AD-787 199

A COST ANALYSIS OF THE KT-73 INERTIAL MEASUREMENT UNIT REPAIR PROCESS USING ABSORBING MARKOV CHAINS

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August 1974

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REPORT DOCUMENTATION PAGE — READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: SLSR 19-74B	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER: AD-787199	
4. TITLE (and Subtitle): A COST ANALYSIS OF THE KT-73 INERTIAL MEASUREMENT UNIT REPAIR PROCESS USING ABSORBING MARKOV CHAINS	5. TYPE OF REPORT & PERIOD COVERED: Master's Thesis
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): E.B. Watson, Squadron Leader, RAAF Charles R. Waterman Jr., Major, USAF	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Graduate Education Division School of Systems and Logistics Air Force Institute of Technology, WPAFB, Oh	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Department of Research and Communicative Studies (SLGR) AFIT/SLGR, WPAFB, OH 45433	12. REPORT DATE: August 1974
	13. NUMBER OF PAGES: 124
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION, DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Approved for public release IAW AFR 190-17

JERRY C. HIX, Captain, USAF
Director of Information, AFIT

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cost Analysis, Inertial Measurement Unit, Markov Chains, Repair Process

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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In any complex multi-level repair process the interdependence of work performed at one stage on the results achieved at another, together with the multiple feedback loops linking the stages, combine to obscure the influence of any single stage on the success and cost of the repair process as a whole. This thesis describes an analysis of the KT-73 IMU Repair Process at the Aerospace Guidance Metrology Center, Newark, Ohio, to determine which major stages in the process were most critical in terms of their effect on the overall average cost of repairing a single IMU. The process was defined as a discrete Finite State Absorbing Markov Chain and, by use of the Fundamental Matrix to establish mean state occupanices and average cost per unit flow, the improvement potential of each stage was established by selectively "improving" each stage by an arbitrary ten percent. The final result was an ordinal ranking of the stages in terms of the reduction in cost per unit flow which resulted from the arbitrary "improvements." Three critical stages were identified to provide an indication of the most profitable areas in which to concentrate future improvement efforts.

SLSR 19-74B

A COST ANALYSIS OF THE KT-73 INERTIAL MEASUREMENT UNIT REPAIR PROCESS USING ABSORBING MARKOV CHAINS

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

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and approved in an oral examination, has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

DATE: 14 August 1974

COMMITTEE CHAIRMAN

ACKNOWLEDGEMENTS

This thesis is the result of an ongoing research program sponsored by the Aerospace Guidance and Metrology Center, Newark, Ohio and jointly guided by Mr. Russell Genet of AGMC and Lt Colonel Ronald R. Calkins, Assistant Professor of Research Management at the Air Force Institute of Technology. The authors wish to express their appreciation to all members of the AGMC staff for the outstanding support and cooperation received throughout the project. The authors also wish to thank Major Robert L. Sims, whose expert advice on the theory of Markov Chains contributed greatly to the development of this thesis.

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CHAPTER I

BACKGROUND AND JUSTIFICATION FOR THE RESEARCH

Formal Statement of the Problem

The Aerospace Guidance Metrology Center (AGMC), located at Newark, Ohio is responsible for repair of KT-73 Inertial Measurement Units (IMU). Based on past experience and studies of similar repair processes, AGMC personnel believe that the KT-73 Repair Process may include some critical areas which, if improved, could lead to a substantial reduction in the average cost of the process. A detailed analysis of the complete process and it's elements is necessary to determine whether such critical areas exist, as the first step in determining where an improvement effort could most profitably be applied. Such an analysis is necessary now if maximum cost benefits are to be derived from any improvements subsequently introduced.

Introduction

The restoration of unserviceable equipment to a serviceable state is a continuous and costly process within the Air Force, involving many thousands of individual components annually. These components vary widely in type, complexity and capital cost, however almost every component in use, and particularly those complex components used in aircraft, share a common need to be "restored" to a serviceable state at some time in their service lives.

Three "classical" methods which are employed in the restoration of components to an operating condition after failure have been identified by Genet and Handley in a paper titled REBUILD vs REPAIR (5). The three methods are:

a. To throw the malfunctioning component away and replace it with a new component.
b. To completely "rebuild" or "overhaul" the component, which involves complete dismantling and reassembly of the component using new or overhauled parts.
c. To "diagnose and repair as necessary." This involves some form of diagnostic test to determine why the component failed, followed by rebuild or replacement of the part or subsystem that caused the failure without rebuilding the entire component [5:1].

The throwaway approach is most often used for low cost, high volume components for which repair or overhaul is not economical, but this approach becomes prohibitively expensive for complex, high cost components or systems (5:1). Overhaul or repair, or a combination of the two, then form the basic alternatives for the restoration of high cost, complex components to a serviceable or operating condition after failure (5:1).

Repair is potentially cheaper than overhaul because complete dismantling is not required each time the component fails. However, repair processes contain a special class of problems, among which are diagnostic errors, which may cause the wrong part or subsystem to be repaired, and thus increase the cost of the final repair (5:1).

A detailed discussion of the relative merits of overhaul vs repair for a given component is beyond the scope of this thesis, and the distinction between the two has been drawn as an aid to understanding the term "repair process" as it has been defined in this research. The remainder of this paper is devoted to a description of a research effort involving one such "repair process", performed on KT-73 Inertial Measurement Units (IMU) at the Aerospace Guidance Metrology Center, Newark, Ohio.

Objectives of a Repair Process

From a systems approach, repair of a component may be considered to be one phase in a continuing use - repair - use cycle, and when considered in this way, the direct relationship which exists between work performed during repair and the performance of the component during it's "use" phase becomes evident. However, despite this close relationship between "repair" and "use", the repair process itself may be defined as a self contained subsystem, beginning with the arrival of an unserviceable component at the repair facility and ending when the repaired component is shipped from the repair facility back to the user. This definition of a "repair process" will be used throughout the remainder of this paper.

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 (8). These objectives are:

a. To determine the faults of unit(s) received with a maximum of accuracy and a minimum of cost and time.
b. To prescribe the repair action(s) that are most likely to correct the fault(s) 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 [8:4].

Considered individually, these general objectives may be related to four major tasks performed in a repair process; namely, Receipt Testing, Fault Diagnosis, Repair and Final Testing. Considered together, they may be combined into 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 faults present in a component may not be determined accurately, the prescribed repair action may not correct the fault, or the assessment of the "success" of the component when it is returned to use 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 should be evident that one of the reasons for examining a repair process is to identify ways in which the repair objectives may be achieved at 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 [6:4].

The research effort described in this thesis involves the use of a mathematical modeling technique, Finite Markov Chains, to perform a gross cost effectiveness analysis of the KT-73 IMU Repair Process at the AGMC. More detailed objectives of the research will be defined later in this chapter however, before doing so, it is necessary to provide some background information regarding the process, and to examine some of the reasons for analyzing the process at all.

Background Information

The Aerospace Guidance and Metrology Center (AGMC), serves as a repair depot for aircraft navigation system components and aircraft instruments. One of the components being repaired at the center is the KT-73 Inertial Measurement Unit (IMU), which is one of several major components of the Inertial Navigation System installed in A7-D and A7-E aircraft. This component (the IMU) is also known as an Inertial Platform, however, the term IMU will be used throughout this paper.

Repair of the KT-73 IMU at AGMC began in 1971 and until the end of November 1973, 670 of these components had been processed through AGMC and returned to service. As of November 1973, there were 282 IMU's in the Air Force inventory, each costing $60,000 new and an average of $4468 to repair (4).

Even though 670 KT-73 IMU's have been repaired at AGMC, the process is in a relatively early stage of development, and is gradually increasing in magnitude. By 1975 it is predicted that 720 KT-73 IMU's will be repaired at AGMC each year, with potential growth in that volume in later years (4). Two other IMU's, the KT-76 used in the Short Range Attack Missile, and the KT-71 used in the F-105 aircraft, are repaired at AGMC using substantially the same process as that for the KT-73. The total number of KT-71 and KT-76 IMU's being repaired at AGMC will reach 280 per year by 1975 and with the KT-71 and KT-76 included, total output from the combined repair process will reach 1000 units/year by 1975 (4).

Using the figures quoted above, it may seem that, by 1975, the total cost of repairing KT-71, KT-73 and KT-76 IMU's at AGMC will reach $4.468 million per year. If it is assumed that these components have 15 years of service life remaining, the total cost of depot repair of these items, at the 1975 volume and current cost, would be approximately $67 million. More importantly, if by some means the average cost would be reduced by say five percent, the total savings over this same period would amount to $3.35 million.

This figure is provided only as an indication of the total number of IMU's being repaired using the basic KT-73 process, and the magnitude of the total costs involved. Throughout the remainder of the paper, the process will be considered to be applicable to a single IMU, and will be referred to as the KT-73 process.

The KT-73 Repair Process

The KT-73 Repair Process is currently divided into 16 major functional areas each covering either repair and/or test of a major subassembly of the IMU (15). Each major subassembly includes one or more lower level assemblies or components, and repair/test of these lower level components will be referred to as process elements. The term stage will be used throughout this paper to describe one of the 16 major areas, and the term element to describe some action performed within a particular stage.

The entry point for a particular IMU into the repair process is determined as a result of a series of diagnostic tests performed on each IMU on receipt at AGMC. The IMU is then phased through one or more stages of the process, dependent on the particular fault(s) identified. Each stage of the repair process involves some form of functional test, to determine whether the IMU proceeds to the next logical stage in the sequence, or is returned to an earlier stage for correction of some unsatisfactory condition. Consequently, although the process includes 16 major stages, it is possible that any particular IMU will pass through any stage in the process more than once, and will not be processed through some stages at all (18).

The average time taken to repair a KT-73 IMU at AGMC is currently 146.09 hours. This figure has been determined from actual records maintained by AGMC over the two years that the repair line has been in operation. The current average cost to repair an IMU is $4468, based on the repair times quoted above, and the standard man-hour and material rates used at AGMC (4; 16).

