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COST EFFECTIVENESS ANALYSIS OF COMPLEX REPAIR PROCESSES USING GRAPHICAL EVALUATION REVIEW TECHNIQUE (GERT)

Alfred Iwersen, Jr.

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

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This paper presents an approach to analyzing the costs attributable to sources of errors in complex multi-level repair processes which have many feedback loops and branching points. It is shown how computer simulation of such processes can be useful in identifying those general areas or subprocesses, which would, if improved slightly, result in major improvements in cost effectiveness. A hypothetical repair process is presented in the paper and is used to demonstrate a method of analyzing the costs associated with errors that are committed in the hypothetical process. The computer simulation technique shich is used is called Graphical Evaluation Review Technique (GERT), which has been developed by A. A. B. Pritsker. The technique offers the basic advantage exploiting a canned FORTRAN IV simulation program called Q-GERTS.

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By

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FOREWARD

The need for this technical report was established by Air Force Institute of Technology student research reported in two theses from the School of Systems and Logistics. Persons desiring detailed information about how the research project was developed and applied to an Air Force problem may secure the theses from the Defense Documentation Center (DDC), Cameron Station, Alexandria, Virginia 22314. The pilot study was conducted by Major C. R. Waterman, Jr. and Squadron Leader E. B. Watson (AD 787199). The follow on study was conducted by Major A. Iwersen, Jr., Captain J. E. Brawner, Jr. and Captain R. R. Berry (AD B003151L). Permission to secure the follow on document from DDC may be granted by Aerospace Guidance & Metrology Center (AGMC/XRXE), Newark AFS, Ohio 43055.

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INTRODUCTION

This paper essentially offers a practical approach to developing and using a computer simulation model to study certain costs incurred during complex depot-level maintenance operations. The rationale for offering this approach is implied below.

> When one asks if a given management situation can be modeled in the framework of linear programming, or waiting line theory, or inventory theory, what is really being asked is whether some of these structures will give a head start in the evolutionary process of obtaining a useful model [7:B-709].

It is the objective of this paper to provide a framework which will give a "head start" to analysts studying the costs associated with complex depot-level maintenance activities.

Analogy or association with previously well developed logical structures plays an important role in the determination of a starting point (7:B-709). In this paper, it is shown how certain concepts and a computer simulation model can be used to study the costs of a hypothetical complex repair activity. This paper describes how these concepts and the model can be practicably applied in similar cases. Basically then, the approach presented herein, should serve as a general guide to analysts who, through analogy or association, recognize the applicability of the approach to Department of Defense (DOD) depot-level repair activities.

Since the approach involves computer simulation, the limitations of this technique must be addressed. Most operations research analysts look upon digital computer simulation as a "method of last resort." There are two basic reasons for this gloomy attitude. The first reason is the nature of most simulation results. When the model includes uncertain events, the answers stemming from a particular simulation must be viewed only as estimates subject to statistical error. Therefore, when conclusions are drawn from simulation results, the accompanying random variations must be carefully assessed (11:500-501).

The second reason for diffidence about simulation involves the nature of the applications themselves. If a system is so complicated by uncertainties, dynamic interactions, and complex interdependencies, that other operations research tools cannot be used, then the required model-building effort and the subsequent analysis of the simulated results are likely to be difficult (11:501).

Recognizing these factors in a simulation, the analyst is confronted with the problem of developing an acceptable level of confidence in the simulation model. To develop such confidence three general categories of tests are often useful. First verification tests can be performed to insure that the simulation model behaves as intended. Second, validation tests can be conducted to determine the agreement between the behavior of the model and the real repair process. Finally, the simulation results can be statistically analyzed. In this paper, verification and validation procedures will not be discussed in detail.

Perhaps the most useful aspect of the approach described herein is the sensitivity testing capabilities it offers. The computer simulation model, once it has been developed, can provide comprehensible answers to spontaneous "why does..." and "what if..." questions without requiring mammoth crash efforts. Thus, it can provide analysts with a quantitative assessment of what risks are at stake with different actions, what changes in direction are likely to yield cost-effectiveness improvements, and what avenues are promising for further investigation (11:535).

COMPLEX DEPOT-LEVEL MAINTENANCE PROCESSES

Although the general objectives of a repair facility may be thought of simply as "to make bad components good," four more specific objectives of a special repair facility have been enumerated by Genet (5). These objectives are:

a. To determine the faults of units received with maximum accuracy and a minimum of cost and time.

b. To prescribe the repair action(s) most likely to correct the faults without adding additional faults in the process.

c. To implement the prescribed repair actions in an efficient and effective manner.

d. To assess the likelihood of the completed repair being successful for a reasonable period of time [5:4].

