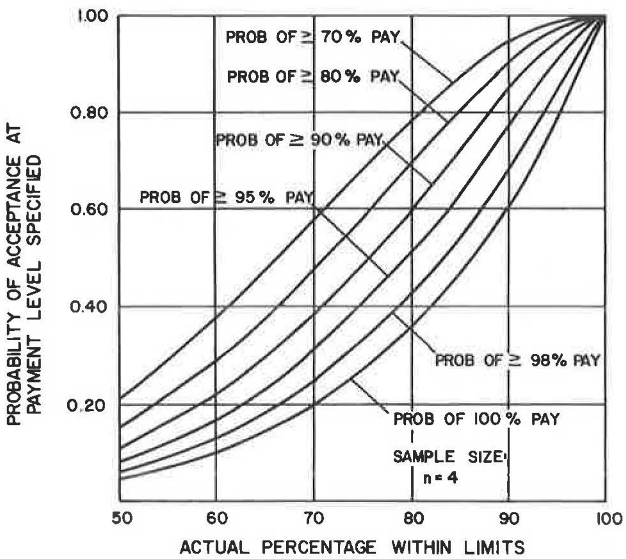
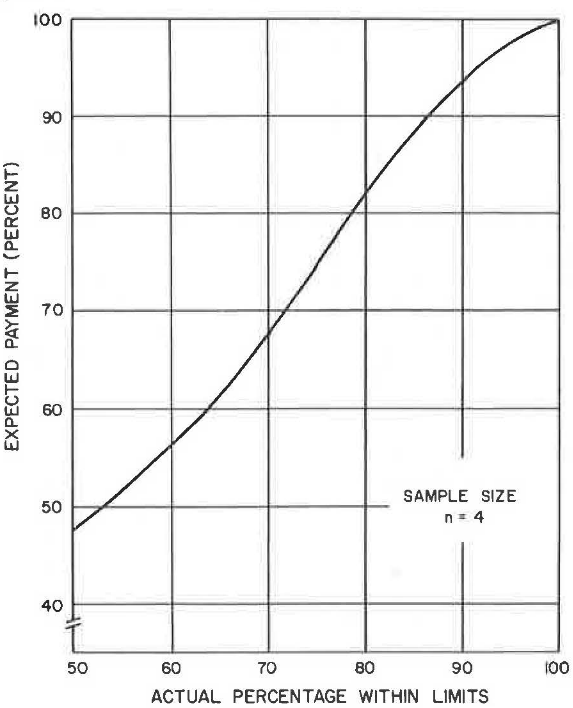


Figure 2. Expected payment curve for FAA density acceptance plan.



cause they appeared to be reasonable. It seems likely that in many cases the option of acceptance at 50 percent payment will be chosen because it is the easiest course of action.

DEVELOPMENT OF PROPOSED ACCEPTANCE PLAN

It was decided to base the development of the acceptance plan and price adjustments on the reasonableness of its OC and expected payment curves. This approach is one of four described by Willenbrock and Kopac (4). Because this approach requires some subjective decisions concerning the reasonableness of the acceptance plan and price adjustments, the starting point used in the development of the proposed acceptance plan was the FAA Eastern Region's density plan.

Range Method Versus Standard Deviation Method

The FAA acceptance plan for density, as outlined in the Eastern Region P-401 specification, is based on the range method for estimating PWL. In this method a quality index Q is calculated for each set of samples. For the case of density, which has only a lower specification limit L, the value of Q_L is calculated from

$$Q_L = (\bar{X}_n - L)/R_n \qquad (1)$$

where

Q_L = quality index for lower specification limit,
$\bar{X}_n$ = mean value of n samples in the lot,
n = number of samples in each lot,
R_n = range (difference between largest and smallest) of n sample in the lot, and
L = lower specification limit.

Once the value of Q_L has been calculated, the estimate of PWL can be determined from tables that relate Q values to estimated PWL.

It has been pointed out (5) that the range method, which is used in the FAA plan, provides a biased estimate of PWL. Willenbrock and Kopac (5) recommend the use of the standard deviation method for estimating the percentage within limits because "it provides unbiased estimates of the percentage within limits.... The standard deviation method also requires smaller sample sizes than the range method in order to provide a given degree of protection." In light of the better estimate afforded by the standard-deviation method, it was recommended that the standard-deviation method be adopted in lieu of the range method. The advantage attributed to the range method is that range is a more easily understood concept. With the advent of inexpensive pocket calculators that provide the capability of quickly determining mean and standard deviation, we consider the use of the range method to be no longer warranted.

The method for estimating PWL in the proposed new acceptance plan is based on the calculation of a quality index for the lot by using the standard-deviation method. The quality index Q_L for density can be calculated from

$$Q_L = (\bar{X}_n - L)/S_n \qquad (2)$$

in which Q_L, $\bar{X}_n$, n, and L are defined as noted earlier and S_n refers to standard deviation of n samples in the lot. S_n can be calculated from

$$S_n = \sqrt{\sum_{i=1}^{n} (X_i - \bar{X}_n)^2/(n-1)} \qquad (3)$$

where X_i, i = 1, 2, 3, ..., n = individual sample results, and n = number of samples in each lot.

As in the case of the range method, once Q_L has been calculated by the standard-deviation method, the estimated value of PWL can be determined from tabled values of Q. Appropriate tables for the standard-deviation method have been developed by Willenbrock and Kopac (5).

Continuous Versus Discrete Price Adjustments

The price adjustment schedule from the FAA acceptance plan was noted earlier in this paper. This discrete schedule works quite well in the long run, as shown by the expected payment curve in Figure 2. However, this type of schedule can present some problems in the short run and, in particular, on smaller projects. There are two potential problems with discrete price adjustment schedules.

The first problem deals with the uncertain areas between different pay levels. Material that is 90-100 percent within limits is to receive 100 percent payment and material that is 85-89 percent within limits is to be paid for at 98 percent of the contract price. This could present problems of interpretation when the estimated PWL is between 89 and 90. These potential areas of uncertainty occur at the boundary of each price adjustment level.

Another area of concern is the large incremental differences in the price adjustment levels. A situation in which, for example, 75.1 PWL is worth 90 percent payment but 74.9 PWL is worth only 80 percent payment is an undesirable one, particularly in light of the uncertain areas between price adjustment levels. It can be argued that in the long run these situations (i.e., 74.9 versus 75.1 PWL) will balance out, as shown by the expected payment curve in Figure 2. However, on a small project or in the case of a contractor who works infrequently under the acceptance plan, there is no long run in which this balancing effect can take place. It is suggested that a continuous rather than discrete price adjustment schedule would eliminate potential problems when the estimated PWL is near the boundary between price adjustment levels. Willenbrock and Kopac (5) have recommended that a specifying agency "seriously consider the use of a continuous price adjustment schedule which can be presented in a graphical fashion or as a series of straight-line equations between the various price adjustment levels. This approach would eliminate a lot of potential field problems of interpretation which could develop." For these reasons, it was decided to use a continuous price adjustment schedule in the proposed new acceptance plan.

Table 1. Continuous price adjustment schedules considered for mat density.

Schedule	Estimated Percentage of Material Above the Specification Limit (PWL)	Percentage of Contract Price to Be Paid
1	90-100	100
	80-90	$\frac{1}{2}$ PWL + 55
	65-80	$\frac{5}{3}$ PWL - 38$\frac{1}{3}$
	Below 65	-[a]
2	90-100	100
	80-90	$\frac{1}{2}$ PWL + 55
	65-80	2 PWL - 65
	Below 65	-[a]
3	90-100	100
	85-90	$\frac{2}{5}$ PWL + 64
	80-85	$\frac{3}{5}$ PWL + 47
	75-80	PWL + 15
	65-75	2 PWL + 60
	Below 65	-[a]
4	90-100	100
	65-90	-606.45 - 6.56 (PWL) + 13.7 $(PWL)^{1/2}$
	Below 65	-[a]
5	90-100	100
	65-90	-1153.40 - 13.8 (PWL) + 263 $(PWL)^{1/2}$
	Below 65	-[a]

Note: PWL = percentage of material within limits.

[a]The lot shall be removed and replaced to meet specification requirements as ordered by the engineer. In lieu of this, the contractor and the engineer may agree in writing that, for practical purposes, the deficient lot shall not be removed and will be paid for at 50 percent of the contract price.

Development of Price Adjustments

Because the development of acceptance plans by the OC curve approach requires some subjective analysis and engineering judgment, it was decided to base the continuous price adjustment on the discrete schedule developed by FAA. This was done for two reasons. First, FAA considered it to be a reasonable schedule and, second, the schedule had gone through one construction season with no major complaints from contractors about its fairness coming to our attention.

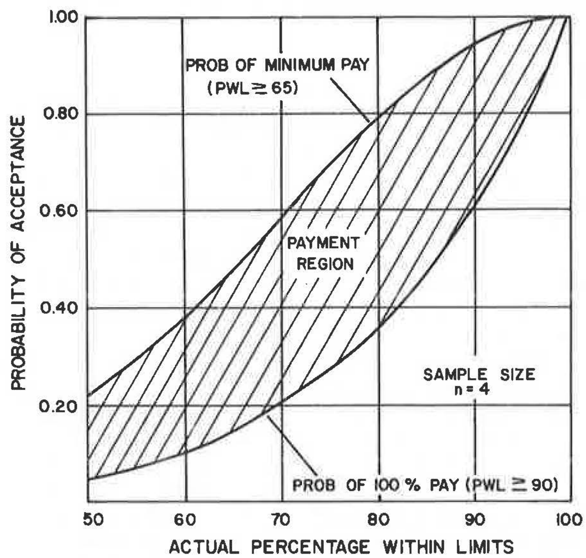
Five different continuous price adjustment schedules, all based on the FAA schedule, were considered. The five price adjustment schedules (labeled 1, 2, 3, 4, and 5) are presented in Table 1. The first three schedules were based on the use of several straight-line equations to relate payment level and estimated PWL. The last two schedules attempted to fit one curved line to the FAA schedule to eliminate the need for more than one equation. These curves were fitted to the FAA plan by using multiple regression analysis and Minitab 2 (1), a general purpose statistical computer system. To choose among these five schedules, it was decided to compare their OC curves and expected payment curves with those of the FAA price adjustment schedule.

It has been shown by Resnikoff and Lieberman (6, 7) that the noncentral t-distribution is appropriate for the estimate of the proportion of a normal population that lies above a given limit. This is the case for the density acceptance plan in which acceptance is based on an estimate of the proportion (or percentage) of the population that falls above the specification limit. A detailed discussion of the use of the noncentral t-distribution to estimate PWL for the case of asphaltic concrete density is presented by Willenbrock and Kopac (8).

The OC curves for the FAA price adjustment schedule and the proposed new schedules were determined by use of a computer program that calculates the area beneath the noncentral t-distribution. This program was subroutine MDTN, obtained from the International Mathematical and Statistical Library (IMSL) of Subprograms (9). This routine, which is available only in single precision in IMSL, was modified for double precision by Terry L. King, a graduate student in the Department of Statistics at Pennsylvania State University.

The set of OC curves for the FAA acceptance plan is shown in Figure 1. For the case of the discrete FAA price adjustment schedule, an OC curve can be developed for each price adjustment level. For the case of a continuous price adjustment schedule, there are an infinite number of OC curves possible because there are an infinite number of potential payment levels. The operating characteristics for the case of a continuous schedule can therefore be indicated by a region that has as its bound a curve corresponding to the probability of receiving 100 percent payment and another curve corresponding to the probability of receiving the minimum possible payment. For each of the five proposed schedules, 100 percent payment occurs at an estimated PWL value ($\hat{PWL}$) of 90 or more, and the minimum payment level occurs at a $\hat{PWL}$ of 65. The operating characteristics of the proposed schedules can be represented, then, by a region bounded by one curve corresponding to the probability of $\hat{PWL}$ equal to or greater than 90 for each actual value of PWL and by another curve corresponding to the probability of $\hat{PWL}$ equal to or greater than 65 for each actual value of PWL. The region within

Figure 3. Payment region for proposed density price adjustment schedule.



these curves corresponds to the probability of receiving some payment.

The payment region for the five proposed schedules for a sample size of four is shown in Figure 3. The upper and lower bounds, which correspond to the probability of receiving some payment, are the same for all five plans. Even though the boundaries of the payment region are the same for all five schedules, a particular payment level may occur at a different location within the region. In order to differentiate the five schedules, it was therefore necessary to determine their expected payment curves.

For the discrete FAA price adjustment schedule, the expected payment curve shown in Figure 2 can be calculated from the relation:

$$\text{Expected payment} = \sum_{\text{all } i} X_i P(X_i) \qquad (4)$$

where

X_i = payment level i and
$P(X_i)$ = probability of receiving payment level i.

The values of $P(X_i)$ are determined by the probabilities that $\hat{PWL}$ will fall within the limits of the various payment levels (e.g., $\hat{PWL} \geq 90$ is necessary for 100 percent payment). These probabilities were determined from the noncentral t-distribution by using subroutine MDTN from IMSL.

For the case of a continuous price adjustment system, an integration procedure must be used because the number of possible price adjustment levels is infinite. The expected payment in this case can be calculated from

$$\text{Expected payment} = \int_{-\infty}^{\infty} G(X)\, P(X) dX \qquad (5)$$

where

X = estimated PWL value ($\hat{PWL}$),
G(X) = payoff function relating the estimated PWL value ($\hat{PWL}$) to the payment level, and
P(X) = probability density function (noncentral t) of the estimated PWL values ($\hat{PWL}$).

This integral is not convenient to use for computational purposes, so a computer program was developed to approximate the integral for the purposes of estimating expected payment. As a convenient approximation to this integral, the potential $\hat{PWL}$ values were partitioned into small intervals. The probability of $\hat{PWL}$ falling within each interval was calculated by using subroutine MDTN to determine the appropriate area under the noncentral t-distribution. The probability of $\hat{PWL}$ falling within an interval was then multiplied by the average payment associated with that interval. These products were then summed for all of the intervals to achieve a good estimate of the expected value. This procedure was performed for six different actual PWL values to identify the expected payment curve.

The area corresponding to a $\hat{PWL}$ greater than 65 but less than 90 is the probability of receiving some reduced payment; the area falling above a $\hat{PWL}$ of 90 is the probability of receiving 100 percent payment; the area falling below a $\hat{PWL}$ of 65 is the probability that the material will have to be either removed and replaced, or accepted as it is at a payment of 50 percent. In determining the expected payment curves for the proposed schedules, the same assumptions concerning the 50 percent payment level were made as were made in the calculation of the expected payment curve for the FAA plan.

To determine the expected payments associated with the partial payment levels, two cases were considered for price adjustment schedule 1. The region between $\hat{PWL}$ equal to 65 and $\hat{PWL}$ equal to 90 was partitioned into 25 and 50 intervals for the two cases. The expected values were then calculated for both cases and compared. At all actual PWL values tested for the two cases, the expected values calculated by using 25 intervals and 50 intervals were identical to four significant figures. It was therefore decided that the results obtained by using 25 intervals were sufficiently accurate. The expected payment curves for the five proposed schedules for sample sizes of four, five, and seven were then calculated by using 25 intervals. Schedules 2 and 4 have expected payment curves that are very similar to those of the FAA plan. These schedules deviate less from the FAA schedule than do the other three schedules, with schedule 2 providing the closest match. All three schedules are very similar, and it is difficult to discriminate among them.

Because the expected payment curves for these three schedules are so similar, the choice between schedule 2 and schedule 4 was based on their ease of application in the field. Schedule 4 has the advantage of having only one equation, but this equation [Percent pay = -606.45 - 6.56 (PWL) + 136.7 $(PWL)^{1/2}$] is somewhat more complicated than the straight-line equations for schedule 2. For this reason, it was decided to adopt price adjustment schedule 2 for the proposed new density acceptance plan. This price adjustment schedule along with the original FAA schedule is illustrated in Figure 4. The expected payment curves for sample sizes of four, five, and seven are shown in Figure 5.

Computer Simulation

In addition to the theoretical development of the OC curves shown in Figure 3, additional OC curves were determined by use of computer simulation. The simulation program used was similar to that used by Willenbrock and Kopac (8) but was modified to use the standard-deviation method rather than the range method for esti-

Figure 4. Proposed density price adjustment, schedule 2.

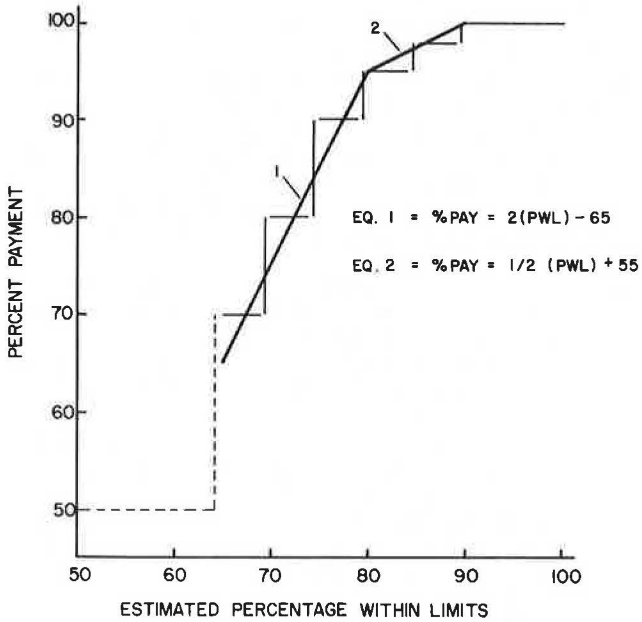
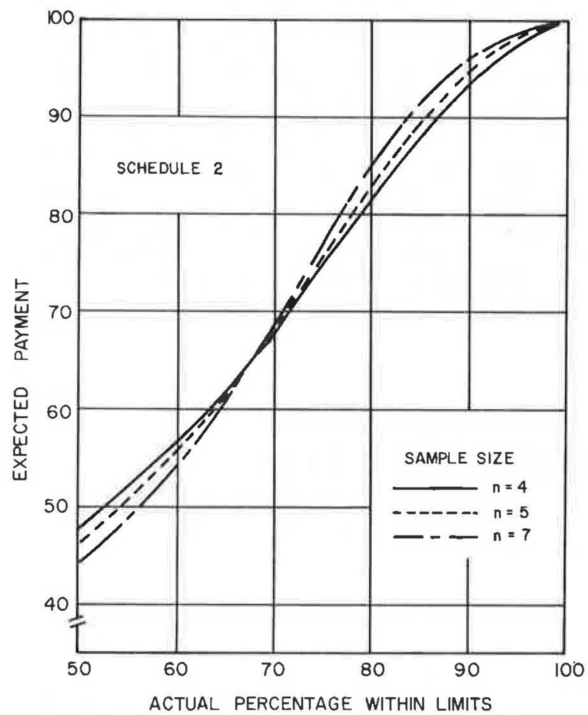


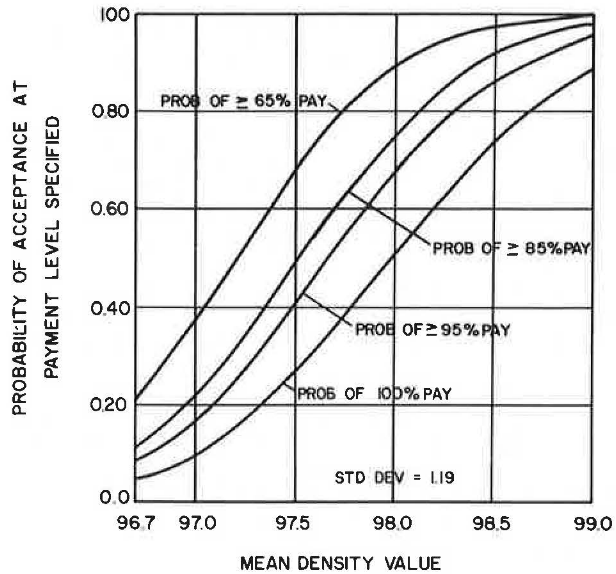
Figure 5. Expected payment curves for proposed density price adjustment, schedule 2.



mating PWL. The program, which is similar in principal to those recommended by Weed (10), was originally written by Charles E. Antle of the Department of Statistics of Pennsylvania State University.