A more comprehensive description of the KT-73 repair process is contained in Chapter II, however, with this brief description as a basis, some of the unique and complex characteristics of a depot repair process, including the sources of error in the process, will be examined in the next section.

The Nature of Complex Repair Processes

In an earlier section, four basic objectives of a special repair facility engaged in repairing complex components were enumerated and, insofar as they relate directly to an understanding of the nature of complex repair processes, are considered to be worthy of repeating here. The objectives are:

a. To determine the faults of unit(s) received with a maximum of accuracy and a minimum of cost and time.
b. To prescribe the repair action(s) that are most likely to correct the fault(s) 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 [8:4].

These objectives may be related to the major activities of Receipt Testing, Fault Diagnosis, Repair and Final Testing performed during the repair of a component. However they do not, by themselves, completely define the complexity of the repair process used for a component such as an IMU.

Three major causes for the complexity and high cost of repairing Inertial Guidance Systems in particular have been identified by Genet, and may be summarized as:

a. The multi-level nature of inertial guidance systems. These levels are usually classified as system 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 higher 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 [9:1-2].

When these three aspects are considered together in terms of a complete repair process, the interdependence of individual components, tests and repair levels should become obvious. Components installed or tests performed at the higher repair levels are dependent upon a progressively greater number of components installed or tests performed at the lower levels. At the subsystem or IMU 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 (9:1-28).

Because of this interdependence between stages of the process, it is evident that the process should be considered as a complete system when an attempt is to be made to identify potential problem areas (6:2). 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 and 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 Error in a Process

From past experience, AGMC personnel consider that the potential sources of error, 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 [3; 17].

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 (8:4). These objectives relate specifically to Receipt Testing and Final Testing of the IMU respectively, however as has been established in the previous section, many other tests are 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 (7:1).

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 (7:11). However for the purposes of this research, 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 [9:18].

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 condition 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 (9:18; 7:1-36).

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 (7:5). 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

In the introduction to 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 (9:25).

The effect of using unreliable parts in a repair process has been demonstrated in a recent study by Burt and Benbow (2). 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 (2:15).

Using historical data on the repair process at AGMC, Burt and Benbow showed that a difference of 25 per cent 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 stage in the process (2:60).

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 Flow of the Repair Process

The "flow" of the repair process, as the term will be used here, refers essentially to the sequence in which the various actions are performed during the entire process, and such a "flow" has been established for repair of the KT-73 IMU at AGMC (22). Although this basic flow plan has been established, the actual path taken by a particular unit undergoing repair may not include all stages in the repair process. The actual sequence is dependent upon the work to be performed on that unit, which is determined as a result of diagnostic tests performed throughout the process (18). Ways in which the flow of a process may be changed or improved have been identified by Genet as:

a. A reduction in diagnostic decision errors (i.e., test errors)
b. Reduction in the percentage of faulty replacement parts
c. Reduction of reassembly (and disassembly) errors
d. Reduction in functional test errors (i.e., the good/bad decisions on the way back up the levels of repair, e.g., reassembly) [9:3].

Examination of the above list will reveal that three of the four items (a, b and d) have already been identified as potential areas of error in a process, and have been discussed in previous sections on test validity and component reliability.

The third item on the list, reduction of reassembly and disassembly errors will not be discussed further at this point, but will merely be identified as a third possible source of errors within a process.

The Concept of Criticality

In the preceding sections the complex interrelationships which exist within a repair process have been examined in some detail. Similarly the effect of making an error in the process, and particularly errors arising from invalid or non-repeatable tests or introduction of low reliability components, has been examined 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 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 [6:4].

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 deficiencies in only a few of the individual stages or elements will yield significant savings in the overall cost for the process, while improvement 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 [9:23-24].

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 error sources) established, the concept of criticality may be tested for <u>that</u> process if some means of determining the effect of making an error, or alternatively not making an error, at each stage can be established. The application of the concept of criticality to the KT-73 IMU Repair Process in this research is summarized by the following Research Proposition.

Research Proposition

The process used at AGMC for repair of KT-73 Inertial Measurement Units contains one or more stages which are critical to the overall cost effectiveness of the process. Relatively small improvement in the efficiency of any one of these critical stages will lead to a major reduction in the average cost to repair an IMU, while an improvement of the same magnitude made to non-critical stages will have little effect on average cost.

Summary of the Design to Test Research Proposition

To test the research proposition a flow model of the KT-73 repair process was constructed, using historical data obtained from AGMC to define the relationship between the stages in the overall flow of the process. The process was then defined as a Discrete Finite State Absorbing Markov Chain and, by use of the Fundamental Matrix to establish mean state occupancies and average cost per unit flow, the improvement potential of each stage was established by selectively "improving" each stage by an arbitrary ten per cent. Complete details of the assumptions made and the techniques employed are contained in Chapter III, while further information concerning the KT-73 Repair Process and a review of The Theory of Markov Processes is contained in Chapter II.

From the results obtained by "improving" each stage, an ordinal ranking of the stages was prepared in terms of the potential reduction in average cost which could be obtained by "improving", or reducing the number of errors at each stage by the same amount. By use of decision criteria established in Chapter III, stages were then designated as critical or non-critical to the overall cost effectiveness of the process. Results of the test are included in Chapter IV.

Although the preceding summary has been described as a "test" of the research proposition, it should be clearly understood that this method does not constitute an empirical test of the proposition. The results of the research are based on the use of a mathematical model of the process, constructed from empirical data and containing one critical assumption, to simulate the effect of a hypothetical set of "improvements" to the process.

The term "test" will be used throughout the remainder of this paper to describe the procedure used to establish support or no support for the research proposition. However the reader should bear in mind that the method employed represents one way of evaluating the effect of changes within the process, and that the method was employed because of the impracticality of performing a field test.

CHAPTER II

THEORETICAL CONCEPTS

Introduction

In Chapter I some of the characteristics of a complex repair process were described, in terms of the interdependency between stages, and the effects of the errors made at individual stages on the overall success and cost effectiveness of the process. Major sources of error in a repair process were identified as test errors, the use of low reliability parts and assembly and disassembly errors.

The concept of criticality was then introduced, as the effect of a few, and only a few, critical stages on the overall cost of repairing a single IMU, from which a Research Proposition was specified in terms of the existence of critical stages in the KT-73 repair process. A summary of the design to test the Research Proposition was then presented, briefly describing the use of Markovian analysis to evaluate the effect of selectively "improving" each stage on the overall cost effectiveness of the process.

Although a brief description of the KT-73 IMU Repair Process was included in Chapter I to facilitate an understanding of some of the concepts introduced in that chapter, a more detailed explanation of the "flow" of the process is included in this chapter as a prelude to the description of The Design to Test the Research Proposition covered in Chapter III. In addition, this chapter includes a brief review of the theory of Markov Processes, which will be used in constructing the test.

The KT-73 Repair Process

Detailed requirements for repair and test of the KT-73 Inertial Measurement Unit are contained in USAF Technical Order 5N-16-3-6-3, originally prepared by the manufacturers of the IMU, the Kearfott Division of the Singer/Link Company (21). The repair flow process used by AGMC was prepared by AGMC prior to commencement of the KT-73 repair program, and closely follows the requirements of TO 5N-16-3-6-3 (21).

As stated in Chapter I, the process is divided into 16 major stages, with each stage covering repair and/or test of one or more subassemblies of the IMU. A flow chart showing each of the 16 stages is included as Figure 1 (22).

In examining this flow chart it should be recognized that each of the 16 major "stages" identified actually represents one or more activities related to the basic

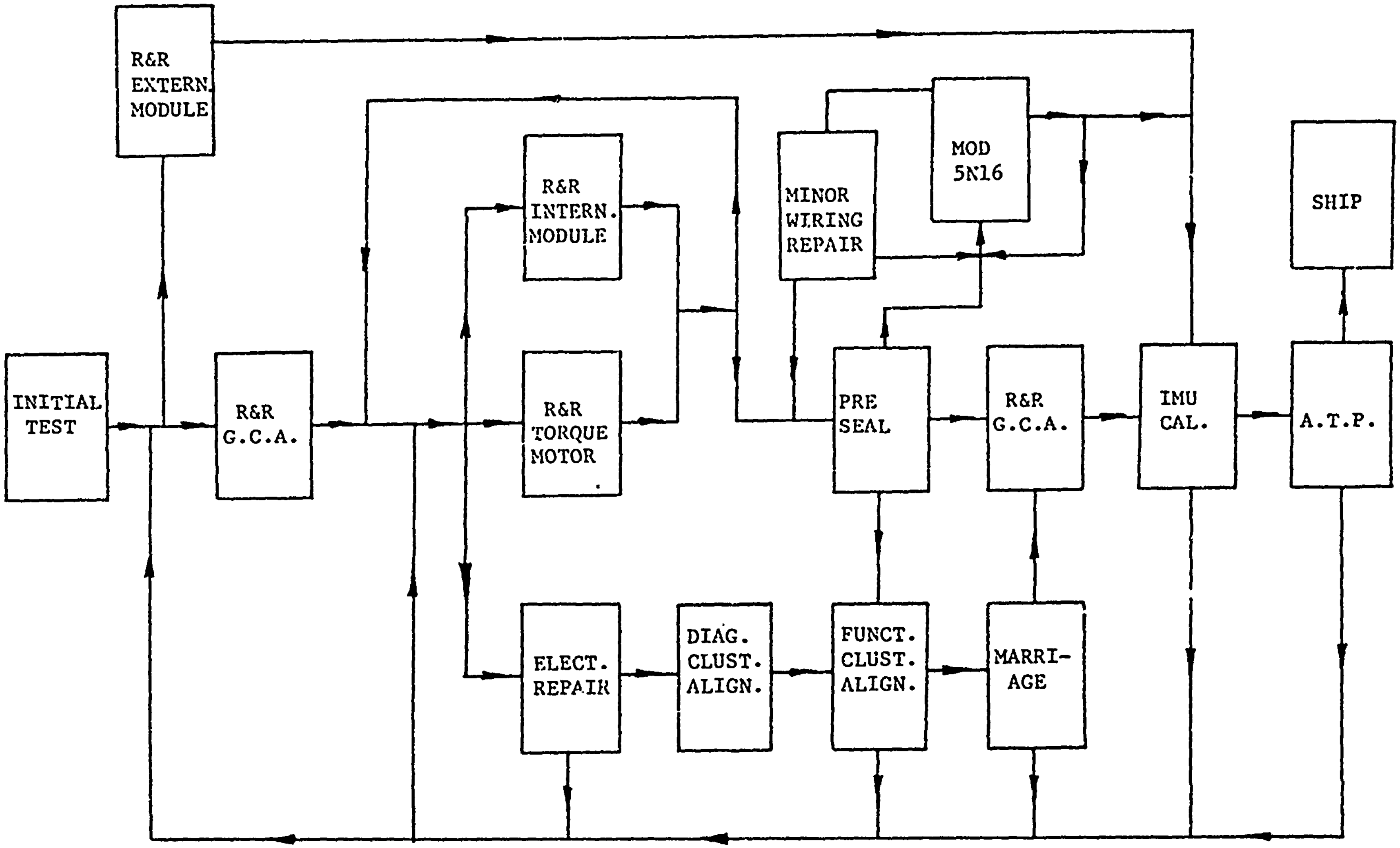

Figure 1. Simplified Flowchart - KT-73 Repair Process.