Considered individually, these general objectives may be related to four major tasks performed in a repair process: (1) Receipt Testing, (2) Fault Diagnosis, (3) Repair and (4) Final Testing. Together these tasks may be considered as a single dimension, that of the cost effectiveness of the process as a whole. The cost effectiveness of the complete process is dependent upon the effectiveness and efficiency with which each of the objectives is attained.

Further consideration of these objectives reveals the possibility that, in the process of repairing a component, some errors will be made. The specific component faults may not be determined accurately, the prescribed repair action may not correct the faults, or the assessment of the "success" of the repair may not be accurate. If any or all of these types of errors occur, it is evident that the repair process is not being executed as efficiently, or as cost-effectively, as possible.

Consequently, it is evident that one of the many reasons for conducting a detailed examination of a repair process is to identify ways in which the repair objectives may be achieved at a lower cost. Genet identifies the objectives of gross cost-effectiveness analysis as to:

> ...identify the general areas or subprocesses which would, if improved slightly, result in major improvements in cost effectiveness, and conversely, areas or subprocesses which, if greatly improved, would have little effect on the overall effectiveness [3:4].

This general concept by Genot will be presented later as the foundation for a specific concept of "criticality" upon which this paper will largely be focused.

a. The multi-level nature of inertial guidance systems. These levels are usually classified as systems level, major subsystem level (e.g., an IMU) and component or module level. The latter two are appropriate to this discussion.

b. The variable performance over time of the precision instruments being repaired, resulting from the mechanical precision of the instruments themselves. These instruments are repaired at the lowest level, and their variability tends to make the performance of high order assemblies also variable over time.

c. Tight, multi-parameter, performance requirements necessitating many tests at each level of repair. Many of these tests are dependent, in that the accuracy or lack of accuracy of a test is likely to affect the outcomes of another test at the same level or at a higher level [6:1-2].

When these three aspects are considered together in terms of any complex depot-level repair process, the interdependence of individual components, tests and repair levels becomes obvious. Components installed or tests performed at the higher repair levels are dependent upon a progressively greater number of component installations or tests performed at the lower levels. At the subsystem level, the overall performance of the component is dependent upon the work done at all lower levels in the process. Final classification of the finished product, as either satisfactory or not satisfactory, may depend on some action that has taken place at a lower level (6:1-28).

Because of this interdependence between stages of the process, it is evident that the process should be considered as a complete system whenever an attempt is made to identify potential problem areas (3:2). Even more importantly, the relationship between actions performed at the various levels and those performed in different stages of the process at both the same level or successively higher levels should be established in terms of their effect on the total process.

While the importance of the interdependence between stages has been expressed in terms of work performed at each stage, reexamination of the causes for complexity quoted earlier will reveal that the errors introduced at any stage were of primary concern. Potential sources for error in a process, and their effect on the overall process will now be discussed.

SOURCES OF ERRORS IN A COMPLEX PROCESS

The potential sources of errors, or general areas for improvement, in a complex repair process may be broadly classified under the following headings:

a. Test and calibration,

b. Component reliability (subassemblies and components of the IMU),

c. The flow of the repair process, which includes the work sequence, order of tests and reassembly procedures [2].

Each of these major areas will now be discussed in some detail.

Test and Calibration

As stated earlier, two of the objectives of a special repair facility are to determine the faults of units received with a maximum of accuracy and a minimum of cost and time, and to assess the likelihood of the completed repair being successful for a reasonable length of time (5:4). These objectives relate specifically to Receipt Testing, and Final Testing respectively, however as has been established in the previous section, many other tests may be involved in the repair process. Insofar as the adequacy of any test performed may have a major effect on the remainder of the process, each test performed must be regarded as playing an important role in the overall success of that process (4:1).

Testing of components in a multi-level repair process is in itself a complex subject, and a number of different types of tests with different purposes have been identified (4:11). However for the purposes of this paper, two major characteristics, or shortcomings, appear to be important. These may be classified under the general headings of:

a. Lack of Validity,
b. Lack of Repeatability [6:18].

The classification of Lack of Validity is used here in a general sense, to describe tests which for some reason fail to provide an accurate identification of the conditions of the component or system being tested, because of some inherent weakness in the test. In this sense Lack of Validity subsumes the concept of Lack of Repeatability, which refers to the inconsistency of a test, or more simply the characteristic of giving different results at different times when two otherwise equivalent units are being tested (6:18; 4:1-36).