The program determines the operating characteristics of the proposed acceptance plan by simulating the random sampling of 10 000 lots of material. The specification limits are variables that are entered into the program. The program is designed for both an upper and lower specification limit, so it is very convenient for properties such as air voids or asphalt content. In fact, a simulation program such as this

Figure 6. Operating characteristics for proposed density acceptance plan for a standard deviation of 1.19.



is the best way for determining the operating characteristics for an acceptance plan that has two specification limits because it is possible for material to be outside both limits simultaneously. This program was used to investigate acceptance plans for Marshall stability, flow, and air voids as well as for density during the course of the research efforts (11). A copy of the program, together with a discussion of its use, can be found in Burati and Willenbrock (11).

In order to test the simulation program, it was used to determine the OC curves for the density acceptance plan. Because the program is set up for both an upper and lower specification limit and density has only a lower specification limit, a very high value that was certain never to be exceeded was entered as the upper limit. The operating characteristics derived from the simulation were compared with those obtained from the theoretical solution by using the noncentral t-distribution. The results agreed quite closely, thus verifying the applicability of the program.

The use of the computer simulation has an advantage over the theoretical solution. The results of the theoretical solution are presented in terms of the actual PWL. It is difficult for a contractor to relate what is meant by 90 PWL to the construction process. The simulation program allows the operating characteristics to be easily related to the mean density values for a given value of standard deviation. The contractor can determine from past tests results what values of mean and standard deviation can be achieved with the construction process. The simulation program would then allow the contractor to determine OC curves in terms of the mean target value and standard deviation that are being achieved. To do this the contractor must know the price adjustment schedule. Figure 6 presents OC curves for a standard deviation value of 1.19. The value of 1.19 is the pooled standard deviation for all the projects included in the research study. The figure shows curves for the probability of receiving payment greater than or equal to 100 percent, the minimum payment of 65 percent, and intermediate payments of 95 and 85 percent.

CONCLUSION

This paper has presented many methods in which the computer can be used in the development of a statistically based acceptance plan. These methods include the following:

1. Preliminary data analysis to determine parameters necessary for the development of the plan;
2. The determination of areas under probability distributions by mathematical algorithms, thereby eliminating the need for tedious hand calculations and interpolations from tables;
3. A means for obtaining a good estimate of the expected payment curves for acceptance plans that incorporate continuous rather than discrete price adjustment schedules;
4. Computer simulation to develop OC curves in terms of means and standard deviations that can easily be related to the contractor's process capabilities; and
5. Computer simulation to develop OC curves for acceptance properties requiring both upper and lower specification limits that would not be practical if theoretical methods were used.

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We wish to acknowledge FAA's support of the research described in this paper. We are indebted to Carl Steinhaur, Mel Rosen, and Roy McQueen of FAA for their assistance in the collection of data for the study. Although the research described in this paper was carried out under FAA auspices, the analyses of the data and all conclusions and recommendations are our responsibility and may not necessarily reflect official FAA views or policies. This paper does not constitute a standard, specification, or regulation.

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Conversational Programming: Making Computer Technology More Accessible

Richard M. Weed

Although the most practical way to handle many of today's sophisticated engineering and statistical analyses is with high-speed electronic computers, engineers often lack the programming skills necessary to take full advantage of this approach. Conversational programming, which provides explicit instructions to the user at an interactive terminal, enables even less-skilled subordinates to perform complex tasks on the computer. Almost any quantitative analysis can be computerized, and the potential applications are virtually endless and are limited only by the imagination and inventiveness of the program writer. Benefits of conversational programming are discussed, and a reference is cited to aid in the development of programs of this type. An example is presented that deals with the testing of statistical acceptance procedures by computer simulation, an extremely powerful technique of great potential value to quality assurance engineers. By using another conversational program, a theoretical analysis is made and compared with the simulation results.

In a time that historians are beginning to call the computer age, many engineers still have little or no programming ability. Although computer terminals are readily accessible to engineers in most organizations and computer programming is now strongly emphasized in engineering colleges, many practicing engineers have never acquired the ability to take full advantage of these facilities. In some cases, this means that considerable time will be wasted in making complex calculations that could be performed much more efficiently by computer. In other cases, potentially useful analyses may never be attempted because of the impracticality of doing them by any means other than a large computer. Although many engineering functions have been computerized by software specialists in recent years, much still remains to be done.

As more and more engineering graduates enter the profession, this shortcoming will gradually disappear.

Eventually, programming ability will be as commonplace as the ability to use a slide rule was to earlier generations of engineers. Until that time, however, engineers will not realize the full potential of the computer unless a means can be found to make its capabilities more readily accessible to them. One way to accomplish this is by using conversational programming.

CONVERSATIONAL PROGRAMMING

Conversational programming refers to a technique in which a computer appears to converse with a user operating an interactive terminal. In actuality, the program writer has anticipated virtually every bit of dialogue that might reasonably occur and has included the necessary checks to cause the proper messages to be typed out (or appear on a video screen) at the appropriate times. Sophisticated programs of this type are quite involved and seem to endow the computer with almost human intelligence.

For engineering and statistical applications, somewhat less sophistication is required. Basic instructions must be provided to guide the user, and various checks and diagnostic messages must be included to guard against misuse. About all that is required of the user is an awareness of the purpose of the program and the ability to follow simple instructions. There is no need to be familiar with programming techniques nor is an intimate knowledge of the analytical procedure required.

The examples that follow illustrate the more common features of typical conversational programs. The first program is one that might be written to enable quality assurance engineers to test statistical acceptance procedures by computer simulation. The second example illustrates how a particular type of acceptance procedure can be evaluated analytically and is used to check the results of the first program. The messages printed out by the computer are in capital letters and the user's replies are in lower case, just as they would appear with most interactive terminals. Brief commentaries in parentheses have been added at appropriate points.

ACCEPTANCE PROCEDURE SIMULATION (EXAMPLE 1)

ENTER NAME OF ANALYSIS TO BE PERFORMED
acceptance procedure simulation

(The program "acceptance procedure simulation" is one of several contained in this particular package. Very probably, the computer is required to read only the first few letters of the user's reply to identify this program.)

DO YOU WISH AN EXPLANATION OF THIS PROGRAM?
yes

THIS PROGRAM PERMITS THE TESTING OF VARIOUS ACCEPTANCE PROCEDURES BY COMPUTER SIMULATION. THE USER SPECIFIES THE ACCEPTANCE CRITERIA, THE SAMPLE SIZE, THE TYPE OF DISTRIBUTION, THE DISTRIBUTION PARAMETERS, AND THE NUMBER OF LOTS TO BE SIMULATED. THE USER SELECTS THE DESIRED OUTPUT FORMAT WHICH MAY INCLUDE HISTOGRAMS AND ELEMENTARY STATISTICS FOR THE RANDOMLY GENERATED DATA, THE PERCENTAGE OF LOTS FAILING EACH ACCEPTANCE REQUIREMENT, THE ESTIMATED PROBABILITY OF ACCEPTANCE, AND CONFIDENCE LIMITS FOR THIS ESTIMATE.

ENTER NUMBER OF ACCEPTANCE CRITERIA TO BE USED
2

(Many specifications use multiple acceptance criteria. This program provides the capability of testing various combinations of these criteria.)

ENTER CODE NUMBERS FOR ACCEPTANCE CRITERIA TO BE USED
explain

(Conversational programs usually provide a means for the user to request additional assistance. In this example, the word "explain" is entered in place of the expected numerical quantities. This cues the computer to type out an explanation of the various acceptance criteria that may be selected.)

THE FOLLOWING ACCEPTANCE CRITERIA MAY BE SELECTED
1. LOWER LIMIT ON SAMPLE MEAN
2. UPPER LIMIT ON SAMPLE MEAN
3. LOWER LIMIT ON INDIVIDUAL VALUES
4. UPPER LIMIT ON INDIVIDUAL VALUES
5. MAXIMUM PERCENT DEFECTIVE BELOW LOWER LIMIT
6. MAXIMUM PERCENT DEFECTIVE ABOVE UPPER LIMIT
7. MAXIMUM TOTAL PERCENT DEFECTIVE OUTSIDE LOWER AND UPPER LIMITS
8. MAXIMUM VALUE FOR SAMPLE STANDARD DEVIATION
9. MAXIMUM VALUE FOR SAMPLE RANGE

ENTER CODE NUMBERS FOR ACCEPTANCE CRITERIA TO BE USED
1 3

[Following the explanation, the input instruction is repeated. The user has selected codes 1 and 3, which specify dual acceptance criteria to be applied to the mean and lowest value of each sample—a type of specification frequently recommended by both the American Society for Testing and Materials (1) and the American Concrete Institute (2).]

ENTER LOWER LIMIT FOR SAMPLE MEAN
3000

ENTER LOWER LIMIT FOR INDIVIDUAL VALUES
2500

(The user is testing an acceptance procedure for some quality characteristic with limits of 3000 and 2500 for the mean and individual values, respectively. The specific units are not identified in this example and may be regarded as either metric or customary quantities.)

ENTER SAMPLE SIZE (MAXIMUM 30)
3

ENTER CODE NUMBER FOR DISTRIBUTION TYPE
explain

THE FOLLOWING DISTRIBUTIONS MAY BE SELECTED
1. UNIFORM
2. NORMAL
3. SKEWED NORMAL
4. EXPONENTIAL
5. POISSON

ENTER CODE NUMBER FOR DISTRIBUTION TYPE
2

(Although most construction quality characteristics are normally distributed, the program provides the capability to test the acceptance procedure on other types of distributions.)

ENTER CODE NUMBER FOR MEASURE OF VARIABILITY TO BE USED
explain

THE FOLLOWING MEASURES OF VARIABILITY MAY BE SELECTED
1. STANDARD DEVIATION
2. COEFFICIENT OF VARIATION
3. VARIANCE

ENTER CODE NUMBER FOR MEASURE OF VARIABILITY TO BE USED
2

ENTER COEFFICIENT OF VARIATION (PERCENT)
15

ENTER MINIMUM, MAXIMUM, AND STEP SIZE FOR POPULATION MEANS
2500 4400 100

(The user has decided to test the acceptance procedure over a series of possible mean production values ranging from 2500 to 4400 in increments of 100.)

ENTER NUMBER OF LOTS TO BE SIMULATED FOR EACH RUN (MAXIMUM 5000)
2000

ENTER RANDOM GENERATOR SEED NUMBER (7-DIGIT ODD NUMBER)
1234560

ERROR IN INPUT
SEED NUMBER MUST BE ODD

ENTER RANDOM GENERATOR SEED NUMBER (7-DIGIT ODD NUMBER)
1234567

(To guard against their misuse, conversational programs must have an elaborate system of checks to detect improper input data. The random generators in this program require that a single odd number be entered to initiate their operation. The computer checked the input, found it to be an even number, typed out an error message, and repeated the input instruction. The user then entered an appropriate seed number.)

ENTER CODE NUMBERS FOR OUTPUT INFORMATION DESIRED
explain

THE FOLLOWING OUTPUT INFORMATION MAY BE SELECTED
1. SUMMARY OF INPUT INFORMATION
2. HISTOGRAMS FOR RANDOMLY GENERATED DATA
3. ELEMENTARY STATISTICS FOR RANDOMLY GENERATED DATA
4. PERCENTAGE OF SIMULATED LOTS FAILING EACH REQUIREMENT
5. ESTIMATED PROBABILITY OF ACCEPTANCE
6. CONFIDENCE LIMITS FOR PROBABILITY OF ACCEPTANCE

ENTER CODE NUMBERS FOR OUTPUT INFORMATION DESIRED
1 5 6

ENTER CONFIDENCE LEVEL FOR PROBABILITY OF ACCEPTANCE (PERCENT)
95

A novice just becoming acquainted with this program might wish to print out all the available output information in order to become familiar with the simulation process. The user in this example has selected a more abbreviated printout (Figure 1). For the particular input values chosen, the output provides the data necessary to plot an operating characteristics curve that gives the probability of acceptance for any mean production value. This would enable a specification writer to decide if any modifications of the acceptance procedure should be made.

Because the development of acceptance criteria is often a trial-and-error process, it is likely that the user of this program will wish to make several repeat runs. Although not shown in this example, a convenient means would be provided for the user to return to various points in the input sequence. (The order in which the input information was entered in this example was chosen to simplify the presentation. A somewhat different order

Figure 1. Sample of printout for example 1 shows results of computer simulation.

```
ACCEPTANCE CRITERIA
   LOWER LIMIT ON SAMPLE MEAN = 3000.000
   LOWER LIMIT ON INDIVIDUAL VALUES = 2500.000

SAMPLE SIZE = 3

NORMAL DISTRIBUTION PARAMETERS
   MEAN = 2500.000 TO 4400.000 BY 100.000
   COEFFICIENT OF VARIATION = 15.0

NUMBER OF SIMULATED LOTS PER RUN = 2000

SEED NUMBER = 1234567

CONFIDENCE LEVEL = 95.0
```

POPULATION MEAN	ESTIMATED PROBABILITY OF ACCEPTANCE	95.0 PERCENT CONFIDENCE INTERVAL
2500.000	0.01	0.00 - 0.01
2600.000	0.03	0.03 - 0.04
2700.000	0.09	0.08 - 0.10
2800.000	0.19	0.17 - 0.21
2900.000	0.30	0.28 - 0.32
3000.000	0.45	0.43 - 0.47
3100.000	0.57	0.55 - 0.59
3200.000	0.72	0.70 - 0.74
3300.000	0.79	0.77 - 0.81
3400.000	0.84	0.83 - 0.86
3500.000	0.90	0.89 - 0.92
3600.000	0.91	0.90 - 0.92
3700.000	0.95	0.94 - 0.96
3800.000	0.96	0.96 - 0.97
3900.000	0.97	0.97 - 0.98
4000.000	0.98	0.97 - 0.98
4100.000	0.99	0.98 - 0.99
4200.000	0.99	0.98 - 0.99
4300.000	0.99	0.99 - 1.00
4400.000	0.99	0.99 - 1.00

would be more efficient for an actual program.)

ANALYTICAL EVALUATION OF ACCEPTANCE PROCEDURE (EXAMPLE 2)

Depending on the type of acceptance procedure, it is not always possible to determine the probability of acceptance analytically. In these cases, computer simulation is the only practical method of analysis. For a dual acceptance procedure, such as the mean and lower limit specification in the first example, an analytical solution for the exact probability of acceptance is not known. However, lower and upper bounds for this value can be calculated from an expression I developed in another paper that appears in this Record on multiple acceptance criteria—i.e., $P_1P_2 \leq P[ACCEPT] \leq MINIMUM[P_1, P_2]$ in which P_1 and P_2 are the (somewhat correlated) probabilities of passing the individual requirements separately. An analysis of this type is less involved than a simulation, but it does require extensive use of normal distribution theory and is sufficiently tedious to warrant computer assistance. The following conversational program would greatly simplify this task:

ENTER NAME OF ANALYSIS TO BE PERFORMED
dual criteria evaluation

DO YOU WISH AN EXPLANATION OF THIS PROGRAM?
yes

THIS PROGRAM COMPUTES LOWER AND UPPER BOUNDS FOR THE PROBABILITY OF ACCEPTANCE RESULTING FROM DUAL ACCEPTANCE CRITERIA APPLIED TO SAMPLES FROM A NORMAL POPULATION. THE USER SPECIFIES THE NORMAL DISTRIBUTION PARAMETERS, THE SAMPLE SIZE, AND LIMITS FOR BOTH THE SAMPLE MEAN AND INDIVIDUAL VALUES.