tasks identified. The stage shown as Repair and Replace External Module, for example, actually covers repair or replacement of four different modules, as well as a test to ensure that the fault identified has actually been repaired (18). Consequently, although 16 stages are shown, the work performed at each of these stages actually covers correction of a range of specific malfunctions, and does not represent a set of "standard" tasks (18).

After a KT-73 IMU is received at AGMC, and the necessary paperwork is completed, the IMU is forwarded to the KT-73 Repair Shop. All IMU's arriving at the shop from the field are then processed through the Receiving Stage. During this stage a complete check of the IMU is performed using an automated test station, to confirm the malfunction reported by the previous user and to identify any additional problem areas (18).

Dependent upon the results of the receipt tests, the IMU is classified as requiring either internal (cluster) repair or repair of one of the external modules. If internal repair is required, the IMU is sent to one of the stages at the next level, shown on Figure 1 as Repair and Replace Internal Module, Repair and Replace Torque Motor or Electronics Repair stages. If external repair is required, the IMU is sent to Repair and Replace External Module Stage (18). The necessary repair is then performed at the particular stage to which the IMU has been sent, and the IMU is tested to determine whether the repair was successful.

Provided that the results of the test show that the original malfunction has been corrected, the IMU then moves to the next stage in the repair sequence. As noted in Chapter I, the actual repair sequence for an IMU is dependent upon the fault or faults present in the particular unit, and consequently all IMU's do not follow the same path through the process (18). From Figure 1 then, it may be seen that the number of paths which a unit may follow after leaving one of the four stages identified earlier increases rapidly, dependent on the actual faults present. This progression from stage to stage in the process continues until the IMU finally reaches the final test stages (18).

Final test and calibration of a repaired IMU is carried out in the IMU Calibration and Final Test stages, and as a result of the tests conducted during these stages the IMU is classified either as "satisfactory" for return to service, or as "unsatisfactory" and requiring further repair. Each of these stages comprises a number of specific functional tests. The Final Test stage, for example, includes 13 individual tests, each designed to evaluate the performance of the IMU in a particular phase of its operation. Successful completion of all 13 tests is required before the IMU is classified as satisfactory (18; 21).

Although the preceding discussion has treated only the case where an IMU passes the test at a stage and moves to the next sequential stage in the process, the action taken when a unit fails the test is most important from the standpoint of this research, since it introduces "feedback" into the process. "Feedback", or the return of a unit to an earlier stage in the process for correction of a fault introduced at that stage, was explained in Chapter I as resulting from the interdependence between the work performed at different stages in the process. This concept may now be reinforced by reference to an example.

Consider, for example, the case where an IMU which has been repaired at the Internal Module Stage reaches the Final Test Stage and is found to be unsatisfactory. If the unsatisfactory condition can be directly attributed to an error made at the Internal Module Stage, the IMU must then be "fed back" to that stage for correction of the fault. However, because of the error early in the process, the unit must repeat not only the Internal Module and Final Test stages, but all intervening stages in the process.

While this type of feedback is costly enough, next consider the same situation, i.e., a unit repaired at the Internal Module Stage and found to be unsatisfactory at the Final Test, where the error introduced at the Internal Module Stage cannot be directly attributed to that stage, because of a deficiency in the Final Test. In this case the IMU may be incorrectly returned to some other stage in the process for correction of an error which was introduced at the Internal Module Stage and which must eventually be fixed there. If this situation occurs a number of stages may have to be repeated more than once because of an error introduced at one stage, e.g., a bad part at Internal Module, compounded by a test error at the Final Test Stage, with a corresponding increase in cost.

While the preceding description of the KT-73 repair process was by no means comprehensive in terms of the actual work performed at each stage, it was intended to illustrate the interaction of the stages in the process and to provide a basis for a better understanding of the applicability of Markovian analysis to the KT-73 Repair Process. A review of the basic concepts of Markov Processes is contained in the next section.

Markov Processes

A Markov process, or chain, is a mathematical model used in the study of complex stochastic, or probabistic, systems (12:1-3). Basic elements of a Markov process are "states", which describe the conditions existing in the system at a given time, and "transitions", which describe the movement of the system from one state to another (12:1-3). The concepts of "states" and "transitions" can best be illustrated by reference to Figure 2, representing a simple four stage process of some type.

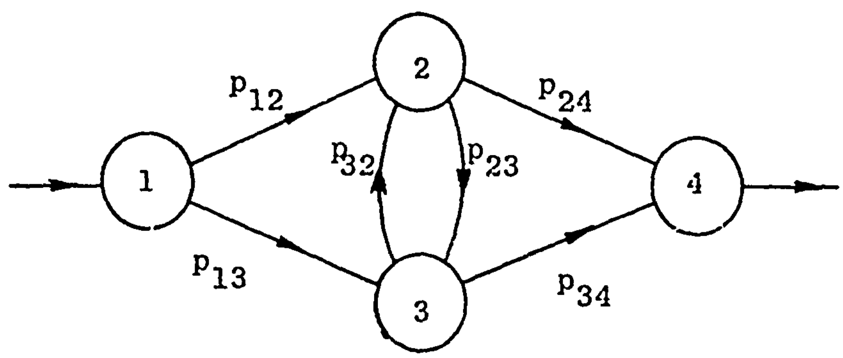

Figure 2. Simple Markov Process.

In the process illustrated above the four nodes represent the possible "states", or sets of conditions which may exist in the system. These four states may represent the stages in a four stage repair process, where "state 1" of the process, could be an item in Initial Test, and "state 4" an item in Final Test. Since there are only four states, this system is termed a "finite state process" (11:1-3; 14-35).

The lines joining the nodes represent the possible "transitions" which the system can make or, in different terms, the changes which may take place from one time period to the next. In terms of a repair process, movement of an item from stage 1 to stage 2 represents a "transition" of the system from state 1 to state 2.

From the direction of the arrows on the lines joining the nodes it may be seen that an item entering the process at stage 1 may move either to stage 2 or stage 3 on its first transition. Assuming it goes to stage 3 on this transition it may then be seen that there are again two possibilities on the next transition, involving a move to either stage 2 or stage 4. If the item moves to stage 2 on the second transition there are once again two possibilities, either back to stage 3 or to stage 4. These transitions continue until the item eventually moves to stage 4, which may occur as early as the second transition or which may not take place until a large number of transitions have been made between stages 2 and 3.

From Figure 2 is may be seen that when an item reaches stage 4 it cannot return to either stage 2 or 3 since there is no path back to either stage but must leave the system. When this situation exists in a Markov process the stage or "state" involved is termed an "absorbing state", because an item reaching that state is "absorbed" and cannot return to the system (10:430; 14:35).

States 1, 2, and 3 in the process described above are termed transient states, and are said to form a transient set (14:35). While in the transient set the item can move from one state to any other state, however once it leaves the transient set it cannot return (14:35) Howard (11:22), defines a transient state as one which has a zero probability of occupancy after a large number of transitions, which says simply that an item entering at state 1 will eventually reach state 4 and leave the system.

If the process is stochastic, each path or "transition" in the system has a certain probability, P_{ij}, associated with it, e.g., the probability that an item in state 2 will move next to stage 4, designated P_{24}. The probabilities associated with each path are termed transition probabilities, and for any stage in the process the sum of the probabilities on all paths leading from that stage must be equal to one (11:5). In mathematical terms this definition is

$$\sum_{j=1}^{n} P_{ij} = 1.0 \qquad i = 1,2,\ldots,n \text{ (11:5).}$$

A stochastic process is said to possess the Markov Property when the probability of any future event, e.g., transition from state 2 to state 3 given that the process is now in state 2, (P_{23}), is <u>independent</u> of any past event, and dependent only upon the current state of the process (10:403). Consequently if the process described by Figure 2 is Markovian in nature, the transition probabilities associiated with the movement of an item from state 2 to either stage 3 or stage 4 (P_{23}, P_{24}) are assumed to be independent of any previous history in the process, or in other words not dependent upon the path taken by the item in reaching stage 2. Further, if these transition probabilities do not change from one period to the next they are termed stationary transition probabilities (10:404).

Although the foregoing brief review of the theory of Markov Processes has been expressed in very simple terms, it was intended only as an introduction to the application of Markov Processes covered in Chapter III. For the reader interested in pursuing the subject in greater depth the following excellent texts are recommended (10; 11; 12; 14).

Summary

From the preceding section the basic applicability of Markov Processes to an analysis of a complete repair process, such as that described earlier in the chapter for the KT-73 IMU, should now be evident. The major stages in the process are equivalent to the "states" of a Markov Process, while transitions within the system describe the movement of an IMU from one stage to another in the process.