The primary purpose of a test used in a complex repair process is to provide some form of decision rule, to assess future actions to be taken on the component being tested (4:5). Since the decision taken at any point in the process concerning future action will almost certainly influence the remainder of the process, it may be assumed that a test which leads to the wrong decision will almost certainly lead to some unnecessary work and unnecessary cost. It would follow then that identification of those tests possessing either or both of the characteristics described above is necessary in analyzing the overall cost effectiveness of any process.

Component Reliability

Earlier in this paper, one function of a repair process was identified as the replacement of malfunctioning parts with new or rebuilt parts. The reliability, or lack of reliability, of these parts leads to the next major source of errors in a process, in the sense that the total reliability of the system may be assumed to be dependent upon the reliability of each and every part, and failure of any part later in the repair process can cause failure of the entire system (6:25).

The effect of using unreliable parts in a repair process has been demonstrated in a recent study by Burt and Benbow (1). In this study the authors created the concept of Costly Replacement of Inexpensive Parts (CRIP) and tested a hypothesis that a variation in the reliability rates of two low cost bearings ($38.00), built to identical engineering specifications by different manufacturers, would have a significant effect on the overall cost to repair G-200 gyros at AGMC (1:15).

Using historical data on the repair process at AGMC, Burt and Benbow showed that a difference of 25 percent in the reliability rate for the two bearings resulted in a difference in average cost to repair of approximately $600.00 per gyro. Over a two year period the additional cost of using the lower reliability bearing was some $800,000.00, of which only $60,000.00 was attributed to the extra cost of low reliability bearings required to complete the repair. The remaining $740,000.00 was incurred in additional process time caused by the failure of the bearing at some later state in the process (3:60).

Although the results of this study cannot be generalized beyond the G-200 gyro repair process, they do indicate that the overall cost of a complete process can be significantly affected by the reliability of a single component used in that process. Consequently in considering the effects of "errors" introduced at various stages of a process, it should be recognized that introduction of an error in the form of a low reliability component may have a significant effect in terms of the success, and cost, of the complete process.

THE CONCEPT OF CRITICALITY

In the preceding sections the complex interrelationships which exist within a repair process have been examined in some detail. Additionally the effect of making errors in the process, and particularly errors arising from invalid or non-repeatable tests or introduction of low reliability components, has been addressed in terms of the effect of the error on the ultimate success, and cost of the complete process.

The necessity for establishing these relationships was covered earlier in a different form, as the objectives of gross cost effectiveness analysis of a process. These objectives repeated here were to:

> ...determine the general areas or subprocesses which would, if improved slightly, result in major improvements in cost effectiveness, and conversely, areas or subprocesses which, if greatly improved, would have little effect on the overall cost effectiveness [3:4].

The statement of these gross objectives originates from the concept that only a few of the stages or elements in a process are critical to the overall cost effectiveness of that process. In somewhat different terms, improvement of errors or inefficiencies in only a few of the individual stages or elements will yield significant savings in the overall cost for the process, while improvements or elimination of errors in the remainder of the stages or elements will have little overall effect. This overall concept has been stated in terms of a complete repair process as follows:

> Given some complex multi-level repair process with many feedback loops and branching points, given hundreds of different sources (or possible improvements) of error at various points in the process and given that an accurate flow model of the process were available that included all the error sources, then the sensitivity of the overall repair process to the reduction and/or elimination of each error source could be examined. It has always been found in the past, and can be substantiated theoretically, that all complete processes are sensitive to changes in just a few of the many hundreds of parameters, and that, in fact, the total elimination of most of the errors will have no appreciable effect whatsoever on the overall process [6:23-24].

The application of this concept to a particular process, to determine whether critical stages or elements actually exist and, if so, where they exist, is governed to a large extent by the specific variables associated with that process. However, once the repair process has been adequately defined, and the relationships between individual stages (or the error sources) established, the concept of criticality may be tested for that process if a means for determining the effect of making an error, or alternatively not making an error, at each stage can be established.

THE CONCEPT OF FEEDBACK

Figure 1 depicts a hypothetical repair process consisting of seven repair stages. In this paper such stages represent groups of closely related maintenance tasks to which cost or cost distributions can be attributed. That is, whenever a system (component, equipment, etc.) is processed through such a stage, cost can be assigned.