ENTER CODE NUMBER FOR MEASURE OF VARIABILITY TO BE USED
2

ENTER COEFFICIENT OF VARIATION (PERCENT)
15

ENTER MINIMUM, MAXIMUM, AND STEP SIZE FOR POPULATION MEANS
2500 4400 100

ENTER SAMPLE SIZE
3

ENTER CODE NUMBER FOR DUAL CRITERIA COMBINATION
explain

THE FOLLOWING COMBINATIONS MAY BE SELECTED
1. LOWER LIMITS ON MEAN AND INDIVIDUAL VALUES
2. UPPER LIMITS ON MEAN AND INDIVIDUAL VALUES
3. LOWER AND UPPER LIMITS ON MEAN AND INDIVIDUAL VALUES

ENTER CODE NUMBER FOR DUAL CRITERIA COMBINATION
1

ENTER LOWER LIMIT FOR SAMPLE MEAN
3000

ENTER LOWER LIMIT FOR INDIVIDUAL VALUES
2500

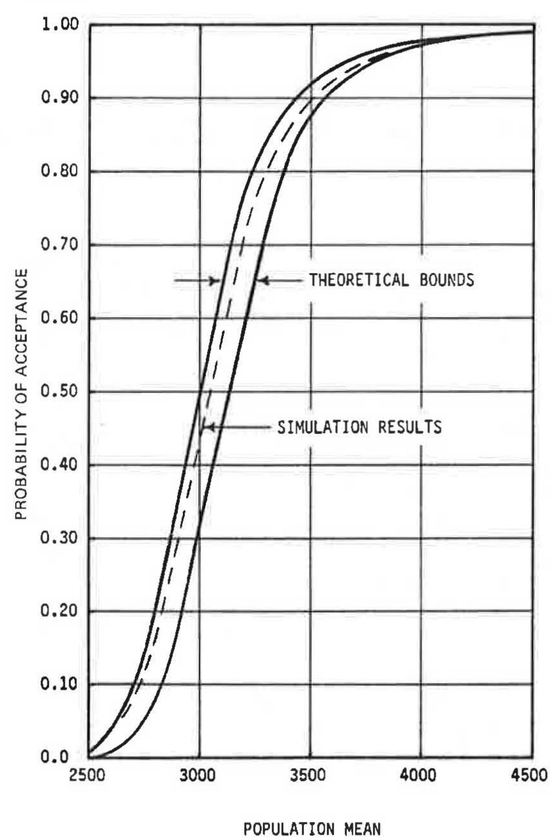
The printout for this example is shown in Figure 2. Like the output for the first example, this provides the information necessary for a specification writer to evaluate the effectiveness of the acceptance procedure.

The output presented for both of these examples was obtained from actual computer runs. It is interesting to observe that the results obtained by simulation fall within the theoretically predicted bounds in every case. For ease of comparison, these results are plotted in Figure 3.

Figure 2. Sample of printout for example 2 shows results for analytical evaluation.

```
ACCEPTANCE CRITERIA
   LOWER LIMIT ON SAMPLE MEAN = 3000.000
   LOWER LIMIT ON INDIVIDUAL VALUES = 2500.000

SAMPLE SIZE = 3

NORMAL DISTRIBUTION PARAMETERS
   MEAN = 2500.000 TO 4400.000 BY 100.000
   COEFFICIENT OF VARIATION = 15.0

POPULATION             ANALYTICAL BOUNDS FOR
   MEAN              PROBABILITY OF ACCEPTANCE

 2500.000                   0.00 - 0.01
 2600.000                   0.01 - 0.04
 2700.000                   0.03 - 0.10
 2800.000                   0.09 - 0.20
 2900.000                   0.19 - 0.35

 3000.000                   0.33 - 0.50
 3100.000                   0.47 - 0.65
 3200.000                   0.61 - 0.76
 3300.000                   0.72 - 0.85
 3400.000                   0.81 - 0.89

 3500.000                   0.87 - 0.92
 3600.000                   0.91 - 0.94
 3700.000                   0.94 - 0.95
 3800.000                   0.96 - 0.97
 3900.000                   0.97 - 0.98

 4000.000                   0.98 - 0.98
 4100.000                   0.99 - 0.99
 4200.000                   0.99 - 0.99
 4300.000                   0.99 - 0.99
 4400.000                   0.99 - 0.99
```

Figure 3. Comparison of simulation results with theoretical bounds.



BENEFITS OF CONVERSATIONAL PROGRAMMING

The major benefit to be derived from conversational programming is the tremendous computational power it provides to anyone with access to a computer terminal. The examples presented in this paper illustrate how a broad range of acceptance procedures can be tested by following a few simple instructions. Ordinarily, analyses of this type would require a working knowledge of quality-control theory, statistical analysis, computer programming, and simulation techniques. When developed as conversational programs, these analyses can be delegated to individuals with very little specialized training.

Like these examples, many of today's engineering problems require expertise in a variety of disciplines. Frequently, when individuals capable of applying the multidisciplinary approach are not readily available, these problems are referred to outside consultants. Depending on the nature of the analyses required, it may often be possible to develop general conversational programs that would permit the in-house solution of similar problems in the future. In many cases, a well-planned conversational program might obviate the need for the repeated use of outside consulting services.

Other obvious benefits are speed and accuracy. Once the program has been tested and validated, it can be depended on to produce reliable results. Because of the tremendous speed of the computer, many runs can be made in a short period of time in order to thoroughly analyze the problem at hand. In most cases, this capability would translate directly into economic savings.

Finally, conversational programming can result in the more efficient use of engineering specialists. If it appears that there will be repeated requests for a particular type of analysis, it will often be advantageous to develop a general solution and put it in the form of a conversational program. Future applications will then require minimal involvement on the part of the specialist.

CONCLUSION

Although engineers can benefit greatly from the use of computers, many do not have sufficient programming ability to take full advantage of this approach. Conversational programming provides a means to make the benefits of computer technology available to a much broader segment of the engineering profession. The examples illustrate how complex analyses can be performed by anyone capable of following simple instructions. The use of programs of this type can enable engineers to do better work, do it with less effort, and save both time and money. The reader interested in further examples of conversational programming along with the appropriate FORTRAN IV coding is referred to a publication on computer simulation by the Federal Highway Administration (3).

REFERENCES

1. Standard Specification for Precast Concrete Barrier, Annual ASTM Standards, Part 16. American Society for Testing and Materials, Philadelphia, C825-76, 1976.
2. Building Code Requirements for Reinforced Concrete. American Concrete Institute, Detroit, ACI 318-71, 1971.
3. R. M. Weed. An Introduction to Computer Simulation. Federal Highway Administration, 1976.

Quality Assurance Through Computers

S. C. Shah

A sound quality assurance program is one that must be capable of providing information to users and not just data. It is information prepared from analysis of data that is important. Such information should be provided rapidly, economically, and efficiently. Such information flow can only be accomplished through the use of computers. However, a necessary prerequisite to this flow or feedback of information is its availability at a centralized location, namely, computer files. This residence requirement further mandates a fast data-entry system on on-going operations. Louisiana's Material Test (MATT) data-reporting system comes close to satisfying the requirements of a user-oriented quality assurance feedback system. The system is an on-line computer-based system through which data generated on construction projects can be entered, corrected, updated, deleted, and retrieved through the department's terminal network system. The system, which has been in operation since the early part of 1978, is capable of providing information not only to those responsible for monitoring the construction projects but also to those involved in the planning, design, evaluation, research, and maintenance of pavement systems. Specific examples of the application of the computerized system related to quality assurance are presented in the paper. An overview of the system, with respect to design, development, hardware, and software, is also discussed. The paper emphasizes the need for a computerized quality assurance system as a subsystem of the overall pavement management system.

In recent years the task of recovering information from construction and material testing has increased enormously. This has largely been due to the accelerated quality assurance program within the Louisiana State Department of Transportation and Development (LDOT) and an increased awareness of the constant improvement in the acceptance sampling plans and specifications. Literally thousands of pieces of inspection and test-related data are generated from various sources in a year. The sheer volume of data has created two separate but related problems:

1. The continuing increase in effort required by various personnel in collecting, recording, and processing the data on a variety of test documents, and
2. The difficult and, at times, frustrating task of retrieving these data manually for use in on-going operations, research, problem solving, and planning for the future.

To resolve these problems, LDOT initiated a project that would provide an integrated computer-based system by which the various districts of LDOT can transmit the construction and material test data through the terminals for storage, analysis, and retrieval. The overall thrust was to provide easy access to the construction and material test data for final certification of construction projects and also for evaluation of construction and materials quality assurance and acceptance procedures.

Specifically, the objectives to develop such a system can be defined in terms of the following benefits the system would provide:

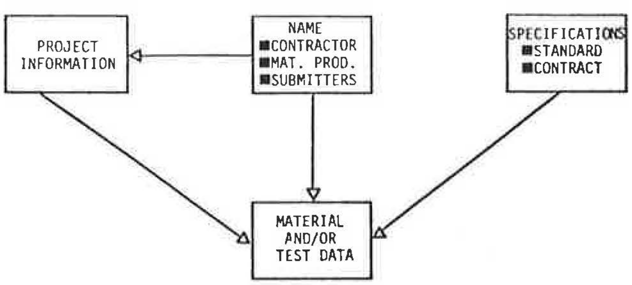
1. Standardization of reporting procedures coupled with savings in time spent manually in typing, auditing, or spot-checking various test reports;
2. Availability of a continuous log of major construction material tests at a centralized location (i.e., computer files);
3. Elimination of the final manual audit of sampling and testing compliance and an accelerated certification of construction items;
4. An organized and easily accessible data file for comparative and statistical analyses with respect to processes, sampling and testing frequency, producer profiles, and specification revisions and updates; and
5. Service as an important subsystem of an overall pavement management system.

DESIGN AND DEVELOPMENT OF COMPUTERIZED SYSTEM

The system was designed and developed by using a task-group approach. Three task groups—one each for concrete, asphaltic concrete, and soil and aggregate base course—were formed; each group was represented by a project engineer, a district laboratory engineer, and staff from the central laboratory, research and development, and data-processing sections. The primary function of each group was to define user requirements with respect to input forms, map formats, and output report formats. Such a task-group approach combines user needs and knowledge with system and data-processing expertise to provide an efficient user-oriented system.

The primary design philosophy of the project was to make the system user-oriented. Thus, the system design was geared toward maximizing the following criteria: (a) quick access to construction information via remote computer terminals that provide formatted input-output capability, (b) low core use, (c) efficient use of computer system resources, and (d) attractiveness to nonprogramming staff. To satisfy these criteria, the following principles served as a base: (a) data-entry system as opposed to a full on-line system; (b) exception reporting to minimize printing of unneeded data; (c) overnight off-line evaluation of test results as opposed to immediate on-line evaluation; and (d) elimination of many current manual, duplicated, and non-standard reporting procedures.

Figure 1. Composition of the MATT system.



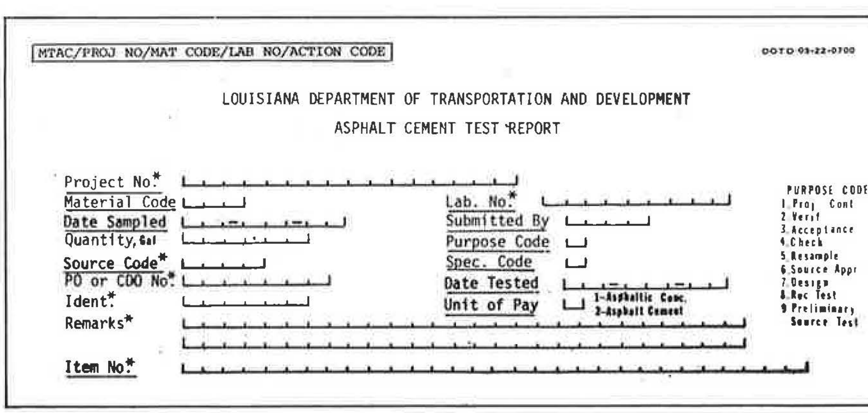
OVERVIEW OF SYSTEM'S OPERATION

Louisiana's computerized Material Test (MATT) system is composed of a number of small subsystems. Figure 1 shows the composition of the system. The three subsystems—project, specification, and name—provide support to the total system and are basic to the material subsystem. In other words, no data can be entered on any of the materials included in the material subsystem unless the project information, the specifications governing the material to be used on that project, and the names of the project engineer, contractor, and material producers are already on file in the computer.

Each of the subsystems defined in Figure 1 is represented on the computer video terminal as a map. Thus, there is a project information map, a name map, an asphalt cement test map, and so on. Furthermore, each map is a replica of the input data form. In other words, a particular map on the display screen looks similar to the input data form. This similarity provides for easy and rapid entry of test data.

The input forms for recording data are combination work-report forms. The header information on most of the forms is basically the same. In a majority of cases, these forms accompany samples sent to the laboratory for testing. The field inspectors record data pertinent to the project and sample identification in the top portion of the form (header information), and the laboratory records the test data generated by them in the respective test-item fields. This has eliminated transfer of data from one form to the other. Figure 2 is an example of the type of header information that appears on the forms. Items of information considered mandatory for data entry are underlined. This manda-

Figure 2. Type of header information on input forms.


MTAC/PROJ NO/MAT CODE/LAB NO/ACTION CODE

DOTD 03-22-0700

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

ASPHALT CEMENT TEST REPORT

Project No.*
Material Code
Date Sampled
Quantity, Gal
Source Code*
PO or COO No.*
Ident.*
Remarks*
Item No.*

Lab. No.*
Submitted By
Purpose Code
Spec. Code
Date Tested
Unit of Pay 1-Asphaltic Conc. 2-Asphalt Cement

PURPOSE CODES
1 Proj Cont
2 Verif
3 Acceptance
4 Check
5 Resample
6 Source Appr
7 Design
8 Rec Test
9 Preliminary Source Test

tory requirement has standardized the reporting procedures throughout the state.

The MATT system is capable of on-line entry, inquiry, correction, update, and deletion of data systems. The operation of the system is briefly described here.

On-Line Operation

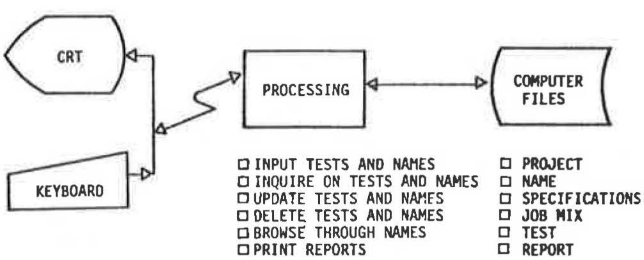
The input forms are filled out with the appropriate information by field and laboratory personnel and sent to the terminal operator for data entry. The operator enters the four-character transaction code and certain other key items of information appropriate to that subsystem. This information appears in the upper left corner of each input form (Figure 2). This transaction-line entry triggers the computer system to project the correct map format for that subsystem onto the terminal display. The information from the input form is then entered onto the screen and transmitted to the computer where it is edited for errors. If any errors are found, they are flagged and these data are returned to the terminal for correction; the error field becomes doubly highlighted as a result of this action. Once the data are error free, the program does the necessary data manipulations, after which a record is written to the test-result file for overnight processing in an off-line mode. Figure 3 depicts the daytime operations of the MATT system. Figure 4 lists the transaction lines for each MATT subsystem.

Off-Line Operation

Virtually all of the MATT system off-line processing is done after normal working hours. The test results entered during the day are processed that night by the test processor against the appropriate specification record and are flagged according to whether they pass or fail. The test processor creates logging and exception (LOGEX) report files. The data stored in the test file can be accessed for any of the operations shown in Figure 3 except report printing. The next day, logging and exception reports are provided after the LOGEX files are sorted and processed by the report program.

Another off-line operation is the purging of old processed test data from the disk and writing them on tape, where they will be kept for historical and data analysis. This purging is done as projects are completed and certified.

Figure 3. On-line operation of the MATT system.



MATT SYSTEM FILES

The MATT system uses these files: name, specification, project, mix design, test, logging and exception report, and tape files of all of the preceding except logging and exception report. A brief discussion of each of these files follows.

Name

As was pointed out in Figure 1, the name file is a prerequisite to the overall operation of the MATT system. The file is an on-line file and contains the code numbers and the corresponding names and addresses of material producers and suppliers, sample submitters (project engineers, prestress plant inspectors, and so forth), and contractors.

Specification

The specification file is also a prerequisite to any material test data entry. For security reasons the file is not an on-line file and, therefore, all new entries, updates, deletions, and so forth have to be done in an off-line mode through card input. The file contains both standard and contract (special provisions) specifications.

Project

The project file is another prerequisite to the MATT

Figure 4. List of transaction lines for on-line data management.

SUBSYSTEM NAME	MATT ID	TRANSACTION LINE
NAME	....	MTNM/SOURCE TYPE CODE/ACTION CODE (N,I,U,D,L)/SEQUENCE NO
PROJECT INFORMATION	....	MTPI/PROJ NO/ACTION CODE (N,I,U)
ROADWAY XSECTION	....	MTRC/PROJ NO/ACTION CODE (U,I)
AGGREGATE	B	MTAG/PROJ NO/MATERIAL CODE/LAB NO/ACTION CODE (N,I,U,D)
ASPHALT CEMENT	C	MTAC/PROJ NO/MATERIAL CODE/LAB NO/ACTION CODE (N,I,U,D)
LIQUID ASPHALT	D	MTLA/PROJ NO/MATERIAL CODE/LAB NO/ACTION CODE (N,I,U,D)
CEMENT	E	MTCT/PROJ NO/MATERIAL CODE/LAB NO/ACTION CODE (N,I,U,D)
STEEL BAR	F	MTSB/PROJ NO/MATERIAL CODE/LAB NO/ACTION CODE (N,I,U,D)
STEEL WIRE	G	MTSW/PROJ NO/MATERIAL CODE/LAB NO/ACTION CODE (N,I,U,D)
CONCRETE JOBMIX	A,I	MTCJ/PROJ NO/MATERIAL ID/MATERIAL CODE/ACTION CODE (N,I,U,D)
STRUCTURAL CONCRETE	A	MTSC/PROJ NO/MATERIAL CODE/LOT NO/ACTION (N,I,U,D)
PAVING CONCRETE	I	MTPC/PROJ NO/MATERIAL CODE/LOT NO/ACTION (N,I,U,D)
ASPHALT CONCRETE JOBMIX	H	MTHJ/PROJ NO/SEQUENCE NO/ACTION CODE (N,I,U,D)
ASPHALT CONCRETE INSPECTION	H	MTHM/PROJ NO/LOT NO/MIX USE/MIX TYPE/PURPOSE CODE/ACTION CODE (N,I,U,D)
SOIL ANALYSIS	L	MTSA/PROJ NO/LAB NO/ACTION CODE (N,I,U,D)
DENSITY/MOISTURE	J	MTDM/PROJ NO/MATERIAL CODE/ZONE & TEST NO/ACTION NO (N,I,U,D)
THICKNESS/WIDTH	K	MTTW/PROJ NO/MATERIAL CODE/ACTION CODE (N,I,U,D)
MISCELLANEOUS DATA ENTRY	M	MTMS/PROJ NO/MATERIAL CODE/LAB NO/ACTION CODE (N,I,U,D)
MISCELLANEOUS MAINTENANCE	....	MTMM/ACTION CODE (N,I,U,D)
REPORT REQUEST	....	MTRR/DISTRICT NO/PROJ NO/REPORT TYPE CODE/OPTION CODE/ACTION CODE (N,I,D)
REPORT RETRIEVAL	....	MTLE/DISTRICT NO/1=LOG, 2=EXCEPTION, 3=2059
NOTE........................	....	SOURCE TYPE CODES ARE: B=CONTRACTORS,C=MATERIAL PRODUCERS,D=SUBMITTERS REPORT TYPE CODES ARE: 1=COMPLETE LOGGING,2=2059,3=STAX SUMMARY OPTION CODES ARE: 1=ON-LINE,2=OFF-LINE(MAILED) ACTION CODES ARE: N=NEW, I=INQUIRY, U=UPDATE, D=DELETE & L=BROWSE

system. It contains data pertinent to the project and related cross section of the roadway. It includes information such as project location, route number, length, cost, type of surface, and base, shoulder, and related dimensions.