The assumption of independence described in the previous section is, however, of major importance in the definition of an actual repair process as a Markov Process. The justification of this assumption for the KT-73 IMU process, and the application of the theory described in this chapter to an analysis of the process, will be explained in detail in the next chapter.

CHAPTER III

DESIGN TO TEST RESEARCH PROPOSITION

Introduction

A summary of the design to Test the Research Proposition was provided at the end of Chapter I, in which it was specified that a mathematical model of the KT-73 Repair Process would be constructed using data obtained from AGMC and based on the assumption that the process was Markovian in nature. Complete details of the method used to construct this model, including the assumptions necessary for its use, and its application to an analysis of the KT-73 process, as well as the development of decision rules to test for support of the research proposition, are contained in this chapter.

Data

Process Flowchart

The data used in constructing the model to test the research proposition was derived from data collected by AGMC during the period 1 July 1973 to 1 December 1973, and supplemented by interviews with AGMC personnel involved with the KT-73 Repair Process (4; 13; 15; 16; 17; 18; 21). The basic data provided was in the form of a simplified flowchart of the Process, showing the relationship between the individual stages and the number of units actually passing through each stage during the period 1 July 1973 to 1 December 1973, based on an input of 100 units to the process. The basic flowchart of the KT-73 process is shown in Figure 3. It is relevant to note at this point that the number of items passing through each stage, shown in Table 1, may be read directly as the relative frequency of occurrence of each stage during the data collection period. Since the figures shown are based on an input of 100 units, a stage through which 49 units passed has a relative frequency of .49. This fact will be used later in this chapter to check the validity of the model. The "original" relative frequencies of occurrence for each stage, observed at AGMC during the period 1 July 1973 to 1 December 1973, are displayed in Table 1.

Manhours Data

Also included in the data obtained from AGMC were the average manhours expended in each stage between 1 July 1973 and 1 December 1973, as well as the standard number of manhours expended on a unit passing through each stage (15; 22). The standard manhours figure represents the

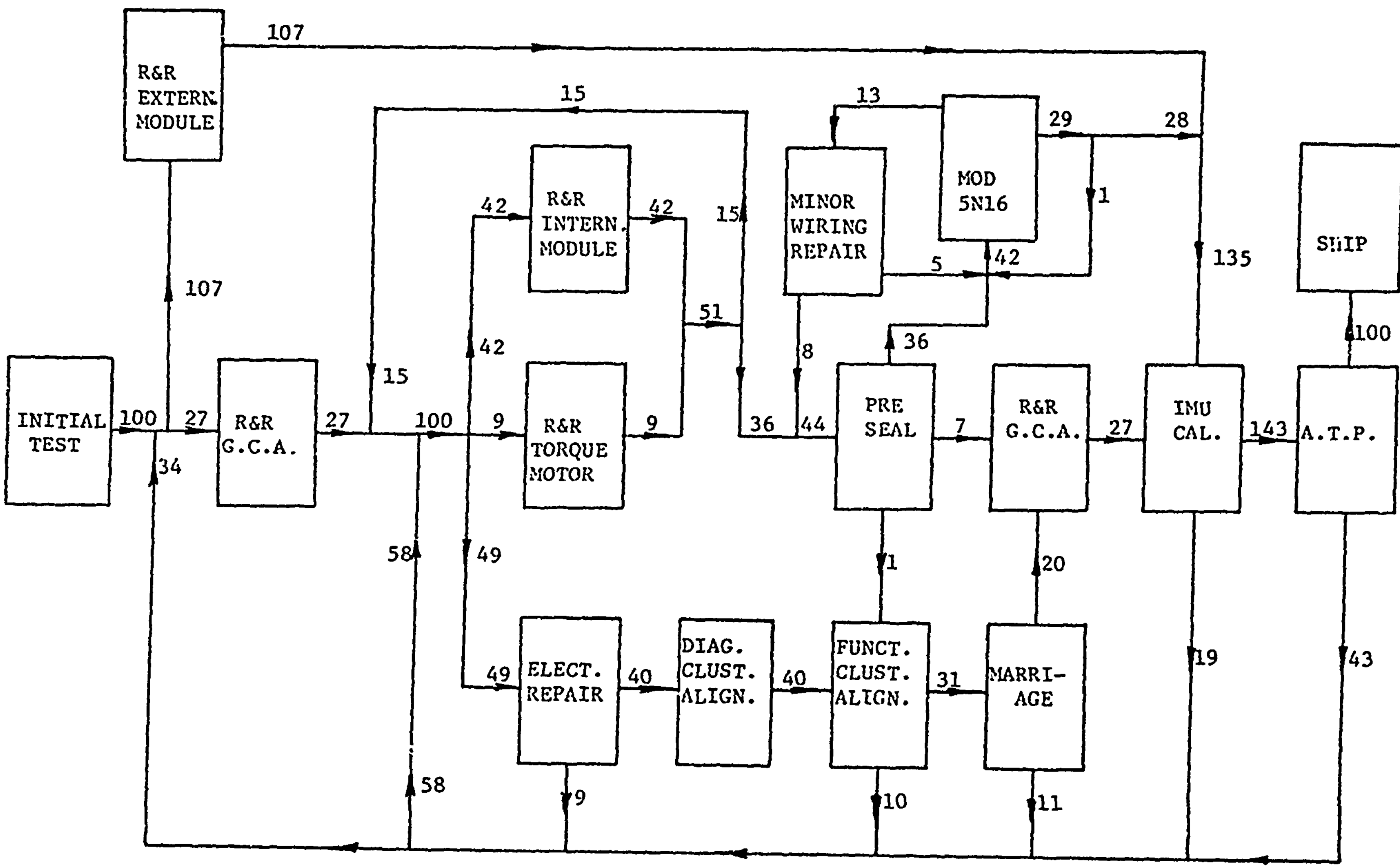

Figure 3. KT-73 Repair Process Flowchart - Original Data.

TABLE 1

ORIGINAL RELATIVE FREQUENCY OF OCCURRENCE FOR EACH STAGE

Stage Name	Units Passing Through Each Stage Based on 100 Units Input	Relative Frequency of Occurrence
Receiving	100	1.0
R&R External Module	107	1.07
R&R G.C.A.	27	.27
Electronic Repair	49	.49
R&R Torque Motor	9	.09
R&R Internal Module	42	.42
Diag. Cluster Align.	40	.40
Funct. Cluster Align.	41	.41
Marriage	31	.31
Preseal	44	.44
R&R G.C.A.	27	.27
Minor Wir. Rpr	13	.13
Mod 5N16	42	.42
IMU Cal.	162	1.62
ATP	143	1.43
Ship	100	1.0

standard job times developed by AGMC for the tasks in each stage (15). The average and standard manhours for each stage are shown in Table 2.

For four of the stages the average and standard manhour figures include work performed in associated workshops (15). The source of these additional manhours is also shown in Table 2. It will be noted that the total average manhours for all stages is 146.09 hours, identified in Chapter I as the average number of manhours expended per IMU repaired.

Average Cost Data

The average cost to repair an IMU between 1 July 1973 and 1 December 1973 was $4468.00, of which a total of $3234.00 was absorbed in direct labor and material costs. The remaining $1234.00 represents fixed overhead allocated by AGMC to each item repaired (16). By use of an assumption identified later in this chapter (Assumption Number 4), a variable cost for each stage was derived for use later in the test. These "stage costs" are also shown in Table 2.

Population

The population tested consisted of all 207 KT-73 IMU's which were repaired at AGMC during the period 1 July 1973 to 1 December 1973.

As defined, the population is a subset of a uni-

TABLE 2

MANHOURS AND COST DATA KT-73 REPAIR PROCESS

Stage Name	Average Manhours	Standard Manhours	Standard Cost (Variable) $
Receiving	10.57*	10.57	234
R&R External Module	7.39**	6.91	153
R&R G.C.A.	0	0	0
Electronic Repair	1.77	3.61	80
Diag. Cluster Align.	3.36	8.40	186
R&R Torque Motor	1.46	16.27	360
Funct. Cluster Align.	6.02	14.69	325
R&R Internal Module	44.87***	106.83	2365
Marriage	4.18	13.47	298
R&R G.C.A.	.63	2.32	51
Preseal	3.55	8.06	179
Minor Wir Rpr	.09	.67	15
Mod 5N16	.08	.19	4
IMU Cal	29.56****	18.31	405
ATP	30.75	21.5	476
Shipping	1.71	1.71	38
Departure	0	0	0

* .41 manhours added for machine shop repair.

** 6.14 manhours added for external repair line external module cards.

*** 43.72 manhours added for external line repair internal module gyro.

**** .13 manhours added for IMU repair.

verse of 750 KT-73 IMU's, which represents the total number of KT-73 IMUs repaired at AGMC since the process began in 1971. However, since the process has undergone a number of major changes since its inception, including a learning curve, data relative to the population of 207 units was judgementally selected as being most representative of the current process at AGMC. The data used is based on a census of the population.

Confining the study to the most recent period for which data was available served to ensure that the data used accurately represented the current "flow" of the process, and that process times recorded early in the "learning" period were not included in the average manhours per stage data used. (For a discussion of effects of the "learning" curve in tasks of this nature, see Chase and Aquilano (3:486-493).

Description of Variables

The following variables were considered in testing the research proposition:

Time - the measurement of time in this study relates to the average number of manhours taken to process an IMU through individual stages. Time to complete a stage is expressed in hours, tenths and hundredths of hours, and constitutes at least interval level data.

Elapsed time to complete the entire process, which includes waiting and transit time between stages, was not considered in this study.

Cost - the calculation and application of the variables of cost per stage and average cost for the complete process is discussed under the heading of General Assumptions. Costs are expressed in whole dollars, rounded to the nearest dollar, and are considered to be at least interval level data.