Ideally, after a system entered the hypothetical repair process, it would always move from left to right. Thus it would move from stage 1 to stage 2; then to either stage 3, 4, or 5; next to stage 6; and finally to stage 7. If, however, an error were made while the system was undergoing repair, then some maintenance tasks would have to be repeated. In effect, the system under such circumstances would be moving from right to left. Such movement is represented in the figure by the "feedback" paths marked A, B, C and D. Clearly, the greater the incidence of errors, the greater the incidence of feedback along such paths.

In the remainder of this paper a distinction will be drawn between individual feedback paths and sets of feedback paths. As the name implies, an individual feedback path is a path such a path A, B, C or D in figure 1. A set of feedback paths consists of all feedback paths which terminate in one stage. Thus one set of feedback paths in figure 1 is comprised of paths A, C and D.

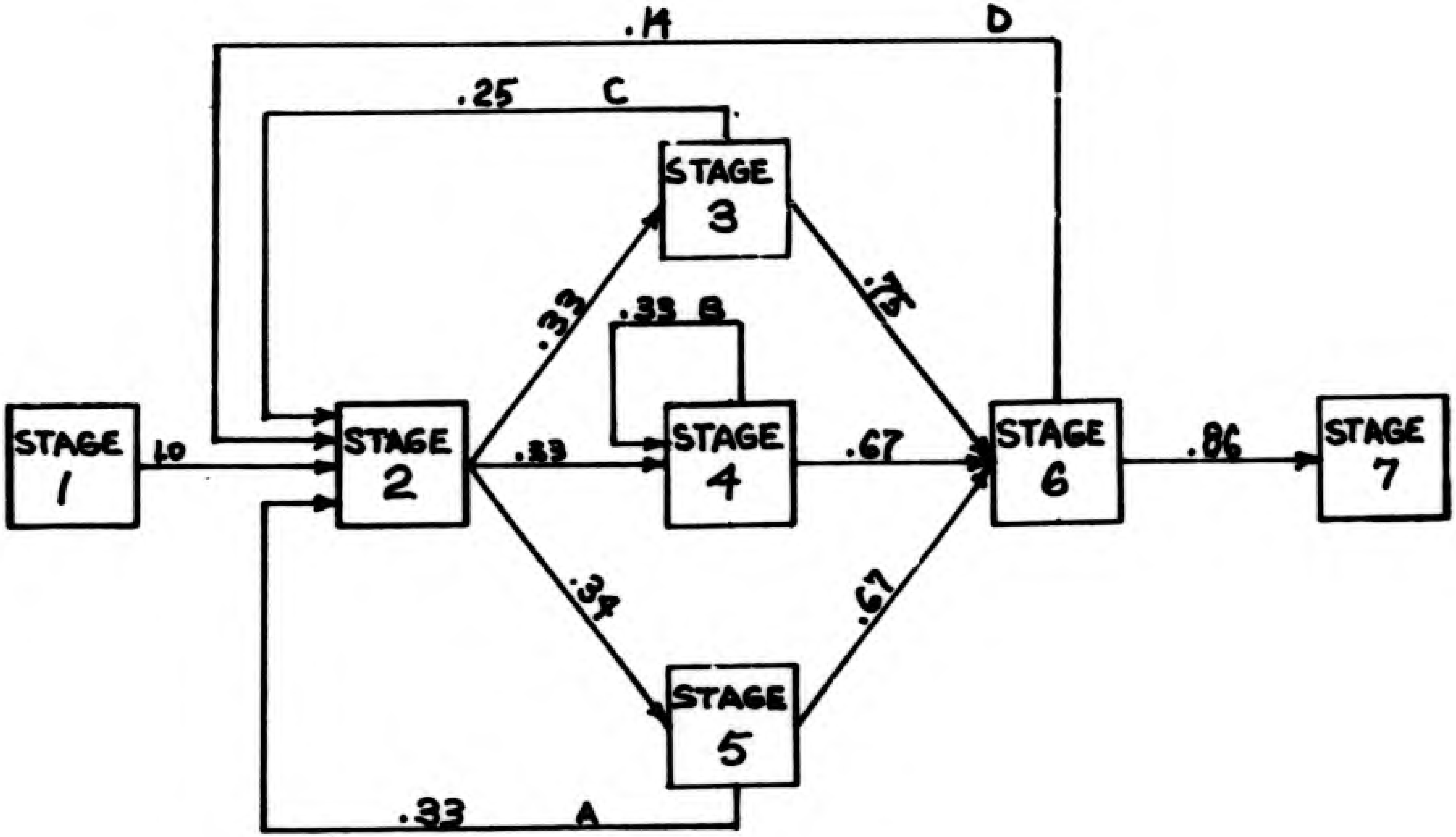

Figure 1
Hypothetical Repair Process with Transition Probabilities

Another set simply consists of the individual feedback path B.