Mix Design

The mix design file contains information related to the mix design of both asphaltic concrete and portland cement concrete. The file is a prerequisite to entering data on the acceptance criteria of these two materials.

Test

Test results of all materials and tests appear in this file. The file contains processed test data, including pass-fail flags, of the following materials or tests: aggregates; asphalt cements; liquid asphalts; cements; steel bars; steel wires; structural concrete slump, air, and strength data; paving concrete strength and thickness data; asphaltic concrete stability, compaction, gradation, and smoothness data; soil analysis test data; density and moisture test data of embankment and base course; thickness and width measurements of base course; and miscellaneous materials (total, 104). Of all the materials subsystems, the miscellaneous subsystem is the most comprehensive and flexible one. The user has complete flexibility in adding new materials to this file and creating his or her own map for those materials.

Logging and Exception

The logging and exception file is a temporary file of one-day duration. It contains data in report format that are entered the previous day and retrieved daily by the districts.

Tape Files

As specifications change or projects are completed, records are copied to tapes and a "date deleted" field added to the record. These tapes will be made available for historical review, analysis, and examination of test data.

USES OF THE MATT SYSTEM—OUTPUT REPORTS

To function effectively, a quality assurance program must be able to provide the needed information feedback not only to those involved in testing and inspection but also to those in the planning, design, evaluation, and maintenance phases of the pavement system. A necessary prerequisite to such information flow is the availability of a computer-based data system such as the one discussed in the preceding sections of this paper. Software programs can be written to generate user-required reports such as the ones provided by the MATT system and discussed here.

Daily Construction Monitoring Reports

Each day two types of reports are routinely provided to the project engineer responsible for day-to-day monitoring of the construction project. These reports are the logging reports and the exception reports. The logging reports are the summary-type reports that consist of information relative to the sample or test such as project number, sample identification, purpose, material type, quantity, item number, and pass-or-fail comment. In some cases, critical numerical values of the measured characteristic are also listed on the printout. Such reports provide a quick means of review for the engineer of the inspection, material, and test control level associated with the multiproject activities.

The distribution of these reports is based on the sample submitter, the terminal through which data are entered, and the laboratory performing the test (laboratory number). With these three criteria, it is possible to retrieve reports on a given test at three places. Thus, if a sample is submitted by the engineer in district A, tested by district B, and entered by district C, the report on this sample will be transmitted to all three districts. This has greatly minimized delays associated with mailing of reports by the central laboratory to the nine districts and other submitters for which it does voluminous testing.

Figure 5 is an example of logging reports on three material types. Samples indicated as failing on the logging reports are supplemented with exception reports of the type indicated in Figure 6. This particular sample is listed as a failing sample under miscellaneous material tests in Figure 5. Such exception reports provide guidelines to making equitable decisions between acceptance or rejection of the sample on the basis of how critical the point of failure is. (The MATT system uses customary units only. Therefore, values in Figures 5-9 are not given in SI units.)

Certification Reports

During the life of a construction project, constant monitoring is required to ensure that sampling and testing frequencies and specification conformance are satisfied, according to stated requirements, on the multitude of materials incorporated into the project. At the end of the project, this quality assurance check is duplicated to prepare a final document identified as Form 2059. This final effort is geared toward compilation of all documents generated on that project, with emphasis on cross-referencing of passing and failing samples and an explanation of the disposition of such failing materials, tests, locations, and so forth. Prior to the implementation of the MATT system, Form 2059 was prepared manually. The complexities and difficulties encountered in this manual effort were directly associated to the length or size of the project. The larger the project in terms of materials and tests, the more complex and time-consuming this final audit.

The MATT system provides this final document at the user's request in a matter of hours. The basic format of this 2059 report is similar to that of the daily logging reports except that it is item-number oriented. In other words, all materials are reported under the item number for which they were sampled and tested. Furthermore, all coded fields appear decoded in the report.

The 2059 report has three parts. Part 1 consists of a listing of all materials or tests under their respective item numbers. Part 2 lists the disposition of the failing samples as appearing in the remarks field of each failing test report. Part 3 lists all the job mix releases issued on the project. This report is reviewed by headquarters personnel prior to final acceptance of the project.

Analysis and Evaluation Reports

These reports are the summary-type reports that provide information relative to the following:

1. Distribution of reduction in pay for asphaltic

Figure 5. Computerized logging report on various materials.

STATE OF LOUISIANA 03-29-79
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
MATERIAL TESTING SYSTEM
LOGGING REPORT FOR
GANG 728

827-03-09 HOT MIX ASPHALTIC CONCRETE TESTS

LOT NO.	--- MIX --- USE	TYPE	AS	PURP CODE	DATE LAID	ADJST PER.	JMF SEQ	ITEMS	TONS		SPEC VALUE	PAY
002	1	01	02	3	03-13-79	1	01	5011B	598	STAB:	1364	100
										COMP:	96.8	100
										TOL :		
										GRAD:		100
003	1	01	02	3	03-15-79	1	01	5011B	750	STAB:	1514	100
										COMP:	96.0	100
										TOL :		
										GRAD:		100

714-23-10 DENSITY AND MOISTURE CONTENT TESTS

MAT. CODE	ZONE TEST	PURP CODE	SPEC CODE	DATE TESTED	STATION	ITEM NUMBER	COMP.	M.C.	PASS FAIL
03	01-001	3	1	03-27-79	17+88	303(1)	97.4		PASS
03	03-001	3	1	03-26-79	31+65	303(1)	96.0		PASS
03	02-001	3	1	03-26-79	25+90	303(1)	96.1		PASS

043-06-16 MISCELLANEOUS MATERIAL TESTS

MAT. CODE	LAB. NUMBER	PURP CODE	SPEC CODE	IDENT	DATE SAMPLED	ITEM NUMBER	QTY	UNIT	PASS FAIL
106	22-301144	3	1	(1)001	03-22-79	705(1), 705(2), 705(9)			FAIL
136	22-301145	3	1	(2)001	03-22-79	705(1), 705(2), 705(9)			PASS
155	22-301148	3	1	(3)001	03-22-79	705(1), 705(2), 705(9)			PASS
175	22-301143	3	1	(1)004	03-22-79	806(1)			PASS

Figure 6. Computerized exception report on failing material.

STATE OF LOUISIANA 03-29-79
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
MATERIAL TESTING SYSTEM
EXCEPTION REPORT FOR THE TEST OF
BARBED WIRE(106)
DISTRICT 04

PROJECT NUMBER..043-06-16 DATE SAMPLED..03-22-79
LAB NUMBER......22-301144 DATE TESTED...03-27-79
IDENT...........(1)001 QUANTITY......AMPLE
PURPOSE..ACCEPTANCE SPEC CODE.....1
SUBMITTED BY..JERRY BLACKBURN-RESIDENT CONSTRUCTION ENGINEER
SOURCE...MADDEN CONTRACTING
REMARKS..SOURCE CO-OP

ITEM NO..705(1),705(2),705(9)

TEST PROPERTY	VALUE	REMARKS
SPACING OF BARBS,IN.	5	PASS
NO. OF POINTS PER BARB	4 POINTS	PASS
TYPE OF BARBS	DOUBLE WRAPPED	PASS
GAGE OF BARBS	14	PASS
GAGE OF WIRE	13	PASS
BREAKING STRENGTH,LBF	1075	PASS
SPELTER COATING,OZ./SQ. FT.	0.18	FAIL

REMARKS..THE ABOVE TEST RESULTS DO NOT CONFORM TO SPECIFICATIONS

COPIES TO:
JERRY BLACKBURN-RESIDENT CONSTRUCTION ENGINEER
DISTRICT LAB ENGINEER
DISTRICT ENGINEER

HOLLIS B. RUSHING BY ----------------
MATERIALS ENGINEER

concrete and portland cement concrete construction according to specific categories (e.g., project, use, and type);

2. Variability with respect to material type, material producers, project engineer, sampling and testing procedures, and time periods (as a result of a change in the system); and

3. Failure ratio in relation to sampling and testing frequency.

Specific examples of some of the above types of reports are shown in Figures 7-9. Figure 7 shows the distribution (percentage) of the quantity of asphaltic concrete that was deficient in each acceptance criterion at each pay scale. The table also provides further breakdown of this distribution for each criterion according to mix types. Figure 8 is a summary of data showing final adjusted payment for asphaltic concrete. The table shows, for each project, the total number of tons, the total number of lots (N-LOT), the number of lots that had reduced payments (N-LOT-P), and the tons involved in the reduced payment of 50, 80, and 95 percent pay (TONS-50, TONS-80, TONS-95) as defined in LDOT's specifications. The last column (PPPP) represents the final percent pay for each project. The variability information on asphaltic concrete is provided in the format shown in Figure 9. Such periodic information indicates the trend in material or process control.

Other Uses

The MATT files provide easy access to data for simulation of specifications if any changes in these specifications are contemplated. The project information files provide instant information on projects that have to be isolated for performance evaluation relative to such factors as materials, design procedures, and construction procedures. The only constraint to the use of the system as a feedback system is that data be available in the computer files.

HARDWARE-SOFTWARE USED

The MATT system operates with the following hardware and software configurations.

The hardware configuration includes the IBM 370 (Model 3031) computer printout unit; a 6-Mb core; six 3350, four 3330 (Mod 1), and eight 3330 (Mod 2) direct-access storage units; five 3420 nine-track magnetic tapes and one 3420 seven-track magnetic tape; two 1403 Xerox printers; a 2540 card-read punch with punch-feed read; a 3705A communication controller; and 3277 (cluster) communication terminals with 3284 printers.

The MATT system also uses these control softwares: OS/VS2, Release 3.8A; CICS/VS, Release 1.4; and VSAM, Release 2. In addition to these system control softwares, other software packages, such as SAS and Easytrieve, are also used for special-purpose analyses and reports.

MATT System Programs

The system operates under 29 on-line programs and 9 off-line programs. All on-line programs are CICS/VS macro and/or command level COBOL and ASSEMBLER language. The largest program requires approximately 192 000 positions of memory to execute.

SUMMARY

The MATT system discussed in this paper has provided LDOT with an efficient user-oriented material test data entry-and-retrieval system through user knowledge and computer hardware-software expertise. The tedious and time-consuming process of manually typing and processing the multitude of reports generated during project construction has been reduced to a minimum. A continuous log of tests is maintained in an organized and efficient manner at a centralized location for use by managerial, operations, and research personnel. Logging and exception reports are provided daily to the field personnel for project monitoring, while special reports are made available at user request for short- and long-term decision making.

No system can be considered optimum because of the

Figure 7. Summary of pay reduction on projects with deficiencies in asphaltic concrete acceptance criteria.

BASED ON	QUANTITY	PAY @	DISTRIBUTION, % ACCEPTANCE CRITERIA STABILITY	RDWY COMP	SURF TOL	TOTAL
TOTAL TONS	3023116	50	0.09	0.07	0.01	0.17
		80	0.67	0.99	0.25	1.91
		95	1.30	3.07	0.17	4.55
TONS PENALIZED	253296	50	1.32	1.10	0.16	2.58
		80	10.14	14.93	3.72	28.79
		95	19.66	46.32	2.65	68.63
MIX 1WC	54433		2.34	13.38	5.77	21.49
MIX 1BC	14337		0.93	4.73	0	5.66
MIX 2WC	3673		0	1.37	0.08	1.45
MIX 2BC	3116		0	1.23	0	1.23
MIX 3WC	62893		12.79	11.36	0.68	24.83
MIX 3BC	17807		1.92	5.11	0	7.03
MIX 5AC	46100		10.52	7.68	0	18.20
MIX 5BC	50937		2.62	17.49	0	20.11

Figure 8. Distribution of percentage of asphaltic concrete quantity according to pay scale, acceptance criteria, and mix type.

PROJ-NO	TONS	N LOT	N LOT P	TONS 50	TONS 80	TONS 95	PPPP
166-01-21	6798	5	0	0	0	0	100.0
179-01-12	9527	17	1	0	0	1142	99.4
243-01-09	19314	26	4	0	1932	1239	97.7
261-04-08	5450	5	0	0	0	0	100.0
268-02-07	7521	.14	0	0	0	0	100.0
268-02-10	8391	15	3	0	380	960	98.5
279-01-05	14127	16	0	0	0	0	100.0
387-03-02	3583	4	0	0	0	0	100.0
424-05-37	49448	58	0	0	0	0	100.0
454-03-01	61785	42	6	0	3556	2358	98.7
454-03-05	212708	179	17	115	2010	14342	99.2
454-03-06	233258	210	32	2660	9794	21159	98.1
454-04-02	430313	418	59	240	17827	32992	98.8
454-04-06	150134	179	18	196	2163	8218	99.4
857-22-04	2193	5	0	0	0	0	100.0
207-01-22	2779	8	0	0	0	0	100.0
857-05-02	4086	8	0	0	0	0	100.0
170-02-10	6234	6	0	0	0	0	100.0
355-01-05	4337	4	0	0	0	0	100.0
260-05-14	4671	8	0	0	0	0	100.0
263-04-11	9060	16	0	0	0	0	100.0

Figure 9. Variability of type 1 asphaltic concrete mixture.

VARIABLE	N	MEAN	STD DEV	MIN VAL	MAX VAL	C.V.
STABILITY	7356	1553.28	289.96	345.00	3364.00	18.67
COMPACTION	10031	96.36	1.64	86.30	103.90	1.70
1 INCH	2783	100.00	0.09	99.00	100.00	0.02
3/4 INCH	3820	99.72	0.89	85.00	100.00	0.89
1/2 INCH	3814	91.90	4.37	71.00	100.00	4.75
NO. 4	3816	55.98	5.11	35.00	77.00	9.14
NO. 10	3816	41.80	4.56	21.00	61.00	10.89
NO. 40	3816	24.58	3.49	9.00	38.00	14.21
NO. 80	3816	11.53	2.39	4.00	23.00	20.72
NO. 200	3815	6.43	1.55	2.00	18.00	24.13
A.C. %	3816	5.06	0.39	3.00	7.10	7.68

dynamics of the overall system of materials sampling, testing, and construction quality assurance. However, it is felt that changes can be accommodated as they occur. Louisiana's MATT system is geared toward providing an important input to the pavement management system currently under development through an effort funded by the Highway Planning Research (HPR) Program.

ACKNOWLEDGMENT

I wish to acknowledge the cooperation and effort provided by the LDOT Data-Processing Section and members of the various task groups. The study was conducted in cooperation with the Federal Highway Administration under the Louisiana HPR program. The contents of this paper refelct my views and not necessarily those of LDOT or the Federal Highway Administration.

Computer-Controlled Batch Plants

Edward A. Abdun-Nur

Because of its tremendous capacity for and speed of calculation, the computer is used to produce enormous amounts of data analyses that may not be justified for the test data produced in construction control. The relatively crude test methods used in construction and the lack of knowledge about the real meaning of the tests in many instances are the reasons. Using the computer to produce simpler and fewer calculations to guide the judgment of the engineer appears to be more realistic, less costly, and, at the same time, accomplishes the task intended. On the other hand, using the computer in the control of the batching plants and the process of batching and mixing appears to have a higher payoff in quality control and quality assurance. It permits the reduction of variability and, because of its feed-forward capability, it can control the process and even abort batches out of tolerance or stop the plant when it gets out of adjustment. Continuous batching and mixing plants, as developed in Europe, have the inherent advantages of lower capital cost and lower variability due to the elimination of the stop-and-start cycle at every batch, permit more sophisticated and delicate controls, have lower maintenance costs, and elicit more positive operator reactions. Teamed with a computer that makes these plants possible, such facilities are the best that current knowledge and technology have to offer.

When one talks about computers, visions of reams of paper filled with numbers appear. In construction, these numbers are often a waste of time because no one studies them closely. Detailed analyses of test data in construction are not warranted, inasmuch as the tests themselves are relatively crude, and rarely does one know what the test really measures. Therefore, fancy and sophisticated analyses are not only unwarranted but wasteful. The computer comes in handy, however, in process control and can contribute more to quality assurance than such analyses. Because the variability in construction is higher than in most industrial operations, computerized control of processes to reduce such variability can result in significant economic payoffs and improved quality control.

In the last 20 years or so, batch plants have gone from a crude operation in which the operator pulled levers and watched weighing-scale balance beams or gauges to the pushing of buttons to achieve the same thing and on to automated plants. The automated plants go through a complete batching cycle simply at the push of one button. The sequences are controlled by punch cards, assigned standard batch code numbers, or other means that provide a succession of signals to a computer already programmed to operate the various units of the plant in the proper sequence and to generate the various weights required by the particular mix being produced. Also, a record is produced to show what is happening and, in some cases, to print a delivery ticket.

It is not the purpose of this paper to get into the details of the automated plants in current use, whether for batching concrete, bituminous mixtures, or granular base-course materials. Rather, this paper describes automated computer-controlled plants, both of the single-batch type and continuous type, that have been observed in England and France and that appear to me to have substantial merit for use elsewhere.

BRITISH EXPERIENCE

Simon Plants

Some 15 years ago, while on a trip to London, I had an opportunity to observe a continuous concrete batch plant that was being operated on a discontinuous basis to fill ready-mixed concrete trucks. The facility, located in London's West End and operated by Ready-Mixed Concrete (London) Ltd., was known as the Fulham plant.

This type of plant was developed by the Simon Company, which was in the business of manufacturing cattle-feed batching plants and decided to extend its operations into the concrete field. Basically, each bin of aggregate discharges onto a short feed belt that, in turn, discharges onto a collector conveyor belt running at right angles to the bin feed belts. Each bin feed belt has a floating section that weighs the material passing over it. An electronic device transmits signals to the bin gate to adjust the opening, as the need is determined by the weighing device. The modulation results in a continuous series of adjustments that occur in fractions of seconds, thus essentially producing a continuous monitoring of the weight that passes over the belt scale.