Probability of Rejection - detailed discussion of the assumptions and methods used to calculate the probability of rejection at each stage of the process is covered under the headings of General Assumptions and Detailed Design of Test. Because of the need to ensure that the total probability of several output paths from a stage is exactly equal to the input probability, and because of the need to maintain the overall probability of one over several branch paths, probabilities are expressed to three decimal places. Despite the small rounding errors introduced, this data is considered to be measured at the interval level.

General Assumptions

The following assumptions were made in testing the research proposition.

Assumption Number 1

IMU's returned to AGMC were assumed to require some maintenance action before being returned to service.

Assumption Number 2

Successful completion of the final test stage was considered to be both a necessary and sufficient condition for classification of a repaired IMU as serviceable. The possibility that a "serviceable" IMU would not operate when returned to the user is beyond the scope of this study and was not considered.

Assumption Number 3

The current sequence in which various stages of the repair process are performed was considered to be adequate during this study.

Assumption Number 4

The standard cost to process a single unit through each stage was assumed to be a proportion of the average variable cost to repair an IMU ($3234.00). This standard, or unit passage variable cost, was computed for each stage using the following formula and data obtained from AGMC. (See Table 2 and Data Section earlier in this chapter.)

$$C_j = S_j \times \frac{AV}{AM}$$

where

C_j = unit passage variable cost for stage j

S_j = standard manhours to process one unit through stage j

AV = average variable cost to repair one IMU ($3234.00)

AM = average manhours to repair one IMU (146.09 manhours)

Subscript j identifies different stages in the process.

Implicit in this assumption is the further assumption that the overhead of $1234.00 is fixed and will not change if the process is improved. While this may or may not be a valid assumption, the calculation and allocation of overhead costs at AGMC was considered to be outside the province of the researchers, and not directly related to "improvement" of the process.

The second term, $\frac{AV}{AM}$, in the equation used earlier to compute Unit Passage Variable cost, yielded a standard variable cost of $22.14 per manhour. While it is recognized that the allocation of variable cost in this manner may not be truly representative of the actual situation, the cost used was considered to be sufficiently accurate for the purposes of the research. The use of this method was supported by AGMC cost accounting personnel as the most accurate single figure for the cost of one manhour expended in the repair process (4; 16).

Assumption Number 5

The probability of an IMU being rejected to an earlier stage or stages in the process, and hence the probability of successfully passing to the next sequential stage, was assumed to be constant and independent of previous work performed during the repair process. This assumption will be discussed in greater detail under the heading "Development of the Basic Model."

Limitations of the Research

The limitations identified below should be recognized in examining the results of this research:

1. The repair process was considered to be a closed system, in that the effect of work performed during the repair on the performance and reliability of the component when it reenters service was not considered (see Assumption 2).

2. Because of the limitations of the cost data used, the reduction in average cost computed for the improvement of each stage has been used only to establish an ordinal ranking of the stages in terms of their

criticality to the overall cost of the process. The limitations identified in Assumption Number 4 should be carefully considered before any attempt is made to predict gross savings using the results obtained for the "improvement" of each stage.

3. The data used, and the results obtained, reflect the state of the KT-73 Repair Process as it existed between 1 July and 1 December 1973. Any change in the process which affects the "flow" of items through the process, and thus the transition probabilities between stages, may invalidate the results obtained in this research for the "changed" process.

Development of Basic Model

In earlier discussion to the process, it has been implied that many return, or "feedback" paths exist, whereby a unit can be returned to an earlier stage in the process. The first step in constructing the test was to identify all possible paths which a unit can take through the process, which includes all possible feedback paths from each stage. These paths were established using the basic flowchart (Figure 3), and are shown in Figure 4.

On Figure 4 each stage is identified by a single letter and each path by a pair of letters. The first letter in the label for any path represents the stage of

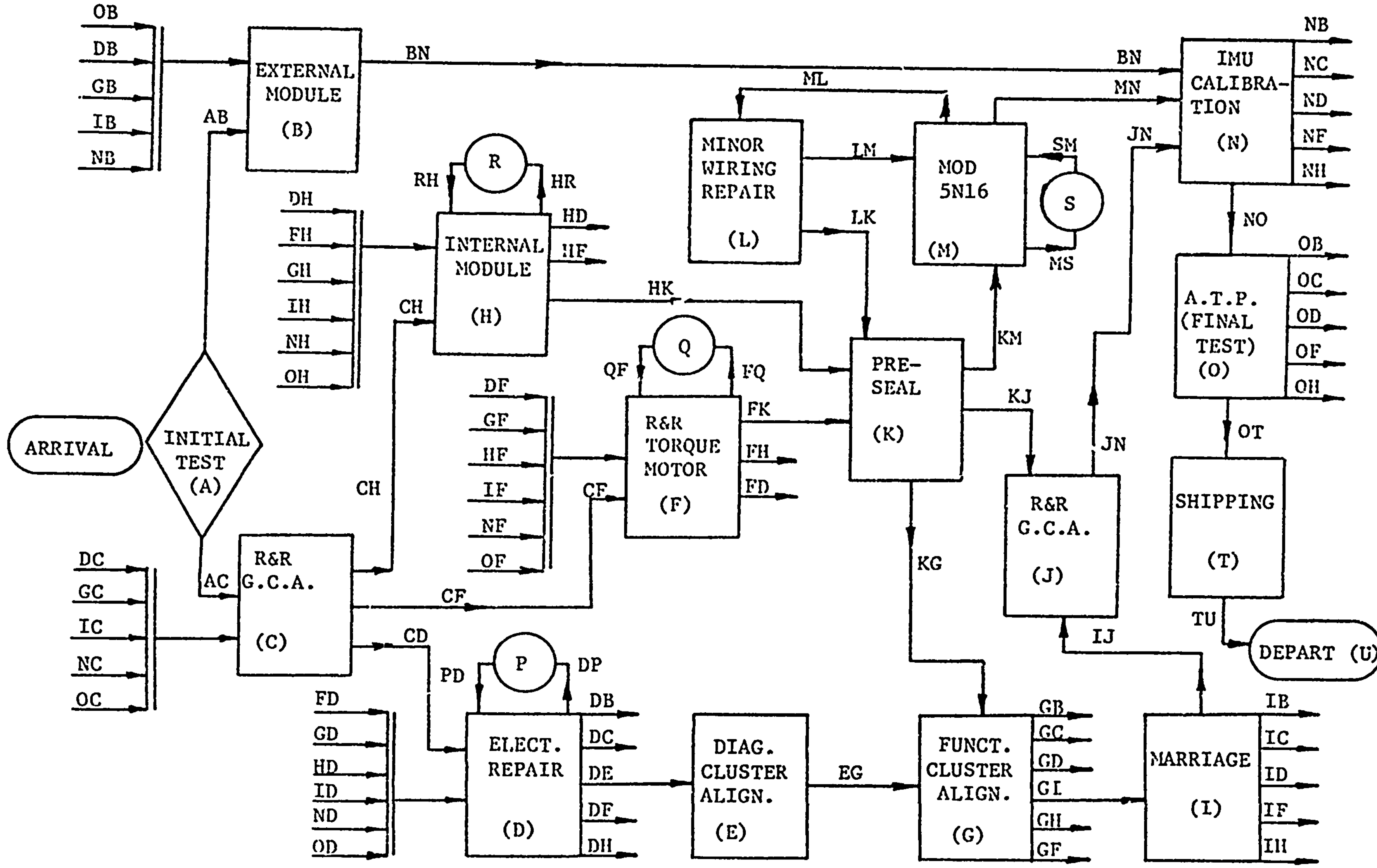

Figure 4. KT-73 Repair Process Showing all Feedback Paths.

origin, and the second the destination stage, e.g., a path labeled DC indicates return from Stage D to Stage C. This labeling convention will be followed through the remainder of this paper.

Each path identified on the flowchart at Figure 4 represents the flow of an IMU from one stage to another stage, as it passes through the repair process. Five dummy stages, identified as P, Q, R, S and U, were introduced to cover the situation where a unit passes from a stage directly back to the same stage (P, Q, R and S) and to provide a zero cost "absorbing" stage (U).

The next step in constructing the model was to compute the probability of an IMU taking a particular path from one stage to another. However, before describing the method employed in calculating these probabilities, it is necessary to discuss the assumption of independence in more detail.

The Assumption of Independence

The Assumption of Independence, as stated earlier (Assumption Number 5), may appear to be inconsistent with earlier discussion of the relationship and interdependence between stages and in practice, for any given unit at any particular stage, the probabilities are almost certainly dependent upon its previous history.

However, despite this obvious limitation for the case of a single component whose history is known, the assumption made in this study is that, in the long run, the probability of a unit moving from one stage to another stage in the process is constant, and dependent only upon the relative frequencies with which all IMU's pass through the stages involved. Thus, if an IMU is in stage X, from which there are two stages (A&B) to which it can move, and it is known from historical data that twice as many IMU's pass through Stage A as Stage B, it is assumed in this study that the probability of going to Stage A is 2/3 and to Stage B is 1/3.

In making this assumption it was recognized that some small inaccuracies may be reflected in the final result, however it was considered that any inaccuracies which were introduced would not significantly affect the final outcome. Support for this position has been obtained through discussion of the actual process with the AGMC staff (4; 15), through discussion with Major Robert L. Sims (19) who has worked extensively with Markov models, and through study of selected literature relative to processes of this type (10; 11; 12; 14).

Further support for the use of this assumption will be presented later in this chapter under the heading Test of Validity of the Model. In this test it was demonstrated that the relative frequency of occurrence obtained from the model using original, independent probabilities varied from the actual relative frequencies shown on Figure 3 and in Table 1 by maximum of point 25 per cent (.0025).

From the description of the process in Chapter II, and using the assumption that the probability of a unit moving from one stage to another is independent of previous work performed, it may then be assumed that the process possesses the characteristics of a discrete, finite state, absorbing Markov Chain. These characteristics are discussed in Chapter II, and have been summarized by Sims (20:1-4) as existing when a process, or stochastic network, fulfills the following requirements:

a. Discrete units of material (IMU's) enter the network at a source or input node (INITIAL TEST) and leave the network through one or more output nodes (SHIPPING) to the environment (Dummy Stage U).

b. The probability of passing from node (stage) i to node (stage) j is independent of previous history.