Critical Feedback

This paper applies the Concept of Criticality to the feedback which exists in a repair process. A critical individual feedback path is said to exist when a simulated reduction in feedback along that individual path leads to a significant reduction in the simulated cost of repair. In figure 1, the feedback path C from stage 3 to stage 2 would be considered a critical individual feedback path if a significant reduction in variable cost occurred when feedback along the path was reduced.

A set of feedback paths is said to be critical if a simulated reduction in feedback within the set leads to a significant reduction in the simulated variable cost of repair. The set of feedback paths, A, C and D in figure 1 would be considered critical if a simulated reduction in feedback within the set resulted in a significant reduction in variable cost.

TRANSITION PROBABILITIES

In some complex repair processes the system does not "flow" through each stage of the process; instead, it may flow through only several. For example, in figure 1, if stage 2 were a diagnostic test stage then, flow sequences might be somewhat determined by that stage. That is, the test could indicate that the system should go to stage 3;

or it could indicate that it should go to stage 4; or perhaps stage 5. Thus, one flow sequence might be from stage 1, to 2, then to 3, on to 6, and finally to stage 7. Another sequence, this one with feedback, might be from stage 1 to 2, then to 5, back to 2, then to 4, and on to 6 and 7.

If maintenance records have been kept that accurately show the sequence in which each system has flowed through the process, then it is possible to assign transition probabilities to each path. A transition probability could for example be assigned to the path between stage 2 and stage 3 in figure 1. If it were 0.33 then one could conclude, given the system is in stage 2, there is a probability of 0.33 that it will go to stage 3. A technique for developing these probabilities is discussed next.

Calculating Transition Probabilities

To develop transition probabilities it is suggested that the maintenance record for each system in a population or in a representative population sample be reviewed in detail. Such records must show how each system flowed through the process.

A convenient method for tabulating such data is through the use of a transition matrix. A transition matrix is shown in figure 2 which would be useful in tabulating transition data for the hypothetical flow process shown in figure 1.

TO

FROM

	1	2	3	4	5	6	7	ROW TOTALS
1		𝍸I						6
2			III	III	III			9
3		I				III		4
4				I		II		3
5		I				II		3
6		I					𝍸I	7

Figure 2

Transition Matrix for Data Collection

The row titles on the left in figure 2 are the stage numbers *from* which systems leave; the column headings are stage numbers *to* which systems go. Thus from the figure it can be seen that six systems went from stage 1 to stage 2 of the hypothetical repair process. Similarly, three systems went from stage 2 to stage 3.

Developing transition probabilities, once the data is in the matrix, is relatively straightforward. It is only necessary to divide each number in the matrix by its corresponding row total. Thus the transition probability of moving from stage 2 to stage 3 would be 3/9 or 0.33. Figure 3 shows the transition matrix with probabilities entered in it.

Figure 1 shows the hypothetical repair process with the transition probabilities associated with each path. The decimal number over each path is the transitional probability associated with that path.

Q-GERTS

Introduction

CERT is a acronym for Graphical Evaluation Review Technique. This technique was designed for analysis and study of stochastic networks composed of nodes and branches (8). GERT networks and associated computer simulator programs were developed by A.A.B. Pritsker, who described the networks as follows:

TO

FROM

	1	2	3	4	5	6	7
1		1.00					
2			0.33	0.33	0.34		
3		0.25				0.75	
4				0.33		0.67	
5		0.33				0.67	
6		0.14					0.86

Figure 3

Transition Matrix with Probabilities

> GERT networks include the concepts and symbolism necessary to analyze complex systems involving logical operations, different types of branching feedback and non-Markovian processes [9:1].