The collecting belt discharges into the back end of a horizontal twin-shaft mixer (very much like a pugmill), which is set at an angle of about 10° with the horizontal. Water was also fed into the back of the mixer, and the mixed concrete moved forward by gravity and the push of the angled position of the mixer paddles, which were set on the two shafts, and was then discharged at the front of the mixer into the waiting truck. The plant was operated on a stop-and-start cycle dictated by the arrival and departure of the trucks into which the premixed concrete was discharged.

More recently, I inspected another of the Simon-type plants operated by this company on the east side of London known as the Stepney plant. The plant was essentially the same as the Fulham plant, but it had a suction fan connected to the back end of the closed mixer, which sucked the cement dust out and discharged it above the plant into the atmosphere (it was not being returned to the cement bin or collected in any container for reuse). As a result, the batch room was very clean.

The advantages of the Simon plant include the following:

1. The operation adjusts itself to the required weights automatically and continuously, thus reducing variability over other types of batching.
2. When operated on a continuous basis, it reduces variability still further, as the variability due to the stop-and-start actions is eliminated. There is only one start at the beginning of a shift.
3. Capital cost is materially reduced over the standard-type plant by using a heavy rotary-drum mixer—the twin-shaft mixer cost is about 60 percent of that for a drum mixer with the same capacity.
4. Because the mixer paddles can be changed by (a) opening the top door that exposes them, (b) unscrewing the worn paddles at the ends of the mixing arms, and (c) replacing them with new ones, less maintenance is required. Two persons can do the job in about 30 min.
5. The machinery is lighter, and vibration and shocks due to the stop-and-start cycles are reduced. Thus, the machinery is subjected to less wear and tear.
6. Only one batch person and one yard person, who sees that the bins remain filled, are required.
7. Better morale and a less tiresome operation produce operators who are much happier on the job.

For ready-mixed concrete to be trucked away, this type of plant can be used only in a discontinuous or batch operation. But, for base-course material batching, it is very popular with contractors for use on a continuous basis. It would appear to me that on dam construction and on large slipform pavement jobs, such plants could be used in the continuous mode and thus gain all the above advantages, particularly in helping to reduce variability, which means less cement (and thus less energy) and lower cost.

Tilcon Batching Plants

The Tilcon plants are essentially the same as the Simon plants but have more sophisticated refinements and portability. The mobility of these plants (a plant can be dismantled into a few pieces in very little time and moved over the road) makes them ideal for contractors. The pieces are manufactured with all ancillary services (pneumatics, electrical cables, controls, and so forth) factory installed so that it is a simple matter to erect and connect the ancillary services. The plant becomes operational immediately.

Basically, the plants (as in the Simon plants) have bins that discharge onto cross-feed belts that, in turn, discharge onto a collecting belt. The belt feeds into the mixer. Each feed belt under a bin of aggregate of a different size has a section that weighs the volume passing over that section on a continuous basis. A floating roller located in the center of the section moves up and down depending on the weight of the material on the belt. A sensitive counterbalanced lever is in contact with this roller and thus moves up and down with it. The free end of the lever is in contact with a transducer that controls the switch contacts, which open and close the radial gate at the bottom of each bin. This provides a continuous modulation of the weight of the volume of material passing over that section and, thus, controls it very closely within the required weighing tolerances.

In the case of the cement silo, specially designed feed valves at the end of screw conveyors discharge onto the feed belt weighing section that controls the speed of the screw conveyor in the same manner as the aggregate belt-weighing mechanism controls the feed gate opening. The Tilcon mixers are of their own design and are still lower in cost than those at the Simon plant; but basically they operate on the same principle. It is understood that these mixers cost about one-fifth of that for a heavy drum mixer of the same capacity and about one-third of that for a Simon mixer.

The batch-room controls are very simple. Separate dials control the weight of each ingredient according to the mix-design formula. Then, another dial for discontinuous concrete delivery operation can be set in terms of the number of cubic meters desired—essentially, a timer runs the plant for just long enough to produce the required volume. Again, the stop-and-start operation increases the variability (as in any batch plant), but this type of plant in contrast to the ordinary batch plants with scale-weighing mechanisms has a lower variability. Many of these plants are used by contractors in the field either for concrete or base-course batching and mixing. Base-course mixtures include either cement or lime and are operated on a continuous basis. Thus, the variability is reduced further because of the elimination of the start-and-stop increments of variability. It would have this same advantage when operated for concrete on a continuous basis, for example, on a dam or slipform paving operation.

FRENCH EXPERIENCE

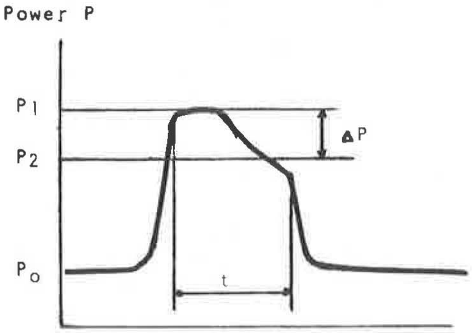
In France, there are plants that aim to do the same thing as the British plants—that is, provide continuous modulating batching and mixing—and are operated either in the continuous mode or in the discontinuous mode depending on the circumstances. In addition, the French plants have developed various types of computer controls for the mixing cycle in batch mixing.

Laboratoire Central des Ponts et Chaussées

This testing and research government institution has developed computer analyses and controls for batch and mixing plants. These have been mounted in a panel truck. The truck can go from plant to plant, hook up to the plant, and produce charts and analyses of what is going on.

The most fascinating part of this work is the analysis of the mixing cycle through a recording wattmeter. The wattmeter not only records the power but draws curves that provide an analysis of what is actually happening in the mixer. Figure 1 is a theoretical delineation of such an analysis. The power required to rotate the empty mixer is P_0. When the materials are introduced, the power rises to P_1; then, as the water is mixed in and the mix becomes plastic, the power drops to P_2. The difference between P_1 and P_2 (aggregates and cement being relatively constant) reflects the amount of water. The mixing time is shown as the distance t. As it is mixed, each batch provides a chart in front of the operator to

Figure 1. Mixing power cycle.



guide him in adjusting the process if needed. The operator can abort a batch that looks too far out to be acceptable. This is not computer control of the mixing, but it provides a sophisticated tool for the operator to see if there is anything wrong with the process. Necessary and quick adjustments can then be made.

Béton de Paris

In France, only about 30 percent of the concrete used is in the form of ready-mixed concrete—a situation diametrically opposite to that in the United States, where about 80 percent is in the form of ready-mixed concrete. Perhaps the largest company producing ready-mixed concrete in one city is Béton de Paris (a subsidiary of Sablières de la Seine, which produces aggregates from the Seine River). This company operates some 25 plants in the Paris metropolitan area. Because of heavy traffic and narrow streets, rarely is concrete delivered more than 5 or 6 km (3.1-3.7 miles) from the plant. Government wheel-load limitations do not permit more than 6 m^3/truckload (9 yd^3/truckload). This company buys its plants manufactured to its specifications and has a subsidiary that designs and installs automation. The plants operate on a batch-to-batch cycle but are completely controlled by computers.

Inasmuch as the load limit is 6 m^3, each load is batched in two 3-m^3 (4.5-yd^3) steps to afford the computer an opportunity to control and adjust the weights. The information for any particular mix is stored on a punched tape. When the tape is inserted in the Singer typewriter terminal, the weights for the various components of the mix are quickly printed on the top line of the lower half of the delivery ticket. The upper half of the ticket contains information about the purchaser, delivery address, mix number and type, truck number, and so forth. Immediately after the calculated weights are printed on the ticket, the first 3-m^3 load is batched, mixed, and discharged into the ready-mixed concrete truck. Then, it is recorded on the second line immediately below the first line. The computer next calculates what the second 3-m^3 weights should be to compensate for the difference between what the computer ordered and what the machinery delivered in the first batch. This information is printed several spaces below on a third line. The computer orders the machinery to batch and mix the second 3-m^3 batch and discharge it into the truck. At the same time, the second batch's actual weights are recorded immediately below the third line (as the fourth line). This gives a visual comparison between the weights ordered or calculated and the weights batched for each half of the total batch (the first line of each pair represents the calculated weights and the second line, the actual weights batched). By adding the second and fourth lines, one obtains the weights of the total batch of the 6-m^3 load. The computer also calculates and prints out the weight per cubic meter of the finished total batch. All this information is printed on the delivery ticket and goes to the purchaser, who then knows exactly what is being delivered.

Every two plants have a quality-control engineer assigned to them. The engineer shuttles between them in a panel truck with the portable testing equipment, and each plant has a small laboratory for heavy testing equipment and for storing the concrete cylinder specimens. In addition, the company maintains a three-story research laboratory in which research and development are carried out and where the quality-control operation for the whole company is centered.

French Continuous Batch Plants

The continuous mixing plants in France have about the same general pattern as those in England but differ in details. There were two of them in operation at the time of my visit, and a much bigger and sophisticated one was due to come on-line shortly after.

Cergy-Pontoise

The Cergy-Pontoise plant is operated for batching concrete into ready-mixed concrete trucks and, therefore, operates on the continuous-discontinuous principle or cycle. It has short conveyor feed belts under the various bins of ingredients. These discharge onto a collector belt that, in turn, discharges into the mixer. It was built by using the Rousseau patent system. Basically, the bins have a patented design that maintains a constant pressure at the discharge gate, regardless of the level of material in the bin. This means that the same amount of material is continuously discharged through the gate. The whole short-feed belt is floating and is weighed with the material on it. The weight of the material on the belt is controlled by varying the speed of the belt and seeing that the amount of material discharged from the gate is always constant. Here again, electronic controls modulate the speed of the belt to maintain constant weight.

Electric moisture meters measure and correct the weight for the water in the aggregates. The mixer is of the twin-shaft type so popular in Europe, and many of the mixers in France are imported from Germany. The claim is that they are better than the French equivalents. This is a recording plant, and the computer completely controls the plant and even issues the bills, as well as the delivery tickets with all the details. It takes about 1.5 min for a 6-m^3 batch to go through the plant operating on this discontinuous batching cycle. The plant capacity is limited by the number of trucks being loaded, how frequently they are available, and the time required to maneuver to receive the load. The capacity would increase significantly if the operation were on the continuous basis and would result in a lower-variability product.

Conflans

The Conflans plant is operated by a syndicate of contractors that has enough demand to permit the plant to operate on a continuous basis—and this is where the advantages of the continuous plants appear. This plant produces stabilized base mixes with either cement or lime as the stabilizing agent. It has a holding hopper to even out the truck traffic without disturbing the plant operation. It is also built in accordance with the Rousseau patents and is completely controlled by a computer that also records and issues delivery tickets that show the weight of the loaded truck and its tare weight. It has a provision for shortcircuiting the holding bin by loading directly into the trucks. It produces 600 metric tons/h (660 tons/h).

COMPUTER ADVANTAGES AND DISADVANTAGES

Computers have become more and more available today—almost as available to people as the washing machine or the automobile. Add to this the fact that computer manufacturers are lowering the cost and increasing the speed of producing calculations, and we have a situation where everyone is tempted to rely on reams of paper filled with calculations generated by computers. Because of availability and speed, the computer is asked for much more than we need or even know what to do with at the current stage of our knowledge. This is particularly so in the case of calculations for quality acceptance and quality control in the construction materials industry. The tests performed are relatively crude when compared with the statistical analyses available through computers. Simple analyses are adequate for the conclusions that can be realistically drawn from such data.

The computer to control the batching and mixing processes is a much more realistic and valuable tool to achieve the production of quality materials with relatively low variability and to maintain proper records, that is, process control. If materials are batched or processed correctly, one needs very little testing and such testing is for historical record rather than for acceptance. Batch or process it right, and it cannot be anything but right (1). The plants described in this paper do just that and, it is felt, are more useful than the computers that crank out reams of paper filled with numbers that leave one aghast and that are really, in many cases, not justified by the physical facts of the work (2).

The mixers in all the plants described in this paper are more realistic in their design than the heavy drum mixers that consume more energy and metal to manufacture, use more energy to run, and cost more to maintain. Moreover, they do not produce mixtures that are any better than the twin-shaft type of mixers that are lighter, have lower operating costs, and require less maintenance. It is time to take this twin-shaft type of mixer more seriously in order to lower capital investment costs, lower energy used in running the mixers, and lower maintenance cost.

Computer-Controlled Plants

The computer is capable of feed-forward that permits it to correct errors before the mixture is discharged or to even abort it, if it cannot be corrected within the acceptable tolerances. It relieves the strain on the operators. It also increases the accuracy and lowers the variability of the production, whether on a batch-to-batch cycle or on a continuous cycle operation. The operators are happier and develop better attitudes toward their work.

Continuous Proportioning and Mixing

By eliminating the stop-and-start operation of the plant, continuous batching and mixing reduce all the vibrations and surges due to the stop-and-start operation that introduce variability in each cycle. It is less hard on mechanisms to operate continuously than to take the shocks and efforts induced by the stop-and-start cycle; therefore, the wear and tear and the maintenance drop appreciably. In addition, the first cost is reduced due to the possibility of a lighter plant that does not have to withstand the shocks of the starting and stopping of heavy mixers. As a result, more sophisticated control is possible because delicate controls do not get as easily out of adjustment due to reduced vibration and shocks in the stop-and-start cycle. In essence, then, one gets better control, more sophisticated proportioning, and reduced variability (which is the real payoff)—all at lower overall capital and operating costs. Finally, side benefits are less strained, happier, and more satisfied operators and better productivity.

CONCLUSIONS

The following conclusions may be drawn regarding computer-controlled batch plants.

1. Because of their huge capacity and speed in producing calculations, computers tend to be used to provide sophisticated analyses of test data that have little significance and need in construction. This is due to the fact that we know very little of the real meaning of such tests and their relative crudeness compared with the refined and sophisticated data developed in this fashion. A much smaller number of calculations to give direction to the decision-making process appears adequate for construction-engineering purposes.
2. On the other hand, computer-controlled batching-and-mixing process operations have a higher payoff in reducing variability, correcting the process as need arises, and recording what transpired. The computer's feed-forward capability permits it not only to correct itself but also to abort batches that are way out of tolerance.
3. The continuous batching-mixing plants have a lower capital cost, lower maintenance, more sensitive control mechanisms, lower inherent variability, and more positive operator reactions. These advantages are all enhanced by the computer control that lowers variability still further and operates the plants more efficiently—thus resulting in increased productivity. Actually, without the computer, such continuous plants would not have been possible.
4. When such computer control is used in conjunction with the continuous batching-mixing plants in use in Europe, it enhances and controls their operation to produce the best that current technology has to offer in this field.

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Analysis of Multiple Acceptance Criteria

Richard M. Weed

A relatively simple type of acceptance procedure currently in use has the dual acceptance requirements that the average value of all items of a sample must equal or exceed a limit and that each individual value must equal or exceed some lower limiting value. Provided the sampling is from a normal population, the probability of passing either of these criteria separately can be calculated quite readily. However, determining the compound probability of passing both requirements of the acceptance procedure is complicated by the fact that the individual probabilities are correlated. A solution is presented that involves the calculation of upper and lower bounds for the desired probability. This solution is then generalized to apply to any number of multiple acceptance criteria. An example is presented to demonstrate that the bounds are usually sufficiently close together to make this a practical approach. Because the calculations are quite tedious, a computer program has been written to simplify this part of the procedure. The speed and convenience of the computerized approach will permit specification writers to experiment with different acceptance limits to determine those that produce suitable producer's and consumer's risks. For the producer, it will provide a means to determine the target value necessary to ensure that the probability of acceptance will be at least the amount desired.

A statistical acceptance procedure in frequent use today requires that the mean of a random sample must equal or exceed a limiting value, and, in addition, all individual sample values must equal or exceed a lower limit. When the sampling is from a normal population, the probability of passing either of these requirements can easily be calculated. However, because both requirements are applied to the same set of sample values, the individual probabilities are correlated to some unknown degree. As a result, the compound probability of passing both requirements cannot readily be determined. To my knowledge, a direct analytical solution of this problem is not known.

To circumvent the correlation problem, a different approach has been taken. Although it may not be possible to determine the exact probability of acceptance, it is possible to calculate upper and lower bounds for this probability. As long as these bounds are not too far apart, this provides a reasonably precise interval estimate of the true probability of acceptance.

Depending on the exact nature of the dual requirements, there are several factors that must be taken into consideration. Before deriving the bounds for the joint probability of passing both requirements, it will be useful to develop the sampling distributions necessary to determine the probabilities of passing each requirement separately.

SAMPLING DISTRIBUTIONS

The first requirement of the acceptance procedure is that the mean of all the test values ($\overline{X}$) must equal or exceed a limiting value ($\overline{X}_L$). Defining σ_p^2 and σ_T^2 as the product and testing variances and provided that the population is approximately normal, the sampling distribution for the mean of N samples of size n is normal with a mean (μ_1) equal to the true product mean (μ_p) and a standard deviation (σ_1) given by Equation 1. (This assumes that the samples are taken from N different portions of product and that, within each portion, the n individual tests are subject only to testing error. Note that when n = 1, σ_1 represents the standard error of the mean of N single samples that can be calculated from the overall standard deviation of individual values without requiring a knowledge of the specific values of σ_p and σ_T.) This distribution is shown in Figure 1.

$$\sigma_1 = \sqrt{(\sigma_P^2/N) + (\sigma_T^2/Nn)} \qquad (1)$$

Defining α_1 as the probability of the sample mean falling below $\overline{X}_L$, Equation 2 gives the probability P_1 of passing the first requirement. The value of α_1 is obtained from a table of the standard normal distribution.

$$P_1 = P[\overline{X} \geq \overline{X}_L] = 1 - \alpha_1 \qquad (2)$$

One way in which the second requirement of the acceptance procedure might be stated is that all of the N × n test values must equal or exceed a limiting value X_L. The requirement that all n values of a sample must equal or exceed X_L is the same as requiring the lowest value (the first-order statistic) to equal or exceed this value. Assuming that the variability of the product and the testing error are approximately normally distributed, the sampling distribution of the first-order statistic will also be approximately normal, as shown in Figure 2, with a mean μ_2 and standard deviation σ_2 given by Equations 3 and 4:

$$\mu_2 = \mu_P + C_1 \sigma_T \qquad (3)$$

$$\sigma_2 = \sqrt{\sigma_P^2 + C_2 \sigma_T^2} \qquad (4)$$

The constants C_1 and C_2 are the mean and variance, respectively, of the first-order statistic for a sample from a standard normal distribution and are obtained from appropriate tables (1). The following table lists values of C_1 and C_2 for sample sizes up to n = 10:

Sample Size (n)	Mean (C_1)	Variance (C_2)
1	0	1
2	-0.564 19	0.681 690 113 9
3	-0.846 28	0.559 467 203 8
4	-1.029 38	0.491 715 236 9
5	-1.162 96	0.447 534 069 1
6	-1.267 21	0.415 927 109 0
7	-1.352 18	0.391 917 776 1
8	-1.423 60	0.372 897 143 4
9	-1.485 01	0.357 353 326 4
10	-1.538 75	0.344 343 823 3

Defining α_2 as the probability of the lowest of the n values in each sample falling below X_L and recognizing that the N sample results are independent of each other, Equation 5 gives the probability P_2 that all N samples will pass the second requirement. The value of α_2, like α_1, is obtained from the standard normal table.

$$P_2 = P[\text{ALL } X \geq X_L] = (1 - \alpha_2)^N \qquad (5)$$

If the second acceptance requirement were applied to the mean of the n individual tests in each sample instead of the lowest value, the use of order statistics would not be required. In this case, Equations 6 and 7 would apply and the sampling distribution would be as shown in Figure 3.

$$\mu_2 = \mu_P \qquad (6)$$

$$\sigma_2 = \sqrt{\sigma_P^2 + (\sigma_T^2/n)} \qquad (7)$$

α_2 and P_2 would still be determined in the manner previously indicated. (Note that when n = 1, σ_2 represents

Figure 1. Sampling distribution of the mean of N samples of size n.