In terms of the Markov process described in Chapter II, each stage of the repair process represents an observable state. The Dummy Stage U, to which all IMU's move from shipping stage, is an absorbing state since an IMU which reaches this stage cannot return to the system.

Stages A to S inclusive are transient states, since after a large number of transitions, the probability of an item occupying one of these states is zero, i.e., all IMU's will eventually leave the repair facility. IMU's passing through the process move from stage to stage (state to state) within the process in accordance with the transition probabilities associated with the various paths linking the stages (14:79-86; 20:1). The method employed in calculating these probabilities will now be described.

The Transition Matrix

The transition probabilities, or probabilities associated with each of the paths identified earlier, and shown at Figure 4, were calculated by the following method:

a. The probability of acceptance or rejection at each stage was calculated using the basic data shown on Figure 3 as follows:

$$P_r \underset{\text{Stage X}}{\text{(acceptance)}} = \frac{\text{No. of units passing to next sequential stage}}{\text{Total No. of units passing through stage X}}$$

$$P_r \underset{\text{Stage X}}{\text{(rejection)}} = 1-P_r \text{ (acceptance)}$$

b. Since an item rejected may return to one of a number of earlier stages, a set of probabilities corresponding to all possible feedback paths from a particular stage were then computed. This was done by tracing individual feedback paths from the stage in question, and obtaining the compound probability that the reject item would end up in each of the earlier stages. At branch points in the simplified flowchart shown at Figure 3 it was assumed that any unit reaching that branch could take any path leading from the branch. The probability associated with each path leading from the branch was determined by the ratio of the number of units taking each path to the total number of units arriving at the branch.

Using the probabilities established in the previous step, a transition matrix of probabilities, P, of dimension 21 x 21, was constructed. In this matrix the P_{ij}^{th} term represents the probability that an IMU currently at stage i in the process will move next to stage j (14: 1-42). The general form of the matrix is shown in Figure 5 where each of the probabilities, designated by two letters, follows the convention established earlier in this section. The actual probabilities calculated for each path are shown in Table 3.

The transition matrix thus established forms the basic Markov model describing the behavior of the system. Each "state" of the system represents a stage of the process, while the possible paths through the process, and the probability of a unit taking that path given that it is at

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
A		AB	AC																		
B														BN							
C				CD		CF		CH													
D		DB	DC		DE	DF		DH								DP					
E							EG														
F				FD				FH			FK						FQ				
G		GB	GC	GD		GF		GH	GI												
H				HD		HF					HK							HR			
I		IB	IC	ID		IF		IH		IJ											
J														JN							
K							KG			KJ			KM								
L											LK		LM								
M												ML		MN					MS		
N		NB	NC	ND		NF		NH							NO						
O		OB	OC	OD		OF		OH												OT	
P				PD																	
Q						QF															
R								RH													
S													SM								
T																					TU
U																					I

Figure 5. Transition Matrix.

TABLE 3

TRANSITION PROBABILITIES

AB = .799
AC = .201

BC = 1.0

CD = .490
CF = .090
CH = .420

DB = .054
DC = .014
DE = .816
DF = .010
DP = .057
DH = .049

EG = 1.0

FD = .144
FH = .124
FK = .706
FQ = .026

GB = .072
GC = .018
GD = .075
GF = .014
GH = .065
GI = .756

HD = .144
HF = .026
HK = .706
HR = .124

IB = .105
IC = .026
ID = .110
IF = .020
IH = .094
IJ = .645

JN = 1.0

KG = .023
KJ = .159
KM = .818

LK = .615
LM = .385

ML = .309
MN = .667
MS = .024

NB = .034
NC = .009
ND = .036
NF = .007
NH = .031
NO = .883

OB = .089
OC = .022
OD = .093
OF = .017
OH = .080
OT = .699

PD = 1.0

QF = 1.0

RH = 1.0

SM = 1.0

TU = 1.0

a particular stage, are defined in the transition matrix. This model was then used to analyze the behavior of the system, using the method described in the following sections.

Application of the Model

Following the method described by Sims (20) and Burke (1), the transition matrix was then partitioned into four sub matrices as follows:

$$P = \left[\begin{array}{c|c} Q & R \\ \hline O & I \end{array}\right]$$

where: Submatrix Q is a 20 x 20 matrix containing the transient states (Stages A-T)

Submatrix R is a 20 x 1 matrix covering transition from the transient states to the absorbing state (Stage U)

Submatrix I is a 1 x 1 identity matrix containing the absorbing state (Stage U)

Submatrix 0 is a 1 x 20 matrix containing all zero elements (1:19; 20:4).

The four submatrices are identified on the Transition Matrix shown in Figure 5, by the position of the dotted lines. (See Page 51.)

Using the partitioned transition matrix defined above, a fundamental matrix, M, may be defined as:

$$M = (I-Q)^{-1}$$

where I in this case, is a 20 x 20 Identity Matrix (1:19; 14:45).

Sims (20:4-7) and Burke (1:20) following a method described by Kemeny and Snell (14:43-48), show that the fundamental matrix M gives the mean number of times each state in the process will have been occupied, for a unit input to the process, before the absorbing state is reached. Further, if $\pi(0)$ is the vector of state probabilities containing the individual probabilities, $\pi_k(0)$, of being in each state at time zero,

$$\pi(0) = [\pi_1(0) \quad \pi_2(0) \text{ ---------- } \pi_n(0)] \quad k=1,2,\ldots,n$$

and defined in this case as a 1 x 20 vector with a probability of being in state 1 at time zero, $\pi_1(0) = 1$ and zeroes in the remaining positions, then the product

$$\pi(0).(I-Q)^{-1}$$

will be contained in the first row of the fundamental matrix M, and represents the total number of times each state was occupied, given that the process began in State 1 (1:20; 20:7).

Consequently it can be seen that, for the KT-73 repair process model described by the Transition Matrix shown in Figure 5, the mean number of times each stage is occupied per unit input, or in other words the relative frequency of occurrence of each stage, may be determined by the technique described in the preceding paragraphs.

Since the relative frequency vector obtained from the first row of the fundamental matrix M represents the average number of times that a single unit input to the process would pass through each stage, average cost for the process can then be determined by multiplying the relative frequency vector by a column vector, C, whose elements are the standard cost per unit processed for each stage in the process (20:7). The result, expressed in matrix notation as

$$\pi(0).\ (I-Q)^{-1}.\ (C)$$

represents the total average cost of repairing a single IMU, for a given set of transition probabilities, i.e., a given set of conditions in the process.

The technique described in the preceding paragraphs was utilized in this research to establish the average cost of processing an IMU through the repair system under different sets of conditions, representing "improvements" to each stage. Inversion of the (I-Q) matrix, to obtain $(I-Q)^{-1}$ and subsequently the new average cost expressed as

$$\pi(0).\ (I-Q)^{-1}.\ (C)$$

was performed using an OMNITAB II computer program described at Appendix A. The rationale and method employed in "improving" the process will be described following a description of the method employed to validate the model.

Test of Validity of the Model

Before the model was used to determine the effect of introducing simulated improvements at each stage, two separate but related checks were performed to establish how well the model described the operation of the actual system. These checks involved comparison of relative frequencies of occurrence and average variable cost obtained from the model to "actual" data included earlier in this chapter. The checks are described in the following paragraphs.

Comparison of Relative Frequencies

It was stated earlier in this chapter that the number of units passing through each stage during the data collection period could be interpreted directly as the relative frequency of occurrence of each stage. These original relative frequencies are shown in Table 1, page 36.

From the previous section it will be recognized that the first row of the $(I-Q)^{-1}$ matrix computed using a given set of transition probabilities also provides the relative frequency of occurrence of each stage (1:20; 20:7). Consequently it was reasoned that, if the model was used to compute relative frequencies using the original set of transition probabilities, which have been assumed to represent the operation of the process during the period 1 July 1973 to 1 December 1973, the relative frequencies obtained should agree quite closely with the "original" relative frequencies if the model adequately represented the operation of the system. The results of this "benchmark" run, together with observed "original" relative frequencies are displayed in Table 4.

From a comparison of "original" relative frequency to "model" relative frequency for each stage it can be seen that very close agreement was obtained, with a maximum error of point 25 per cent of the "original" relative frequency being recorded for stage C. From this result it was concluded that the basic model of the system accurately represented the operation of the actual system during the data collection period.

Comparison of Average Variable Cost

As a further check the average variable cost obtained in the "benchmark" run was compared to the actual average variable cost quoted earlier in this chapter. The average variable cost using the model was \$3236.00 compared to an "actual" average cost of \$3234.00. It should be recognized however, that comparison of the cost figures

TABLE 4

RESULTS OF TEST OF VALIDITY OF THE MODEL

Stage Name	Original Relative Frequency	Relative Frequency Computed Using Model
Receiving	1.0	1.0
R&R External Module	1.07	1.0698
R&R G.C.A.	.27	.2693
Electronic Repair	.49	.4896
Diag. Cluster Align.	.40	.3995
R&R Torque Motor	.09	.0900
Funct. Cluster Align.	.41	.4097
R&R Internal Module	.42	.4208
Marriage	.31	.3097
R&R G.C.A.	.27	.2698
Preseal	.44	.4406
Minor Wir Rpr	.13	.1199
Mod 5N16	.42	.4205
IMU Cal	1.62	1.6202
ATP	1.43	1.4306
Ship	1.0	1.0

does not provide any further validation of the model, but is useful only as a check of computational accuracy in deriving a cost per stage, since the average cost varies directly as relative frequency, i.e.,

$$\text{Av. Variable Cost} = \pi(0).(I-Q)^{-1}.(C)$$

where $\pi(0).(I-Q)^{-1}$ is the relative frequency vector and (C) is the Standard Cost Vector.

From the results presented, it was concluded that the model adequately represented the flow of the KT-73 Repair Process as it existed during the period 1 July 1973 to 1 December 1973, and that it was suitable for use in the remainder of the test. The use of the model in "improving" each stage will now be described.