He went on to describe GERT Networks Characteristics as follows:

> 1. Branches represent activities and are depicted graphically by solid lines. Branches are characterized by:
>
>   a. A probability of being selected;
>
>   b. A time required to perform the activity represented by the branch. The time is specified by defining a parameter set number and distribution type;
>
>   c. A counter type to identify the branches belonging to a particular group of branches; and
>
>   d. An activity number.
>
> 2. Nodes are characterized by:
>
>   a. The number of 'releases'* required to realize the node for the first time;
>
>   b. The number of releases required to realize the node after the first time;
>
>   c. The halting (removal) of activities incident to the node when the node is realized;
>
>   d. The method for scheduling the activities eminating from the node (DETERMINISTIC or PROBABLISTIC);
>
>   e. The special function it performs in the network, e.g., source, sink, statistics or marking; and
>
>   f. The statistical quantities to be estimated for the node if it is a sink or statistics node....
>
> 3. Modification of the network is based on the completion of an activity. A dashed line is used to depict a network modification. The number of the activity causing the modification is placed in a square by the dashed line.

*A 'release' for a node is defined as a completion of an activity that is incident to the node. A node is realized when the specified number of releases is obtained [9:2-3].

The versatility of GERT in modeling complex systems reportedly led to the consideration of the modeling of networks of queues and their associated service operations. It therefore became necessary to define additional new nodes called Q-nodes and S-nodes. GERT networks augmented by Q-nodes and S-nodes were then referred to as Q-GERT networks. The associated computer program for analyzing Q-GERT networks is called Q-GERTS (9:1-2).

According to Pritsker:

> The basic premise of the Q-GERT network language is that a wide class of queuing systems (and other types as well) can be modeled in network form. The Q-GERT network language is designed to simplify the model-building process and to serve as a communications device between the developers of the model and the individuals responsible for using the outputs of the model....
>
> The fundamental philosophy of network modeling is the separation of modeling activities from analysis and programming activities. Basically this assumes that once a network model has been constructed, statistical information concerning the network model can be obtained through the use of 'canned' computer programs. For Q-GERT network models, the Q-GERTS simulation program is used for this purpose. (Since Q-GERTS is written in FORTRAN IV, no special compiler is required for its operation.)
>
> The segregation of modeling and analysis procedures does not relieve the modeler entirely from specifying the types of statistics required to solve or resolve the problem under study. In fact, it emphasizes this modeling task by requiring the modeler to prescribe the problem-related statistical quantities to be collected at the nodes of the network. Network-related statistical quantities are automatically collected. Once a network model has been developed including statistical collection requirements, a computer program can perform the desired network results automatically [10:1].

The canned Q-GERTS simulation program is available on at least one DOD computer system, the CREATE system used by the Air Force Institute of Technology and Air Force Logistics Command. It is reiterated that Q-GERTS is written in FORTRAN IV and therefore is readily adaptable.

The GERT Network

This paper presents a variation in the use of Q-GERTS which facilitates cost analysis. To demonstrate this variation, the hypothetical repair process shown in figure 1 will be used as well as repair costs for each stage in the hypothetical network. The repair costs are shown in Table 1.

Table 1

Repair Stage Costs

Stage Number	Cost
1	$11.00
2	$12.00
3	$13.00
4	$14.00
5	$15.00
6	$16.00
7	$17.00

The GERT network diagram for the hypothetical repair process is shown in figure 4. The reader will recall that the branches between nodes in a GERT network represent activities. The numbers in small circles near each branch are activity numbers. There are 13 activities represented in the network. Above each branch in the network there is at least one set of parentheses. If there is only one set,