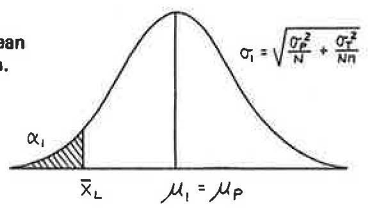


Figure 2. Sampling distribution of the lowest value in a sample of size n.

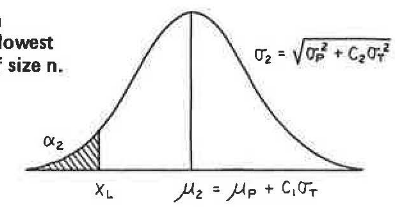
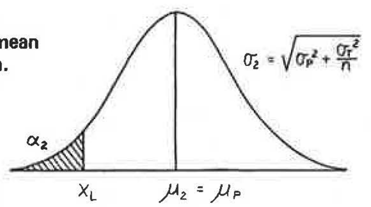


Figure 3. Sampling distribution of the mean of a sample of size n.



the overall standard deviation for individual values and a knowledge of the specific values of σ_P and σ_T is no longer necessary.)

DERIVATION OF UPPER AND LOWER BOUNDS

Once P_1 and P_2 have been determined, it is tempting to assume that the compound probability of passing both requirements would simply be the product P_1P_2. This would be correct if P_1 and P_2 were independent but, because both requirements are applied to the same set of sample values, this is not the case. For example, when a group of higher-than-usual individual values produces an unusually high probability of passing the requirement on individual tests, there will be a corresponding high probability of passing the requirement on the sample mean. As a result, the two probabilities are positively correlated to some degree.

The correlation problem can be avoided by calculating upper and lower bounds for the desired probability of acceptance. To simplify the derivation that follows, call the events of passing the two acceptance criteria A and B. The objective is to determine bounds for the probability of the joint occurrence of A and B under the condition that they are positively correlated to some unknown degree. The exact probability for their joint occurrence can be expressed as

$$P[A \cap B] = P[A|B] \cdot P[B] = P[B|A] \cdot P[A] \quad (8)$$

in accordance with a law of probability usually referred to as the general law of multiplication (2). Because any probability value must be less than or equal to one, it follows that

$$P[A \cap B] \leq P[B] \quad (9)$$

and

$$P[A \cap B] \leq P[A] \quad (10)$$

and, from this,

$$P[A \cap B] \leq \text{MINIMUM}\{P[A], P[B]\} \quad (11)$$

is derived as the upper bound. To obtain the lower bound, it must be noted that when two events are positively correlated, the occurrence of one increases the probability of the occurrence of the other. Therefore,

$$P[A|B] \geq P[A] \quad (12)$$

which, when substituted back into Equation 8, gives

$$P[A \cap B] \geq P[A] \cdot P[B] \quad (13)$$

as the lower bound. Applying these results to the dual acceptance criteria problem yields

$$P_1 P_2 \leq P[\text{ACCEPT}] \leq \text{MINIMUM}[P_1, P_2] \quad (14)$$

which can be generalized to

$$P_1 P_2 \ldots P_N \leq P[\text{ACCEPT}] \leq \text{MINIMUM}[P_1, P_2, \ldots, P_N] \quad (15)$$

provided that none of the acceptance criteria are negatively correlated.

COMPUTER SIMULATION TESTS

In order to check the theoretically derived bounds given by Equation 14, several tests were made by using computer simulation. Each simulated result was the average of a minimum of 1000 replications that used various combinations of product and testing variance. In every case, the value obtained by simulation fell within the theoretically predicted bounds. The results of these computer simulation tests follow:

	Probability of Passing Both Requirements	
Test	Theoretical Bounds	Simulation Result
1	0.03-0.03	0.03
2	0.04-0.08	0.07
3	0.04-0.11	0.08
4	0.30-0.34	0.31
5	0.61-0.67	0.67
6	0.78-0.81	0.81
7	0.92-0.95	0.95
8	0.95-0.96	0.95
9	0.96-0.97	0.97
10	0.99-0.99	0.99

IMPLEMENTATION

When the sampling is from a normal population, both bounds can be calculated directly and, for practical purposes, this is best done by computer. The speed and convenience of the computerized approach will permit a specification writer to experiment with different acceptance limits in order to determine those that produce suitable producer's and consumer's risks. Whereas the consumer will be interested primarily in the upper bounds for probability of acceptance, the producer will be more concerned about the lower bounds. For the producer, the computer program will provide a means to determine the target value necessary to ensure that the probability of acceptance will be at least the amount desired.

EXAMPLE

Based on engineering considerations or historical data,

Figure 4. Typical computer printout for dual acceptance criteria analysis.

```
ENTER NUMBER OF SAMPLES (FOUR TRIAL VALUES)
1 2 5 10

ENTER SIZE OF EACH SAMPLE (MAXIMUM 10)
2

ENTER CODE FOR MANNER IN WHICH REQUIREMENT ON INDIVIDUALS IS APPLIED
(1 = INDIVIDUAL TEST VALUES, 2 = INDIVIDUAL SAMPLE MEANS)
1

ENTER PRODUCT AND TESTING STANDARD DEVIATIONS
500 200

ENTER LOWER LIMITS FOR MEAN AND INDIVIDUAL VALUES
4000 3200

ENTER MINIMUM, MAXIMUM, AND STEP SIZE FOR POPULATION MEANS
3500 4900 100

POPULATION     LOWER AND UPPER BOUNDS FOR PROBABILITY OF ACCEPTANCE
   MEAN           N =  1        N =  2        N =  5        N = 10

   3500        0.11 - 0.17  0.04 - 0.09  0.00 - 0.02  0.00 - 0.00
   3600        0.16 - 0.22  0.07 - 0.14  0.01 - 0.04  0.00 - 0.01
   3700        0.22 - 0.28  0.12 - 0.21  0.03 - 0.10  0.00 - 0.03
   3800        0.29 - 0.35  0.20 - 0.29  0.07 - 0.19  0.02 - 0.11
   3900        0.37 - 0.42  0.30 - 0.39  0.16 - 0.33  0.07 - 0.24

   4000        0.45 - 0.50  0.41 - 0.50  0.30 - 0.50  0.18 - 0.36
   4100        0.54 - 0.58  0.53 - 0.61  0.47 - 0.67  0.36 - 0.50
   4200        0.62 - 0.65  0.64 - 0.71  0.64 - 0.79  0.55 - 0.62
   4300        0.70 - 0.72  0.75 - 0.79  0.77 - 0.86  0.71 - 0.73
   4400        0.76 - 0.78  0.83 - 0.86  0.87 - 0.91  0.82 - 0.82

   4500        0.82 - 0.83  0.89 - 0.91  0.93 - 0.94  0.88 - 0.89
   4600        0.87 - 0.88  0.94 - 0.95  0.96 - 0.96  0.93 - 0.93
   4700        0.91 - 0.91  0.96 - 0.97  0.98 - 0.98  0.96 - 0.96
   4800        0.94 - 0.94  0.98 - 0.99  0.99 - 0.99  0.98 - 0.98
   4900        0.96 - 0.96  0.99 - 0.99  0.99 - 0.99  0.99 - 0.99
```

or a combination of both, a specification writer would have a reasonably good idea of what constitutes acceptable and unacceptable product in terms of the population mean and standard deviation. In order to develop an effective acceptance procedure, the operating characteristics must be investigated to confirm that the probabilities of accepting good material and rejecting bad material are satisfactory. This will usually require a trial-and-error approach in which the specification writer will wish to experiment with different acceptance limits and sample sizes.

To illustrate how this can be done by using an interactive computer program prepared specifically for this purpose, suppose that the specification writer has decided to define a sample as a pair (n = 2) of tests but that the number (N) of samples to be required has not yet been determined. Recalling that the general case (N samples of size n) requires that the product and testing variability be dealt with separately, the program has been written to accommodate this. For this example, values of $\sigma_P = 500$ and $\sigma_T = 200$ will be used. (In order to simplify the presentation, the specific units have not been identified and may be regarded as either metric or customary quantities.)

The remaining input variables required are the two acceptance limits and some additional values that determine the size of the table the computer will print out. For this example, lower limits of 4000 for the sample mean and 3200 for individual test values have been selected. The remaining input values of 3500, 4900, and 100 instruct the computer to make the calculations for population means of 3500 to 4900 in steps of 100. The complete printout for this run is shown in Figure 4.

Several runs of this type would normally be required to analyze the effects of various combinations of product and testing variability or to evaluate different pairs of dual acceptance criteria. For purposes of this example, however, only the run shown in Figure 4 will be analyzed.

ANALYSIS OF RESULTS

Several interesting observations may be made from the values in the computer printout. Each column of probability values represents the points on an operating characteristics curve for the number of samples N indicated at the top of the column. The paired values are the lower and upper bounds for the true probability of acceptance that correspond to each population mean listed in the column at the extreme left.

The specification writer will be concerned primarily with the upper probability value of each pair. For ease of analysis, a portion of the printout that shows the maximum probability of acceptance for various numbers (N) of samples of size n = 2 is reproduced below:

Population Mean	Upper Bounds for Probability of Acceptance N = 1	N = 2	N = 5	N = 10
3500	0.17	0.09	0.02	0.00
3600	0.22	0.14	0.04	0.01
3700	0.28	0.21	0.10	0.03
3800	0.35	0.29	0.19	0.11
3900	0.42	0.39	0.33	0.24

If, for example, it were desirable to have a low probability of acceptance for product with a population mean as low as 3500, these data indicate that a total of N = 2 samples (each of size n = 2) produces a maximum probability of acceptance of 0.09, whereas a total of N = 5 samples lowers this probability to 0.02. Based on these results (and those of other runs), the specification writer would select the appropriate acceptance limits and number of samples to achieve the desired result.

The printout will also be of considerable value to the producer whose product is to be accepted or rejected by this procedure. The producer will be concerned with the lower probability value of each pair.

For convenience, the values of interest are reproduced in the following table:

Population Mean	Lower Bounds for Probability of Acceptance			
	N = 1	N = 2	N = 5	N = 10
4500	0.82	0.89	0.93	0.88
4600	0.87	0.94	0.96	0.93
4700	0.91	0.96	0.98	0.96
4800	0.94	0.98	0.99	0.98
4900	0.96	0.99	0.99	0.99

If, for example, the number of samples is specified to be N = 5 and the producer desires a probability of acceptance of at least 99 percent, these data indicate that a population mean of 4800 must be achieved.

Another interesting observation to be made from the values noted above concerns the effect of increasing the sample size. Ordinarily, increasing the number of samples would be expected to reduce both the producer's and the consumer's risks. However, with dual acceptance procedures of the type used in this example, this is not necessarily the case for producer's risk. For the larger values of the population mean representing higher levels of quality, the probability of acceptance increases up to N = 5 and then begins to decrease as N becomes larger. This is the result of the increased opportunity to fail the requirement on individual test values.

CONCLUSION

Because the probabilities of passing the requirements of a multiple acceptance procedure are correlated, the compound probability of passing all requirements cannot readily be determined. As an alternate approach, upper and lower bounds for the desired probability can be calculated. The theoretical basis for this approach was developed, and the results were tested by computer simulation.

An example was presented that demonstrated that these bounds provide a reasonably precise interval estimate of the true probability of acceptance. The calculations were performed by an interactive computer program that can be a valuable aid, both to the specification writer in developing the acceptance procedure and to the producer in determining the target value necessary to meet it.

The purpose of this paper is to provide guidance in the analysis of multiple acceptance criteria, not to advocate the use of acceptance procedures of this type. Depending on the measure of quality that is used and the manner in which it is related to performance, other acceptance procedures may be preferable. For example, the concept of percent defective (i.e., percentage of a lot falling outside specification limits) is often preferred by both designers and specification writers. For this approach, the methods of Military Standard 414 (3) may be applied.

Looking ahead, the bounds given by Equations 14 and 15 may prove to be useful in other situations in which correlation exists. Successive moving averages, for example, are correlated and may be analyzed in this manner. Also, certain sequential sampling plans, in which a failure results in the taking of a second sample and combining it with the first, produce correlated probabilities that can be analyzed effectively by the boundary approach. In general, any application that involves positively correlated probabilities is a potential candidate for this method.

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Unbiased Graduated Pay Schedules

Richard M. Weed

Conventional graduated pay schedules are biased in the sense that, on the average, they provide less than 100 percent payment for a product that is exactly at the acceptable quality level. The quality index on which they are based is an essentially unbiased indicator of the percent defective of the population but, because the highest level in the pay table is 100 percent, the average pay factor will usually be somewhat less. This may create serious problems in certain instances but can be overcome by developing unbiased pay schedules that are linear functions of the estimate of the population percent defective. This approach can be applied to both continuous and stepped pay schedules and, in both cases, pay factors greater than 100 percent are permitted. These are used to establish credit that may be applied to offset lower pay factors within specified time intervals throughout a construction project. This method is mathematically sound and produces the desired average pay factor at all quality levels. It is not the same as a bonus provision because the overall pay factor for each time period is still limited at 100 percent. The preparation of tables for estimating percent defective is reviewed, and both continuous and stepped pay schedules based on this measure are developed. Operating characteristics curves and optimization curves are presented to compare these approaches and assess their effect on bidding strategies.

Statistical construction specifications are based on a desired end result and usually employ graduated pay schedules to award payment in proportion to the extent that the end result is achieved. An acceptable quality level (AQL) is defined as that level of some quality measure of a product considered necessary for satisfactory performance. When the acceptance procedure indicates that the quality level is greater than or equal to the AQL, the lot is eligible for 100 percent payment. If the tests indicate that the lot quality level is less than the AQL, a graduated pay schedule is used to determine the appropriate reduced pay factor. In addition to the AQL, it is customary to define a rejectable quality level (RQL) below which the buyer reserves the option to require removal and replacement of the defective product. This approach is described in several recent publications (1-3) and has gained favor with many specifying agencies because it provides a practical and equitable way to accept work that is only slightly deficient.

Although this concept has worked reasonably well in practice, conventional pay schedules are biased in that they award less than 100 percent payment, on the average, when the product is exactly at the AQL. Because the highest pay factor in a conventional pay schedule is 100 percent and AQL lots will occasionally receive lower pay factors, the expected average pay factor for AQL product will always be somewhat less than 100 percent. Typical AQL pay factors are often about 98 percent.

In many cases, contractors can compensate for this bias by making small adjustments in their bid prices or by producing at slightly higher quality levels. In some cases, however, this bias can have serious consequences. For example, consider the independent concrete producer who supplies AQL concrete at \$39.24/m^3 (\$30/yd^3) to a general contractor who places it in a structure valued at \$392.39/m^3 (\$300/yd^3). In this case, an average pay factor of 98 percent corresponds to a pay reduction of 0.02 × \$392.39 = \$7.85/m^3 (0.02 × \$300 = \$6/yd^3) that, in all likelihood, would be passed back to the producer.

To offset this expected pay reduction, the producer must either raise the bid price for AQL concrete by \$7.85/m^3 (\$6/yd^3) or else plan to produce concrete at a considerably higher quality level, neither of which is completely satisfactory. The first approach involves an uncertain game of numbers in which the bid price will not realistically reflect the value of the concrete. The second alternative, discussed in a paper on optimum strategy (4), can produce an equitable result for all parties but leads to the extra expense of an average quality level substantially above that which the specifying agency has defined as acceptable. However, countermeasures such as these will not be necessary if unbiased pay schedules that award an average pay factor of 100 percent for AQL product can be developed.

ESTIMATING PERCENT DEFECTIVE

Before proceeding with the development of unbiased pay schedules, it is first necessary to define the measure of quality on which these pay schedules will be based. Of the various ways that an acceptable or unacceptable product might be defined, the concept of percent defective (i.e., percentage of the total population outside specification limits) seems to have considerable appeal to specification writers. The overall proportion within specification limits is felt to be strongly related to a product's performance or service life, or both. This general philosophy is promulgated in Standard 214-77 (5) of the American Concrete Institute (ACI), although the ACI acceptance criteria do not use a pure percent-defective approach.

In order to develop a specification based on percent defective, it is necessary to have an accurate method for estimating the percent defective of a population. Military Standard 414 (6) provides a method that involves the calculation of a quality index from the mean and standard deviation (or range) of a random sample. Once the quality index has been calculated, a table is consulted to obtain the estimate of the percent defective of the lot from which the sample was drawn. This method assumes random sampling from a normal universe, conditions that can be sufficiently met for most construction quality characteristics.

For the standard-deviation method, variability assumed unknown and a lower limit only, the quality index is calculated as

$$Q_L = (\bar{X} - L)/S \quad (1)$$

where

Q_L = quality index (lower limit),
$\bar{X}$ = sample mean,
L = lower limit, and
S = sample standard deviation.

In addition to the standard-deviation method, Military Standard 414 provides a similar approach that uses the sample range as the measure of variability. Although the two methods are essentially equivalent for small sample sizes, the standard-deviation method provides a more precise estimate of the population percent defective as the sample size increases. Also, Willenbrock and Kopac (7) have pointed out that, although the range method is quite accurate, only the standard-deviation method furnishes a true minimum variance unbiased estimate.