Improvement of the Process

In keeping with the objective of the research stated in Chapter I, the model described in the previous section was used to establish the effect of "improving" certain stages in the process one at a time. For each "improvement" introduced, a new average cost to completely repair a single unit was computed as the first step in determining which, if any, stages are "critical" to the overall cost effectiveness of the process.

The rationale and method employed in making the "improvements", as well as the decision criteria used in determining the "criticality" of stages is contained in this section.

Rationale and Method for Improvement of Stages

From discussion of the process in previous chapters, and from examination of the flowchart at Figure 4 and the transition matrix at Figure 5, it is evident that multiple feedback paths exist both to and from a number of stages. It is also evident that a unit returned from Stage I to Stage D, for example, must pass through stages D, E and G a second time before it again reaches Stage I.

While the effect of this return on the relative frequency of stages D, E, G and I, and the additional cost of having the unit repeat these stages was discussed in detail in Chapter II, it is important to reemphasize that the unit may have been returned to the earlier stage for one of two distinct reasons. They are:

a. An actual fault exists which was introduced and went undetected at the earlier stage and now must be corrected at that stage, or

b. No fault exists in the unit, and it was improperly rejected at the later stage because of some deficiency at that stage. In this case an error at the later stage has the same effect as an undetected error at the earlier stage. In terms of the previous example, stages D, E, G and I will be repeated because of the error at I.

From this, it can be seen that, whenever a feedback path exists between any two stages in the process, the occurrence of a unit taking that path could be the result of a fault at either stage. It also follows that this possibility must be accounted for in "improving" different stages in the process. This has been accomplished by the following method,

a. To determine the effect of making an error at a stage, and having the unit rejected at a later stage, the probability of a unit returning to the stage being improved from each of the stages from which it can be returned has been reduced by ten per cent. In this case it has been assumed that "improving" the stage will lead to less units being rejected back to that stage from each stage later in the process.

b. For "test" stages which do not have units returned directly to them, but from which units are rejected to a number of earlier stages, it has been assumed that the number of incorrect rejections could be reduced by "improving" the test. In this case the probability of a unit being rejected to each possible earlier stage in the process has been reduced by ten per cent.

The ten per cent level of improvement was established after discussion with AGMC personnel (4;17) and, insofar as it is intended to provide a basis for comparison of different stages, is not critical to the results of the test. The application of this improvement does require the assumption that each stage is capable of beir'. improved, i.e., that it is not already perfect, however from general discussion of the process with AGMC personnel throughout the period over which the research was conducted, this assumption is not considered to be in any way restrictive.

Using the methods described above, a new set of transition probabilities was calculated for the "improvement" of each stage, to represent the behavior of the system if a ten per cent improvement could be made at that stage. In each case the changed transition probabilities were inserted in the basic transition matrix, and a new average cost calculated using the method described on page 55. By comparison of the new average cost to an original average cost calculated using the original transition probabilities, the reduction in average cost resulting from "improvement" of each stage has been obtained. These results are presented in Chapter IV.

Stages Improved in the Process

From the original flowchart of the KT-73 Repair Process presented earlier in this chapter (Figure 3), it may be seen that five of the major stages are shown as having "straight through" flow, i.e., no units are rejected either from or directly back to these stages. The stages involved are the Receiving and Shipping Stages (Stages A and T), Diagnostic Cluster Alignment (Stage E), Minor Wiring (Stage L) and Repair and Replace GCA (Stage J). The work performed at a sixth stage, also entitled Repair and Replace GCA (Stage C) is shown on the original flowchart as being included with other stages, and on the advice of AGMC was treated as a zero manhours, zero cost stage (15).

Consequently, since no probabilities could be computed for rejection from or to the first five stages listed above from the data provided, and since the sixth stage does not contribute to the overall cost of the process, the method described earlier could not be employed to compute an "improvement" for these stages. For this reason, the six stages listed above were not able to be "improved" in this test, and the results shown in Chapter IV cover only the remaining ten stages in the process.

Criteria for Establishing Support or No Support for Research Proposition

From Chapter I the reader will recall that the basic purpose in performing the test described in this chapter was to develop support or no support for the concept of "critical" stages within a process. Critical stages were defined as those which, for a relatively small improvement, would yield a major reduction in overall average cost for the process. The improvement of non critical stages by a similar amount would have little overall effect.

This concept may now be stated somewhat differently in terms of the characteristics which must be exhibited by a stage if it is to be defined as critical. From the above definition and from the discussion in Chapter I, these may be seen to be:

a. A small improvement to the stage must cause a major reduction in the average cost to repair each item passing through the process.

b. The reduction in average cost resulting from this improvement must be large in relation to the reduction obtained by improving other stages in the process by a similar amount.

Although the general criteria for determining whether a stage is critical do not appear to present any real difficulty, translation from the general to the specific becomes somewhat more involved. To apply the criteria in a specific case requires that the terms "major reduction" and "large in relation to other stages" be defined. However, in the absence of any generally accepted standards, their definition is completely subjective and dependent upon the perception of individual readers.

Consequently since no "standards" could be established for either term, the researchers have established definitions for both a "major reduction" and "large in relation to other stages" for use in this test. These "standards" were established after considerable discussion of "Repair Processes" with Mr. Russell Genet of AGMC (4) and, while they are certainly open to debate, are considered to provide for adequate definition of critical stages in the context of earlier discussion in this paper. The decision rules arising from these "standards" are as follows.

Decision Rules

The following decision rules were employed in determining whether a stage could be termed "critical" to the overall cost of the process:

a. For a simulated ten per cent improvement to a stage the reduction in average variable cost to repair an IMU must exceed five per cent of the current average variable cost, and

b. The reduction in average variable cost corresponding to a simulated ten per cent improvement for a stage must be at least twice the average reduction obtained from improvement of all stages in the process by ten per cent.

The application of these decision rules to determine support or no support for the Research Proposition is explained in Chapter IV.

Summary List of Assumptions

The following assumptions were used in testing the research proposition and hypothesis:

a. That a unit returned to AGMC will require some maintenance action.

b. Successful completion of the Final Test stage is necessary and sufficient for classification of a repaired IMU as serviceable.

c. The current sequence of the process is adequate.

d. Cost for each stage can be expressed as a proportion of overall average variable cost.

e. The probability of a unit proceeding to the next sequential stage, or returning to an earlier stage,is independent of previous repair action performed.

Summary List of Limitations

The following limitations should be recognized in examining the results of this research:

a. The process was considered to be a closed system in that actions performed on a unit outside of AGMC were not considered.

b. Because of the limitations of the cost data used, the reduction in average cost resulting from the improvement of each stage can be used only to establish an ordinal ranking of the stages in terms of their criticality to the overall cost of the process.

c. The results obtained in this research are applicable only to the KT-73 Repair Process as it existed between 1 July and 1 December 1973.

CHAPTER IV

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

Introduction

In Chapter III, the method employed to test the research proposition was explained in detail. In this chapter the results obtained by selectively "improving" stages by ten per cent are presented and discussed, first in terms of the research proposition and then in terms of their practical implementation. Finally some possible limitations of the model used are identified and discussed, leading to recommendations for future research in this area.

Restatement of Research Proposition

The proposition tested in this research was:

> The process used at AGMC for repair of KT-73 Inertial Measurement Units contains one or more stages which are critical to the overall cost effectiveness of the process. Relatively small improvement in the efficiency of any one of these critical stages will lead to a major reduction in the average cost to repair an IMU, while an improvement of the same magnitude made to non-critical stages will have little effect on the overall cost.

Results

As detailed in Chapter III, the basic model constructed for the process was used to determine the effect of introducing a simulated ten per cent improvement at ten of the sixteen stages in the process. The rationale and method employed in making this "improvement" was fully discussed in Chapter III and will not be described here.

The results obtained from the model for the improvement of each of the ten stages are presented in two parts, in Appendix B and Table 5 respectively.

Appendix B comprises Tables 6 to 15 inclusive, each of which includes the following information for one of the ten stages improved;

a. Transition probabilities changed to implement the improvement, including both the old and new probability values.

b. The relative frequency of occurrence for every stage in the process obtained from the model by improving one stage in the process.

c. The new average variable cost to repair one IMU for the "improved" process.

Table 5 contains an ordinal ranking of the ten stages, in terms of the magnitude of the reduction in average variable cost obtained by "improving" each stage by ten per cent.

To determine the effect of improving any one of the ten stages by a factor of ten per cent, the reader

TABLE 5

RANKING OF STAGES BY MAGNITUDE OF REDUCTION IN VARIABLE COST FOR TEN PER CENT IMPROVEMENT

Stage	Name	Average Variable Cost After 10% Improvement	Reduction in Average Variable Cost	Projected Savings for Ten Years at 1000 Units Per Year
O	ATP	$3069*	$167	$1,670,000
H	R&R Internal Module	$3095*	$141	$1,410,000
D	Electronic Repair	$3129*	$107	$1,070,000
N	IMU Cal	$3191*	$ 45	$ 450,000
F	R&R Torque Motor	$3196*	$ 40	$ 400,000
B	R&R External Module	$3199*	$ 37	$ 370,000
I	Marriage	$3228*	$ 8	$ 80,000
K	Preseal	$3232*	$ 4	$ 40,000
G	Func Cluster Alignment	$3232*	$ 4	$ 40,000
M	Mod 5N16	$3233*	$ 3	$ 30,000

*Note: Original average variable cost = $3236 (Actual at AGMC = $3234) obtained from model.

Add $1234 in overhead cost to obtain total average cost to repair one IMU.

should refer to the appropriate Table in Appendix B. The data in Table 5 permits a comparison of the reductions in average variable cost which were obtained by selectively improving each of the ten stages considered.

In addition to the ten per cent improvement data obtained for each stage, two additional runs were made representing the improvement of the Internal Module and Electronics Repair stages by twenty per cent. The results of these runs, shown in Appendix C, are provided for information only and will not be discussed further.