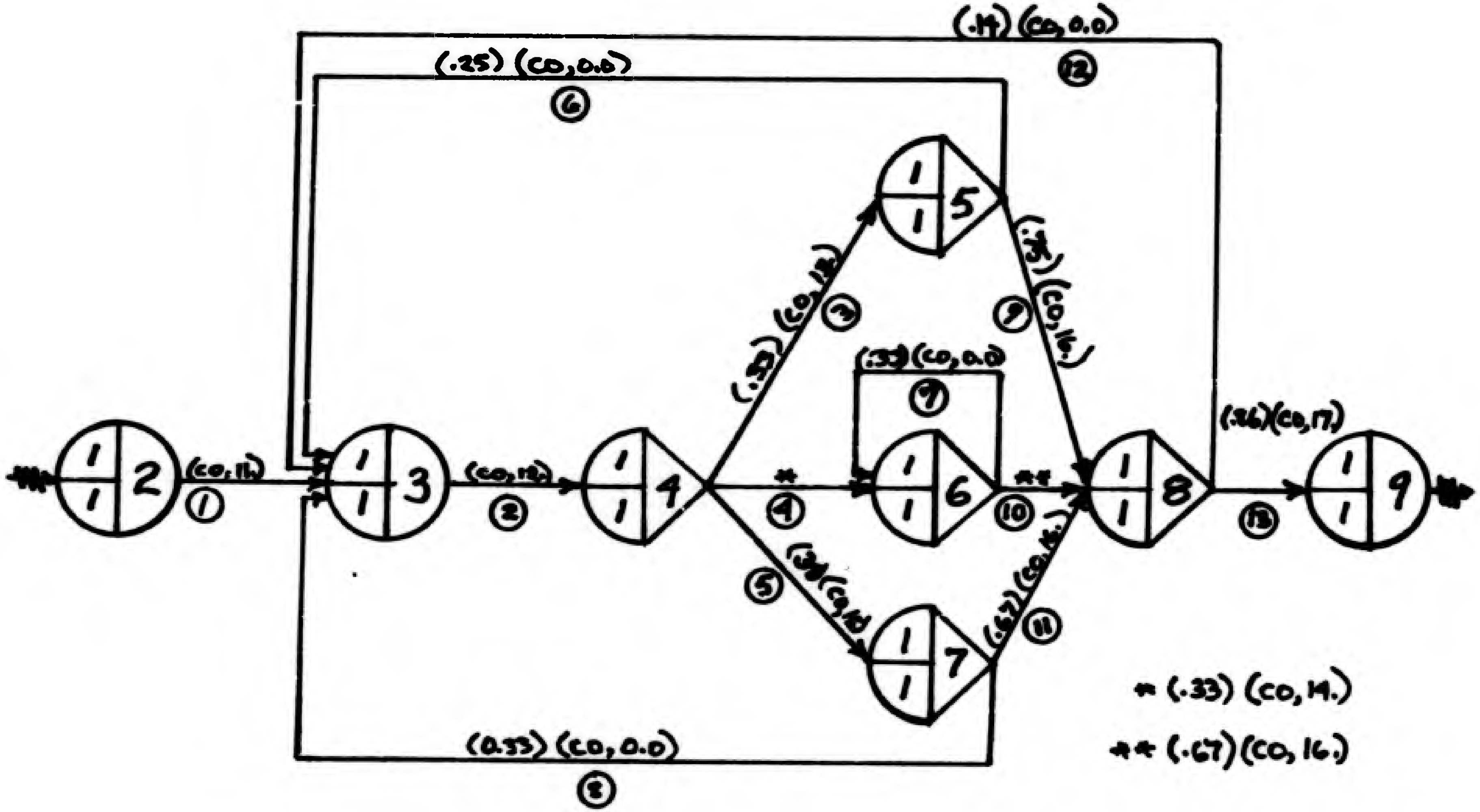

Figure 4
GERT Network Diagram

then the two alphabetic characters in the set describe the type of distribution which activities follow (e.g., CO designates constant, NO means normal, ER indicates erlang, etc.). The numbers following the letters within the set of parentheses normally are used to identify the parameter set which describes the parameters of the distribtuion; however, in this case, since costs are treated as constants, the numbers following the letters indicate the constant activity cost. If two sets of parentheses appear above a branch, the first set indicates the probability that the activity will take place. The reader will note in figure 4 that the probability of activity 3 occurring is 0.33; that its cost is constant (CO); and that the cost is $13.00. Similarly, for an individual feedback branch such as activity 8 in figure 4, there is a probability of 0.33 that the activity will occur, and the cost is constant with a value of $0.00. All feedback paths in the GERT network have a constant cost of $0.00.

The Q-GERTS Program

After a GERT network has been developed to depict the repair process, it is a relatively straightforward process to translate the diagram to the required input format for the canned Q-GERTS program. To demonstrate just how straightforward this procedure is, the Q-GERTS input statements for the GERT networks diagram in figure 4 are shown in Table 2. These input statements are shown merely to give an impression to the reader about the programming simplicity which Q-GERTS offers.