Willenbrock and Kopac (7) illustrate how Pearson's Tables of the Incomplete Beta Function (8) can be used to develop the Military Standard 414 tables that relate the quality index to the estimate of percent defective. By using Pearson's tables, it is possible to obtain both a greater number of significant figures and a greater selection of sample sizes than are presented in Military Standard 414. Although it is possible to work directly from Pearson's tables, it is far more efficient to perform this entire operation by computer. A typical table developed in this manner is shown in Figure 1.

DEVELOPING THE PAY SCHEDULE

Before developing the mechanics of the pay schedule, it is first necessary to determine the amount of payment appropriate for various quality levels of work. Several methods have already been proposed (1, 2). When information is available that relates a product's quality to its performance, as is the case with the American Association of State Highway Officials' nomographs for pavement design (9), I favor an economic approach (3) in which the pay reduction is the present value of the extra future cost anticipated as the result of deficient-quality construction. Because this method takes into account the salvage value of pavement that has reached the terminal serviceability index, it tends to award higher pay factors than some of the other methods and, because it relates payment directly to value received, this approach is believed to be both equitable and legally defensible.

When applied to concrete pavement, the economic approach produces a nearly linear relation between percent defective and the appropriate pay factor as shown in Figure 2. Although a pay schedule could be developed that follows the curved relation, a straight-line approximation is felt to be adequate for practical purposes. Since the primary points of interest are at the AQL and RQL, the linear approximation will be made to pass through these two points. Because the curve is concave upward, the linear approach will produce slightly inflated pay factors between the AQL and RQL.

By means of the economic approach, or one of the other methods, suppose that the desired pay factors at the AQL and RQL are determined to be as follows:

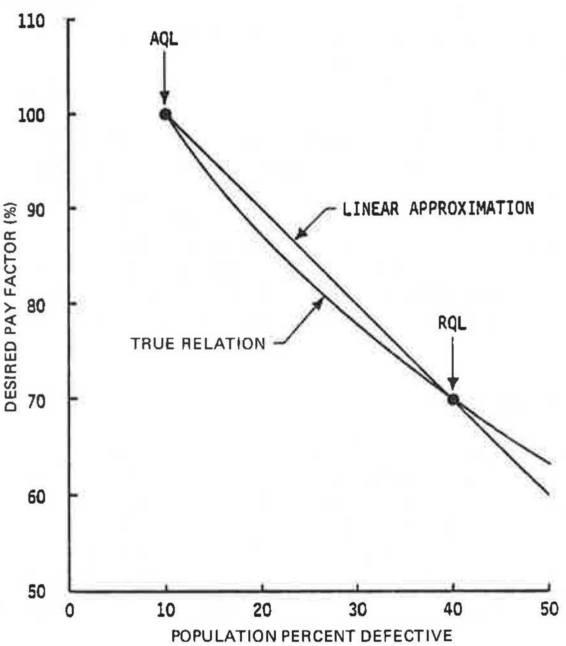
Quality Level	Percent Defective	Pay Factor (%)
AQL	10	100
RQL	40	70

Figure 1. Typical table used to estimate the percent defective of a normal population (standard-deviation method).

N = 7

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.63	49.25	48.88	48.50	48.13	47.75	47.38	47.01	46.63
0.1	46.26	45.89	45.51	45.14	44.77	44.40	44.03	43.65	43.28	42.91
0.2	42.54	42.17	41.80	41.44	41.07	40.70	40.33	39.97	39.60	39.23
0.3	38.87	38.50	38.14	37.78	37.42	37.06	36.69	36.33	35.98	35.62
0.4	35.26	34.90	34.55	34.19	33.84	33.49	33.13	32.78	32.43	32.08
0.5	31.74	31.39	31.04	30.70	30.36	30.01	29.67	29.33	28.99	28.66
0.6	28.32	27.98	27.65	27.32	26.99	26.66	26.33	26.00	25.68	25.35
0.7	25.03	24.71	24.39	24.07	23.75	23.44	23.12	22.81	22.50	22.19
0.8	21.88	21.58	21.27	20.97	20.67	20.37	20.07	19.78	19.48	19.19
0.9	18.90	18.61	18.33	18.04	17.76	17.48	17.20	16.92	16.65	16.37
1.0	16.10	15.83	15.56	15.30	15.03	14.77	14.51	14.26	14.00	13.75
1.1	13.49	13.25	13.00	12.75	12.51	12.27	12.03	11.80	11.56	11.33
1.2	11.10	10.87	10.65	10.42	10.20	9.98	9.77	9.55	9.34	9.13
1.3	8.93	8.72	8.52	8.32	8.12	7.93	7.73	7.54	7.35	7.17
1.4	6.98	6.80	6.62	6.45	6.27	6.10	5.93	5.77	5.60	5.44
1.5	5.28	5.13	4.97	4.82	4.67	4.52	4.38	4.24	4.10	3.96
1.6	3.83	3.70	3.57	3.44	3.31	3.19	3.07	2.96	2.84	2.73
1.7	2.62	2.51	2.41	2.30	2.20	2.11	2.01	1.92	1.83	1.74
1.8	1.66	1.57	1.49	1.41	1.34	1.26	1.19	1.12	1.06	0.99
1.9	0.93	0.87	0.81	0.76	0.70	0.65	0.61	0.56	0.51	0.47
2.0	0.43	0.39	0.36	0.32	0.29	0.26	0.23	0.21	0.18	0.16
2.1	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.03	0.02
2.2	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.0	0.0	0.0

Figure 2. Typical relation between percent defective and desired pay factor.



This leads to two equations in two unknowns that can be solved to give the slope and intercept of the linear function passing through these two points. This yields

$$PF = 110 - PD \quad (2)$$

where PF = pay factor and PD = percent defective.

Equation 2 can be regarded as a continuous pay schedule that awards payment as a linear function of the estimate of the population percent defective. As this estimate approaches zero, the pay factor approaches a maximum of 110 percent. The possibility of obtaining pay factors greater than 100 percent could be interpreted as a bonus provision if the specifying agency wished to treat it as such. However, for purposes of this paper, it will not be considered as a bonus because it is proposed that pay factors above 100 percent be used only to establish credit to offset pay factors less than 100 percent. Under this provision, the total payment for any billing period cannot exceed 100 percent.

A stepped pay schedule (equivalent to Equation 2) can be constructed, as shown below, in which discrete pay levels are associated with specific ranges of percent defective:

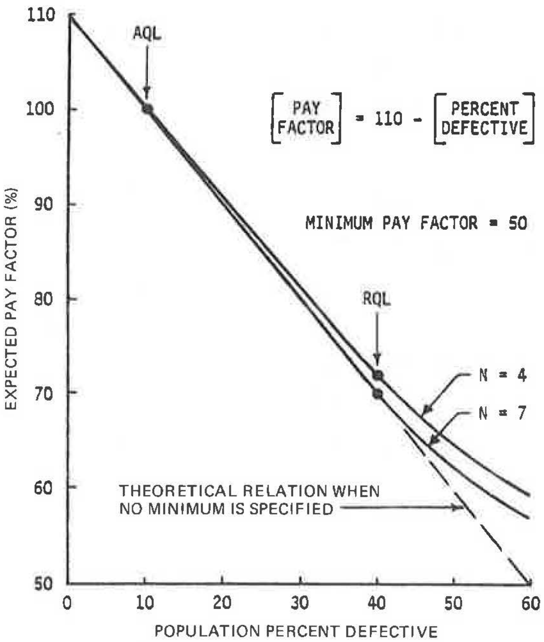
Percent Defective	Pay Factor (%)
<5	110
5-14.99	100
15-24.99	90
25-34.99	80
35-44.99	70
45-54.99	60
≥55	50

Frequently, stepped schedules are based directly on the quality index (for specific sample sizes) and do not include an estimate of the population percent defective. This eliminates the need for special tables to convert the quality index to percent defective but may be less meaningful to those who lack an understanding of the theoretical basis for this approach.

The minimum pay factor in the stepped pay schedule shown is 50 percent. If this same limitation is imposed on the continuous pay schedule given by Equation 2, it can be demonstrated by computer simulation that the two pay schedules have essentially the same operating characteristics curves as shown in Figure 3. Although the existence of a minimum pay factor is a biasing influence, both pay schedules remain unbiased at the AQL because they both provide expected pay factors of 100 percent at that point. At the RQL, the expected pay factor is very close to the desired value of 70 percent for a sample size of N = 7 but, for a sample size of N = 4, it is biased upward by about 2 percent. This slight amount of bias at the RQL can probably be tolerated but, if not, it can be removed by increasing the sample size or by lowering the minimum pay factor.

If no minimum pay factor is specified, both pay schedules have exactly the same operating characteristics curve for all sample sizes, which continues in a straight line down to a pay factor of 10 percent at 100 percent

Figure 3. Typical operating characteristics curves produced by unbiased pay schedules.



defective. This relation results from the fact that the pay factor serves as a linear function of the percent-defective estimate that, in turn, is an unbiased estimate of the population percent defective. When a minimum pay factor is specified, the operating characteristics curve becomes asymptotic to that value as the percent defective increases.

Although either type of pay schedule, continuous or stepped, will produce the same result in the long run, the continuous type may produce more satisfactory short-term results. With the stepped schedule, the difference in pay between two successive steps may be fairly substantial. Whenever the true population percent defective happens to fall close to one of the boundaries in a stepped schedule, it is largely a matter of chance whether the higher or lower pay factor will be received. Although this tends to balance out in the long run, it could work to the disadvantage of either party on a project that has a small number of lots. The continuous pay schedule, on the other hand, avoids this problem and is limited only by the precision of the estimate of the population percent defective.

REFINEMENTS OF THE UNBIASED APPROACH

One refinement, the setting of a minimum pay factor, has already been shown to have very little effect on the operating characteristics curves down to the RQL, provided that the minimum pay factor is set at a level somewhat below that associated with the RQL. The purpose for such a provision is to establish a minimum payment level for rejectable work that, for practical reasons, the specifying agency has allowed to remain in place. For example, if either unbiased pay schedule is used and the acceptance procedure has indicated a lot percent defective of 65 percent, the lot is considered to be rejectable and the specifying agency has the option to require that it be removed and replaced at the contractor's expense. However, in certain noncritical situations, the specifying agency may not wish to exercise this option. The continuous pay schedule of Equation 2 would award a pay factor of PF = 110 - 65 = 45 percent that, in this case, would be raised to the minimum level of 50 percent. If the acceptance procedure had indicated a percent defective of 50 percent, this would still be considered to be of RQL quality but would receive a pay factor of PF = 110 - 50 = 60 percent if allowed to remain in place.

Another refinement that may be desirable is a limit on the length of time or number of lots over which the contractor is allowed to apply credit obtained from pay factors in excess of 100 percent. The concern here is that a large accumulation of credit during the early stages of a project could diminish the incentive to maintain high quality standards later on and, possibly, the reverse situation might also occur. Because accounting procedures are frequently based on one-month billing periods, this may be a practical time interval within which to permit crediting. An alternate approach would be to establish a fixed number of lots in lieu of a specific time interval. In either case, however, it is desirable that the total number of lots within the credit interval be reasonably large to permit the averaging process to operate effectively.

Still another refinement that specification writers may wish to make is the setting of a lower limit below which a pay factor would not be eligible to receive credit. This must be pursued with caution, however, because it lowers the operating characteristics curve and may affect the pay factor at the AQL. It is recommended that this limiting pay factor be set no higher than that associated with the RQL.

A final refinement concerns the situation in which there are items of different unit value. If lots of substantially different value are allowed to be averaged together by the crediting process, the degree of incentive to produce good quality will be roughly proportional to the in-place cost of the lot. This may or may not be desirable from the specifying agency's standpoint and must be taken into consideration in deciding how the procedure is to be administered. If this approach were incorporated into a concrete specification, for example, it might be advisable to treat pavement and structural items separately because of the considerable difference in unit price.

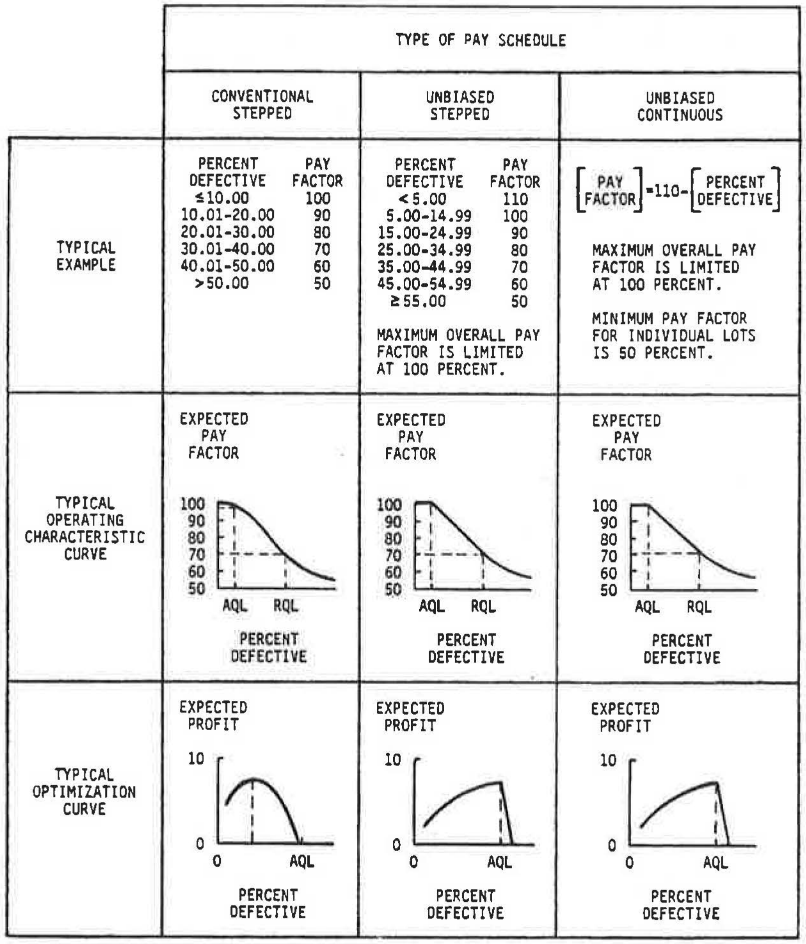
IMPLEMENTATION

The implementation of this procedure lends itself to a computerized approach, although a similar format can be prepared quite readily by hand. Either way, the basic input information for each lot would include the date, job and section number, contracting firm, item code, lot size, unit price, design value, sample size, and the individual test values. The itemized format would include all this information plus the calculation of the quality index, percent defective, pay factor, contract value, and the credit or reduction in payment for each lot included within the pay period. The net payment for the period would then be computed in a brief summary as shown below:

SUMMARY FOR PAY PERIOD 07/01/79 THROUGH 07/31/79

TOTAL NUMBER OF LOTS INCLUDED IN THIS PAY PERIOD	30
NUMBER OF LOTS ACCEPTED AT FULL PAYMENT OR EXTRA CREDIT	25
NUMBER OF LOTS ACCEPTED AT REDUCED PAYMENT	5
NUMBER OF LOTS JUDGED UNACCEPTABLE	0

Figure 4. Comparison of three types of pay schedules.



TOTAL CONTRACT AMOUNT FOR THIS PAY PERIOD	$827 300.00
TOTAL CREDIT	$ 17 983.16
TOTAL REDUCTION	$ 16 856.23
NET REDUCTION	$ 0.00
TOTAL PAYMENT DUE FOR THIS PAY PERIOD	$827 300.00

In this particular example, since the total credits exceeded the sum of the pay reductions, the contractor would have been entitled to a small bonus if such a provision were in effect. Because this is not the case, the contractor receives the maximum of 100 percent payment for this period.

EFFECT ON BIDDING STRATEGIES

It has been shown that conventional pay schedules may create problems for both the contractor and the specifying agency (4). The contractor who bids on and produces exactly at the AQL will fail to achieve the desired profit margin and may even suffer a loss. In order to maximize profits, it is often necessary to bid and produce at levels substantially above the AQL. As a result, both the quality and the price will be higher than the specifying agency anticipated and, in fact, may not be economically justifiable from a cost-benefit standpoint. However, these problems can be avoided with the use of unbiased pay schedules that produce an average pay factor of 100 percent at the AQL.

Typical operating characteristics curves and optimization curves for three types of pay schedules—conventional stepped, unbiased stepped, and unbiased continuous—are compared in Figure 4. The optimization curves shown in this figure represent the expected outcome for a concrete producer supplying structural grade concrete under a statistical specification. With the conventional stepped pay schedule, the producer must set the target strength well above the AQL in order to achieve the maximum profit margin. In contrast to this, the optimum point falls exactly at the AQL for the two unbiased pay schedules. As a result, unbiased pay schedules will tend to cause producers to control their production close to the AQL level.

When making the optimization calculations, the operating characteristics curves for the unbiased pay schedules are modified slightly to reflect the provision that the total payment for any pay period cannot exceed 100 percent. The curves in Figure 4 are identical to those shown in Figure 3 except that they plateau at a pay factor of 100 percent. It is this discontinuity combined with the 100 percent limit that produces the rather sharp peak in the optimization curves. Because of the very steep decline of the optimization curves as the percent defective increases above the AQL, the prudent producer may still wish to set the target strength above the AQL value by a small amount.

CONCLUSION

Conventional pay schedules are biased in that they award less than 100 percent payment, on the average, for product that is exactly at the AQL. Besides being basically undesirable, this bias can create difficulties for both contractors and specifying agencies in many instances. Bidding strategies may be adversely affected and the average quality level produced may be quite different from what specification writers expect.

Unbiased pay schedules can be developed by permitting pay factors in excess of 100 percent to offset lower pay factors with the provision that total payment for any billing period cannot exceed 100 percent. Pay schedules of this type award payment in direct proportion to the quality of the product up to an expected pay factor of 100 percent at the AQL. This overcomes a basic deficiency of conventional pay schedules and tends to encourage contractors to perform at or just above the AQL.

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Information Systems in Highway Construction: The State of the Art

Errol C. Noel

This paper is the result of an in-depth analysis of automated data-processing techniques used in managing information that is normally generated during highway construction. Such information includes material availability, results of material testing, and quality-control decisions. Information systems used by New York, Colorado, Pennsylvania, Louisiana, Illinois, West Virginia, Georgia, and Minnesota are briefly reviewed. Three categories of material and test data information (MATTI) systems are discussed: batch information systems, on-line interactive information systems, and on-line interactive laboratory information systems. These systems represent the state of the art. Research indicates that there is currently insufficient coordination among the states in sharing experience in the development and use of MATTI systems. Because MATTI systems compete with other large users of computer resources, the need for careful planning is emphasized so that too-sophisticated systems are not developed where less-sophisticated systems are more than adequate. The need for multidisciplinary involvement throughout systems development requires greater emphasis.

This paper is the result of an in-depth analysis of automated data-processing techniques used in managing information that is normally generated during highway construction. This information includes material availability, results of material testing, and quality-control decisions.

Information systems used in New York, Colorado, Pennsylvania, Louisiana, Illinois, West Virginia, Georgia, and Minnesota are briefly examined. Detailed descriptions of systems structure, use, and capabilities can be found elsewhere (1).

Three categories of material and test data information (MATTI) systems are analyzed: batch information systems, on-line interactive information systems, and on-line interactive laboratory information systems. These systems represent the state of the art.

BACKGROUND

The increasing need for improved quality of highway materials has led to a search for new and more effective quality-control methods (2,3). This search began in the early 1960s with the application of statistical analysis techniques to material performance data and culminated in the implementation of statistically derived specifications for highway construction materials and procedures. Applying statistical quality-control methods to specification writing has now become standard practice. However, there is a continued need for the periodic updating of specifications and for more efficient methods of providing basic data for justifying adjustments to existing specifications. Manual methods for satisfying this need have been less than satisfactory (4). Efficient manual processing and monitoring of material information are practically impossible for large highway projects because of the difficulty in retrieving historical data and managing the more current accumulation. This management problem is not only due to tedious data-gathering procedures but also to inconsistencies in test-result recording procedures and filing methods used by various administrative districts within each state.

Recent efforts to improve the materials management process have focused on the adoption of the systems engineering concept. With this adoption, it became apparent that high-speed data processing is necessary for improving the standard written specification and test-reporting methods (5). Thus, the trend in the 1970s has been the use of high-speed electronic computers for providing continuous feedback related to material use, test performance, availability, specifications, and any pertinent recorded construction information. A variety of materials and test data management systems are in use in several states. These include systems developed for specific situations and selections from generalized data-base retrieval systems marketed today under various generic names. Such names as data management system, generalized information management systems, and file management systems are popular terms used today.

Basically, computerized information systems belong in two categories: (a) information analysis and (b) information organization and file search. Analysis normally consists of assigning a name to each stored item and to each search request. Organization and file search are concerned with the manner in which the stored information is organized in the file and with the corresponding search procedures. The more elementary systems search sequential files, use simple record structures, and provide only rudimentary report formatting facilities. The more sophisticated systems manage files via indexes or links and function in an on-line or quasi-on-line mode.

PROBLEMS ENCOUNTERED

As the research was well in progress, it became apparent that data collection would be difficult. One of the most significant problems observed was a lack of detailed formal documentation of systems that were either in full operation, being developed, or in the implementation phase. Thus, informal reports designed for office use were used in compiling data on MATTI systems. A comprehensive literature search did not reveal any meaningful publication on the subject. This fact may have constrained the scope of the research, in that valuable contributions to the state of the art may well be lodged in MATTI systems other than those presented in this paper.

Some states, in the development of their system, used the most advanced technology in on-line interactive information systems. Others made use of the less-sophisticated batch information systems. These two extremes of approaches provide a wide range in the quantity of information made available but greatly reduced the possibility of a meaningful item-by-item comparison among systems. Although computer technology is the key to efficient storage and retrieval of information, it became apparent, as the research continued, that this technology was not being fully used by some states. Reasons for such practices could sometimes be traced to the reluctance of some transportation officials to use the state's centralized computer facilities because of the alleged inadequate service provided by some centers. Also related to these two major problems was the lack of uniform definitions for identical data-processing terms. These problems not only caused difficulty in seeking out meaningful information for each state but also restricted the research team from comparing all aspects of MATTI systems for all states visited.

CLASSIFICATION OF MATTI SYSTEMS

There is a wide range in the capabilities of MATTI systems used today. Therefore, the classification of these systems makes it easier to compare those that possess similar capabilities. Classification also has the advantage of presenting distinct levels of sophistication and the various approaches for achieving the same objectives. MATTI systems may be classified in various ways so that specific hardware, operations, and user characteristics are structured in categories of accomplishment. For this research, it is more meaningful to adopt a classification method that clearly depicts user-hardware interaction. With this idea, the functional classification presented below has been adopted.

1. A batch information system is the least complex level of computer processing. At this level, stored programs are executed to process transactions only from a list of job requests. Advanced batch programs perform more complex computation and produce detailed reports of management operations.
2. In an on-line interactive information system, the user communicates with the computer facility via terminals, and requests are processed as they arrive. The user usually gets quick responses that are often used to further query the system for additional information or provide some form of input and output. In order to accomplish this, it is necessary to provide some method of time sharing, unless the system is dedicated to a single user.
3. In an on-line interactive laboratory information system, laboratory technicians communicate with the computer facility via terminals. Information is also transferred automatically from material-testing equipment to the main storage of the computer. All stored information is retrievable but can only be changed by authorized laboratory technicians.

OBSERVED SYSTEMS

The analysis of the data collected in the eight states revealed that the application of a computerized information management technique to material-testing and construction data is the general trend. Three approaches have been identified: (a) batch information system, (b) on-line interactive information system, and (c) on-line interactive laboratory information system. Although there is adequate merit for using all of these approaches, there is no single approach that can be described as best. Each approach tends to satisfy specific conditions and has its advantages and disadvantages.

Batch processing was observed in Georgia, West Virginia, New York, and Minnesota. Although the actual operations of batch processing are standardized, there is some difference in the quality of service among these states. This difference appears to have no correlation with the computer hardware nor the expertise of the data-processing staff. The degree of emphasis on computerized highway construction information, the selection of highway data to be computerized, and the efficiency in data communication appears to be dependent on an undefined priority-determining mechanism adopted by the computer services centers and on whether the bureau of materials or material information ranks favorably on the priority list. Of the observed states using the batch-processing method, only West Virginia clearly enjoyed a good working relation with the state's computer service center. This good relation has fostered broad application of computer technology to diverse highway construction data and has generated a satisfaction about batch processing not yet observed in the other states. The West Virginia system can adequately accommodate the processing of information for which the turnaround time is not shorter than two days. Use of remote job entry-and-return peripheral hardware has potential for further shortening the turnaround time.

Colorado, Louisiana, and Illinois have adopted the on-line approach for processing materials and material-testing data. These states have capitalized on the instantaneous reporting and sorting capabilities of on-line systems and are experiencing relative success in applying the methodology to data required on a demand basis. A difference in the choice of computer hardware and information coverage exists. MATTI systems developed by these states possess similar data-interrogation capabilities (the ability to search, analyze, select, and print reports) but have adopted independent approaches for accomplishing the same objectives.

Of the eight states visited, only Pennsylvania developed an on-line interactive laboratory information system. This type of system is an outgrowth of the need to reduce laboratory paperwork via automatic transfer of test results from equipment to computer through which instantaneous reporting is possible. The system features minicomputers at the central laboratories and has distributive processing capability.

Pennsylvania's automated laboratory testing and reporting system is a classical demonstration of the use of minicomputers to complement batch operations that are scheduled in accordance with priorities determined by an external centralized data-processing unit. Of course, at the time of this reporting, the Pennsylvania system was still growing. Even then, some data-interrogating features were identical to those systems that used only giant equipment.

BATCH VERSUS ON-LINE SYSTEMS

On-line interactive methodology with applications to material information has been observed in Colorado, Pennsylvania, Louisiana, and Illinois. The other states visited—Georgia, West Virginia, New York, and Minnesota—have favored batch processing. However, regardless of sophistication, the trend is in the direction of automatic management of highway construction information. The two distinct approaches offer different capabilities, but the on-line method has a superior capability. However, the superior capability of the on-line systems is only valuable if (a) there is need for quick response, (b) there is an assurance that new information is filed quickly, and (c) existing files are continuously updated.

On-line systems are noted for great demands on operating funds and computer time. Although on-line processing may provide immediate response to an information request and is amenable to nonskilled users, there is a tendency for developers to apply the technology to almost all construction information—even information that is rarely needed on demand. There is a large volume of construction information for which delivery within several days is viewed as timely and has no negative effect on existing quality-control and quality-assurance programs. For information with high flexibility in delivery time, a well-designed batch operation can provide a more-than-satisfactory performance.

On-line interactive information systems and on-line interactive laboratory information systems are inherently more complex than batch information systems. All interactive systems respond in an almost instantaneous manner. They often maintain a direct interface with the intimate originator (the customer) of a transaction, accept whatever demands are placed on it at the instant they occur, and maintain secure control over its data base and processing environment so long as there is a customer expecting service. A transaction initiated at one point in a day may interact with several other transactions occurring at other times of the day. All of these transactions affect a common data base. The system must maintain control over these interactions until the day is over. When all customers obtain answers for the services they requested, the system can be safely locked up. Any failure in the system that occurs during this entire stream of interactive processing may have an immediate and serious effect on the ability of the various users of the system to continue their daily activities.

This characterization of on-line information systems is in sharp contrast to a similarly structured characterization of batch information systems, which, by definition, aggregate transactions as they arrive into efficient processing groups. Inherent in the concept of batch processing is its relative inexpensiveness and the presence of several protective stages between the originator of the transactions and the system. Data provided by the originator are always edited, converted to machine format, and accumulated into batches of similar data many hours or days before processing.

Batch processing is almost always sequential, file-oriented, and multistaged; hence, the interaction between various transactions is trivial. Because of this staged handling of data, reliability and security are easily provided in the passing of data from one file to another with the maintenance of several generations of data for backup. The failure of a computer system in a batch-processing environment is often unobservable to the outside user because of the expected length of time between submission of each transaction and the return of results and the relative simplicity of backing up one batch-processing computer with another.

In contrasting on-line interactive system operations with batch processing, one finds the latter to be composed of simple questions and answers with a few interdependencies. Whereas the on-line interactive system answers more complicated questions, it requires much more complex answers with many greater interdependencies. For example, if a processing step is omitted in the initial design of a batch-processing system, the problem can often be corrected with an additional step. On the other hand, if a similar kind of error is made in an on-line interactive system, corrections may require redesign of the entire data base and have a serious impact on the equipment requirement and the performance of the system. If a batch-processing application exceeds its core memory allocations, the problem can be easily solved by fragmenting the application into several runs—the only difference being a slight increase in total processing time. The on-line interactive system makes highly integrated use of core memory, and, if the application exceeds the core budget, it may be necessary to get more physical core memory because no practical way may exist to fragment the application after it has been designed and programmed.

In summary, it is much more difficult to design an on-line interactive system than to design a batch-processing system because the entire on-line interactive system design must proceed from the outset as a completely integrated entity that considers all possible types of transactions, alone and in combination. Interactive systems generally cannot be handled by fractionalization into sequential runs and, hence, a failure to achieve system performance objectives at the outset cannot be corrected merely by spreading the work over a longer period of time. Throughout all phases of the system design (from concept through implementation to test), the system will be in much more intimate contact with the user environment than in a batch-processing application. A correspondingly higher quality of effort at each stage is required to ensure success. The development organization will be much more exposed to outside criticism than in the case of batch applications.

INTERDISCIPLINARY TEAM IN SYSTEM DEVELOPMENT

The quality of the system design and, ultimately, of the system is highly dependent on the effectiveness of the dialogue between members of the design team and users. During the design effort, both parties are going through a process of problem solving and learning together. The design team learns more about the characteristics and idiosyncracies of the operating environment of the agency and about which computer-based functions will be critical, marginal, or not useful. The user, in turn, learns about the capabilities and limitations of the design team and the developing system and also about the cost and feasibility of various functions. It is critical, therefore, that the design team foster and nourish a cooperative learning climate characterized by mutual respect and confidence. Accomplishing this learning climate is facilitated by a team equipped with computer expertise as well as a knowledge of highway construction information and the expectation of various users.

At the outset of the design process, there may inevitably be considerable ignorance on both sides. Because people do not like to appear ill-informed, a defensive posture that inhibits the free exchange of information and ideas can easily be developed. This problem has no textbook solution, given the variety of possible personalities and situations. Suffice it to say that the interdisciplinary team should be willing to listen and should be adept at winning and keeping the confidence of the users.

A more straightforward aspect of coping with the learning process is for the interdisciplinary team to identify major areas of ignorance early in the initial design stage. The team, for example, may need to learn a lot about the flow of work, document preparation, and decision-making or management control processes in a user area. Correspondingly, the user may have considerable difficulty in stating his or her output requirements because of the user's unawareness of the capabilities and limitations of hardware and software. Once the major gaps in knowledge are identified, a variety of frontal attacks is appropriate—for example, data collections, interviews, seminars, sample program and output discussion, and work experience. It is important not to waste the user's time by using ineffective techniques or by rehashing old materials.

For the eight highway agencies covered by this research, two distinct data-processing environments were observed. The first environment is that in which the agencies make use of the state's or transportation department's centralized data-processing center. With this arrangement, the highway agency performs all tasks except those related to the mechanical information processing performed by computers and their peripheral equipment. The center provides processing services by means of terminals and transmission devices. The second environment is one in which the user-agency controls its environment. This environment allows the agency to be independent of other agencies that use a centralized data-processing center and to be independent of the needs of the centralized center for keeping its machine operational and upgrading its capabilities. For example, in periods when operators of centralized data-processing services are experiencing heavy demand for services, a problem of assigning priority develops, and operators usually take control of the machines and, thus, hinder first-call-first-served operations. This affects low-priority users.

Another disadvantage in using a centralized processing center can be identified as priority interruptions during development. A new application implemented by another agency may require relatively high machine priority in order to operate effectively in such an environment. This is most often true for an on-line application. This high-priority requirement may well interfere with other users of the center and cause conflicts between the needs of users. In addition, it may be that the response time of the new application suffers from contention with other applications for system resources, such as the operating system and direct access storage. Hence, the effect on the response time of a new application being implemented in an environment of centralized processing is relatively uncontrollable, compared with a situation in which the machine is owned and operated by an agency.

Moreover, the deciding factor in justifying the use of an in-house machine versus centralized data processing can be traced to cost. In analyzing the hardware and operating costs for implementing a large in-house machine, the agency or bureau must decide whether to use a full-cost or an incremental-cost approach. Full costing would charge all applications for the resources that are used directly plus a proportionate share of all other resources in the system that are shared. For example, applications would be charged for their use of the computer printout unit and peripheral equipment plus a portion of operating system memory space, floor space occupied by the machine, heating and cooling, and operational staff. It may be desirable in some in-house environments to consider incremental costing, but it must be recognized that there are a number of potential problems raised by this approach.

First, computer personnel expenditures constitute more than 50 percent of a total automated data-processing (ADP) budget and are greater than one-and-a-half times the expenditure for hardware. Thus, excluding these charges along with charges for floor space and system resources used by the operating system implies excluding the majority of all real costs. Second, the incremental-cost approach could be unfair to other system users. In addition, as the needs of the system user grow, additional memory and peripheral devices may have to be purchased. The incremental-cost users may have to justify this cost, and the costing approach may be converted from incremental costing to full costing. Finally, the degree of control of an in-house computer versus centralization could be based on the need to isolate specific applications from the effects of other applications in a central environment.

SELECTING A MATTI SYSTEM

The degree of sophistication required for computerized management of construction information should be based on the following factors:

1. Willingness of employees to abandon old methods and adopt the proposed method (expressed willingness can be very deceptive; it is the spontaneous willingness resulting from high employee morale that should be of great concern);
2. Level of effort that will be made to inform and instruct all relevant personnel about the aims, objectives, operations, and procedures of the new system (a poor effort could result in inadequate use of a highly sophisticated system, thus nullifying anticipated benefits);
3. The responsiveness that is required for critical information needs (it is pointless to have a system that is capable of instantaneous on-line reporting if the same information is infrequently required and reports can be supplied in good time by less costly and sophisticated systems);
4. The quality of countinued training required to involve newly recruited personnel and to maintain the information-processing expertise, regardless of the job-changing habits of key technical personnel;
5. The quality of service available from a general computer center compared with that of a special local computer for providing ADP services to the suborganizational level with the responsibility of managing material information;

6. Whether direct user access to hardware is desirable and justifiable, compared with the creation of special staff positions for operating the computer machinery and processing information;
7. Future trends in the need for certain types of material information and the decreasing need for management of same;
8. Factual determination that current information is too voluminous to be manually or batch processed in a timely manner;
9. Availability of sufficient development, implementation, and operating funding (when funds are scarce, there is a tendency to merely search for inexpensive equipment to do the job, and often its compatability with existing equipment and future expansion is neglected; a staged introduction of equipment with long-term use should be considered so that both equipment purchase and data coverage can be phased; an open-ended system is most amenable to staged implementation); and
10. Experience of other states, which is very valuable.

CONCLUSIONS

The reasons for developing a computerized materials and test data information system vary among states and depend mainly on the expertise of the technical staff and the availability and willingness of administrators to provide funds for its development and implementation. However, there are several essential benefits that are often quoted as the basic motivators behind computerization. It would be fair to say, though, that how well these benefits are realized depends on system sophistication and user acceptability. Probable benefits that can be derived from a computerized MATTI system include the following:

1. Simplifies data documentation;
2. Improves information accuracy;
3. Frees engineers involved with data manipulation so that their time can be directed at more creative exercises;
4. Provides timely access to stored data for verification of on-going operation, research, problem solving, and planning;
5. Reduces number of people needed for processing data;
6. Offers better control of the quality of highway construction materials;
7. Provides efficient and effective transfer of information;
8. Provides improved and timely monitoring of construction projects for compliance with specifications;
9. Maintains a continuous log of basic construction materials for specification development and adjustment;
10. Considerably reduces time spent in manually typing, auditing, or spot-checking test reports;
11. Eliminates final manual audit of testing compliance and the accelerated certification of construction items to the Federal Highway Administration (FHWA);
12. Centralizes storage of all highway construction information; and
13. Provides a more meaningful continuous record of the pattern of variation in personnel (contractors), materials, and machinery for subsequent statistical quality-control evaluation.

There is no doubt that MATTI systems have tremendous capabilities for managing information. But capability alone does not guarantee efficient system use. Hence, there is a need to encourage, when possible, meaningful participation of all potential users of a proposed system during its planning and development. An interdisciplinary effort has tremendous potential for reducing misunderstandings and petty favoritism.

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