Table 2

Q-GERTS Input Statements

INSTRUCTION NUMBER	INSTRUCTION
1	GEN,IWERSEN,2,12,1,1974,1,8,1,1000,155*
2	SOU,2,0,1,D*
3	STA,3,1,1,D*
4	STA,4,1,1,P*
5	STA,5,1,1,P*
6	STA,6,1,1,P*
7	STA,7,1,1,P*
8	STA,8,1,1,P*
9	SIN,9,1,1,D*
10	PAR,1,11.00*
11	PAR,2,12.00*
12	PAR,3,13000*
13	PAR,4,14.00*
14	PAR,5,15.00*
15	PAR,6,16.00*
16	PAR,7,17.00*
17	PAR,8,10.00*
18	ACT,2,3,CO,1,1*
19	ACT,3,4,CO,2,2*
20	ACT,4,5,CO,3,3, ,0.33*
21	ACT,4,6,CO,4,4, ,0.33*
22	ACT,4,7,CO,5,5, ,0.34*
23	ACT,5,8,CO,6,9, ,0.75*
24	ACT,6,8,CO,6,10, ,0.67*
25	ACT,7,8,CO,6,11, ,0.67*
26	ACT,8,9,CO,7,13, ,0.86*
27	ACT,5,3,CO,8,6, ,0.25*
28	ACT,6,6,CO,8,7, ,0.33*
29	ACT,7,3,CO,8,8, ,0.33*
30	ACT,8,3,CO,8,12, ,0.14*
31	FIN*

Using the input date in Table 2, the Q-GERTS program produces output statistics regarding cost. Based on the input data shown in Table 2, the Q-GERTS program would produce the following types of cost statistics based on 1000 simulations of system repairs.

(1) Mean

(2) Standard Deviation

(3) Standard Deviation of the Mean

(4) Minimum Cost

(5) Maximum Cost

That is, the output information would indicate what costs could be expected if 1000 systems were repaired in the repair process. The number of simulations on which these statistics are based can be controlled by the analyst.

CRITICAL FEEDBACK

Given the Q-GERTS program and the Q-GERTS input statements which describe the repair process, it is then possible to evaluate the effect of feedback on cost. To determine these effects all that is essentially necessary is to change appropriate transition probabilities in the Q-GERTS input statements. For example, to determine the cost effects of feedback from stage 6 to stage 2 of the hypothetical repair process, the transitional probability could be reduced by 50% to .07. Then the transitional probability of moving from stage 6 to stage 7 would be raised correspondingly by .07 to .93. To accomplish this in the Q-GERTS input statements, it would only be necessary to change the probabilities in input statements #26 and #30 (see Table 2) accordingly.

One approach used by the author is to first develop, verify and validate a simulation of the process as it exists, and record mean cost and standard deviation of the mean. Next all feedback is eliminated in the simulation by altering the transitional probabilities. By comparing the average cost with feedback, to the average cost without feedback, some idea of the significance of feedback costs can be gained. If such costs are substantial, then it may be useful to identify critical individual feedback paths and critical sets of feedback paths.

As was indicated earlier, when conclusions are drawn from simulation results, the accompanying random variations must be carefully assessed. Q-GERTS results represent no exception. Random variations cannot be ignored, so it is suggested that the standard deviation of the mean be evaluated carefully during the process of verifying and validating the simulation. Since it will decrease as the number of simulation runs is increased, it can be used as a criterion during validation. Moreover, the standard deviation of the mean can be used in conjunction with the concept of criticality to identify critical individual feedback paths and critical sets of feedback paths.

If an average cost has been determined along with a standard deviation of the mean, then random variations can be accounted for. For example, if the mean cost to repair an item (based on 1000 simulations) was found to be $2195.21 and the corresponding standard deviation of the mean was

$46.53 then in subsequent simulations using different random number seeds, 68% of the means would be within ± $46.53 of $2195.21. These random variations would be due to the stochastic nature of the process. One method then of evaluating feedback, is to reduce feedback in an individual feedback path by a given percentage, then run the simulation and determine if a "statistically different" mean occurs. If the mean cost decreases when feedback is reduced, but is within one standard deviation of the mean, then the cost reduction easily can have occurred by chance. But if a reduction is greater than two standard deviations of the mean, then it is less likely to have occurred simply by chance.

In summary, it is possible to identify critical individual feedback paths and critical sets of feedback paths through the use uniform procedures and decision rules. For example critical feedback path could be identified as follows: If feedback along the path is reduced 50% (i.e., the transition probability for the path is halved.) and a cost reduction greater than two standard deviations of the mean results, then the feedback path is critical. Similarly a critical set of feedback paths could be defined as follows: If feedback to a stage is reduced 50% and a cost reduction greater than two standard deviations of the mean results, then the set of feedback paths is critical.

CONCLUSION

In this paper a computer simulation technique is described for identifying critical feedback in a complex repair process. Using the technique, it is possible to ordinally rank critical individual feedback paths and critical sets of feedback paths. From this, analysts may be able to infer what improvements in the repair process are likely to yield the greatest cost reductions. To the extent that such inferences may be drawn, the objectives of gross cost-effectiveness analysis will be fulfilled.

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