Discussion of Results

From the results presented in Table 5 it may be seen that, although each of the ten stages was improved by a uniform ten per cent, the resultant reductions in average variable cost varied significantly between stages. Improvement of three of the stages yielded a reduction in average variable cost in excess of $100, while a similar improvement to the last four stages in the ranking yielded a maximum reduction of $8 per IMU.

The fact that the maximum reduction was obtained by improving the ATP (Final Test) stage was not entirely unexpected. As explained in some detail in earlier chapters, the rejection of an IMU at Final Test to one of the earlier stages in the process causes the unit to repeat not only the stage to which it was rejected, but a number of other stages on its way back through the process to Final Test.

Consequently the "improvement" of Final Test by ten per cent, which simulates the situation where fewer IMU's are being incorrectly rejected at that stage, has an impact on the relative frequency of almost every stage in the process. This effect may be verified by reference to the relative frequencies shown in Appendix B, Table 15.

Similarly, the high position of the Internal Module stage in terms of the reduction in average variable cost was to some extent predictable, because of the high cost of processing a unit through that stage. In this case the "improvement" led to a simulated reduction in the number of units returning to that stage for correction of some deficiency, and although the effect throughout the remainder of the process was not as marked as for improvement of the Final Test stage, it was sufficient to cause a reduction of $141 in the average variable cost to repair a single IMU.

The very low reduction in average variable cost recorded for four of the stages is attributed to three major factors. First, each of these four stages has a relatively low number of feedback paths which could be improved. Second, their position in the process is such that the "feedback loop" is relatively short, i.e., a unit rejected does not have to repeat many stages before returning to the stage of rejection. Third, none of the stages in the "feedback loop" for any of the four "low" stages involves a high unit passage cost. The combination of these factors leads, in each case, to the stage having little overall influence on the behavior of the process as a whole, as may be seen from examination of the results in Appendix B, Tables 9, 11, 12, and 13.

Evidence in Support of Research Proposition

The decision criteria specified in Chapter III for determining whether one or more stages are critical to the overall cost effectiveness of the process were:

a. For a simulated ten per cent improvement to a stage, the reduction in average variable cost to repair an IMU must exceed five per cent of the current average variable cost, and

b. The reduction in average variable cost corresponding to a simulated ten per cent improvement for a stage must be at least twice the average reduction obtained from improvement of all stages in the process by ten per cent.

From the results in Table 5 it may be seen that the average reduction in average variable cost to repair a single IMU was $55.6. Consequently, using the decision rule at subparagraph b above, stages O, H, and D in the model, corresponding to the ATP, R&R Internal Module, and Electronics Repair stages in the KT-73 Repair Process meet one of the requirements defined for a "critical" stage.

The second requirement, to yield a reduction in average variable cost exceeding five per cent of current average variable cost ($3234 X .05 = $161.70), causes stages H and D to be eliminated from consideration as "critical" stages. However, stage O, which yielded a saving of $167, does meet both requirements established for definition as a "critical" stage.

Although stages H and D do not meet both formal requirements established for "critical" stages, it is the opinion of the researchers that both stages meet the general criteria for criticality explained in Chapter I. The simulated improvement of both stages produced a reduction in average variable cost which was large in relation to the fourth ranked stage, while the percentage reductions in average variable cost were 4.35% and 3.3% for stages H and D respectively.

Consequently although only stage O in the model can be formally classified as "critical" in terms of the decision criteria specified, it is the contention of the researchers that the KT-73 Repair Process actually contains three "critical" stages, in stages O, H, and D. Irrespective of the classification of stages H and D as critical or non-critical it is concluded that some support for the concept of "criticality" stated in the Research Proposition has been demonstrated in this case.

Practical Application of the Results

The problem statement in Chapter I defined the identification of critical areas or stages as the first step in determining where an improvement effort could most profitably be applied in the process. The objective of the research was further defined in Chapter I as identification of major critical areas or stages, and it was stressed in Chapter II that the stages defined in the process model each covered a variety of tasks.

Consequently, although three major stages of the process have been identified as "critical" in the preceding sections, it is appropriate to consider the practical application of this finding. In doing so the following list of considerations suggested by Genet (5:35) are repeated here in the form of questions:

a. Can the theoretical improvement actually be achieved in practice?

b. What is the cost of making the improvement?

c. How easily and quickly could the improvement be evaluated after its introduction?

d. How long will it take to realize the expected cost savings?

For the present these questions must remain unanswered for the KT-73 Repair Process since their determination requires a much deeper and more comprehensive analysis of the process than has been possible in this research. Hopefully, however, the gross analysis of the KT-73 process described in this thesis has served three practical purposes, namely:

a. Provided some support for the concept of critical stages in a complex repair process.

b. Demonstrated the applicability of The Theory of Finite Markov Chains to an analysis of repair processes of this type, and

c. Provided a starting point for more detailed analysis of the KT-73 process to identify specific areas in which improvements can be made (or sources of error eliminated).

Limitations of the Model

In addition to the limitations of the research identified in Chapter III, the following limitations have been identified from an evaluation of the performance of the model used to test the Research Proposition.

a. Due to the construction of the model there is no way of evaluating the performance of the Initial Test stage at the beginning of the process (Stage A) in the terms of the "improvement" criteria applied to other stages of the model.

b. Although it was stressed in Chapter II that each major stage in the model represented a number of different tasks, and although the objective of the research was to perform a gross cost effectiveness analysis of the KT-73 process, it was considered that more definitive results may have been obtained by use of a more detailed model established from primary data. This possible shortcoming is addressed as one of the Recommendations for Future Research.

c. While the Assumption of Independence was shown to provide an excellent approximation of the actual behavior of the process (see Validation of Model, Chapter III), the use of this assumption may detract from acceptance of the results by AGMC personnel familiar with complex repair processes. More comprehensive data regarding the behavior of the system would permit the construction of a more complex model, which does not rely on the Assumption of Independence made in this study.

Recommendations for Future Research

In light of comments in the previous section, the following recommendations are made for future research in the areas described:

a. The three stages identified as "critical" to the KT-73 Repair Process should be examined in greater detail to determine whether more specific, critical elements can be identified. This could be accomplished by constructing a more detailed model using primary data available at AGMC.

b. That the technique used in this research, involving analysis of complex repair processes using absorbing Markov chains, be further explored. Such a project may be undertaken by future AFIT thesis teams in conjunction with AGMC.

Conclusions

By the use of a mathematical modeling technique to simulate the operation of the KT-73 Repair Process, it has been shown that the introduction of a simulated ten per cent improvement at each of the stages in the process leads to quite a wide variation in the magnitude of the reduction in <u>average</u> cost to repair one IMU.

While the analysis performed in this case is subject to the limitations identified throughout the paper, it is considered that the <u>technique</u> used has great potential in establishing where an improvement could most profitably be introduced in many of the repair processes in use within the Air Force today. The results obtained showed that if a modest improvement can be made at one of three stages in the process, the average cost to repair <u>each</u> IMU could possibly be reduced by as much as $167. Extended over a ten year period, at the current costs and rates of flow, the <u>total</u> savings would be in the order of $1.5 million. This was the justification for the research.

APPENDIX A

OMNITAB II COMPUTER PROGRAM

Description of the Program

It was specified in Chapter III that the average variable cost for the process could be obtained from the product

$$\pi(0) \cdot (I-Q)^{-1} \cdot (C)$$

where $\pi(0)$, $(I-Q)^{-1}$ and C are as defined in Chapter III, page 54. It was further specified that the product $\pi(0) \cdot (I-Q)^{-1}$ was contained in the first row of the $(I-Q)^{-1}$ matrix (Chapter III, page 54).

The OMNITAB II Computer Program presented in this appendix is designed to take the inverse of an input data matrix, (I-Q). The resultant matrix, $(I-Q)^{-1}$, is then transposed so that the first row of the inverse, which represents relative frequency of occurrence of each stage, is contained in Column 1 of the transpose matrix. Column 1 of the transpose matrix is then multiplied by the row vector (C) whose elements are standard cost per unit flow through each stage. The elements of the resultant vector are summed to obtain an average variable cost for the process.

OMNITAB II is a programming system developed by the National Bureau of Standards to facilitate the use of

Pages 80-81 blank

the computer for complex mathematical analysis. Complete details of the system are contained in National Bureau of Standards Technical Note 552, published in October 1971, and available from the U.S. Government Printing Office, Washington, D.C.

<u>OMNITAB II COMPUTER PROGRAM</u>

```
10##MOVE NORM
20$:IDENT:WP.AFITSL WATERMAN-WATSON
30$:PROGRAM:RLHS
40$:PRMFL:H*.R,R,OMNITAB/SMTAB
50$:REMOTE:P*.SL
60$:REMOTE:SS,SL
70$:LIMITS:39K,,2000
80$:FILE:01,X2R,10L
90$:DATA:05
100:OMNITAB REPAIR PROCESS MODEL
110 SCAN 72S
120 DIMENSION 25,82
130 READ 1***20

1XX INPUT DATA MATRIX (using a row by row input)

340 NULL
350 SET 21

360 INPUT COST VECTOR (as a column input)
380 MINVERT 1,1,20X20,1,22
390 MTRANSPOSE 1,22,20X20,1,43
400 MULTIPLY 21,BY 43, PUT IN 80
410 SUM 80, PUT IN 81
420 HEAD 43/REL FREQ
430 HEAD 80/COST/STAGE
440 PRINT 43,80
450 SPACE 10
460 NOTE CURRENT STATUS OF REPAIR LINE
470 NOTE AVERAGE COST AT 22.14 S/HR
480 ABRIDGE 1,81
490 STOP
500 END
```

APPENDIX B

RESULTS - IMPROVEMENT OF PROCESS STAGES BY TEN PERCENT

TABLE 6

IMPROVEMENT OF EXTERNAL MODULE STAGE BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.059
C	R&R G.C.A.	.27	.268
D	Electronic Rpr	.49	.485
E	Diag Clust Align	.40	.396
F	R&R Torque Motor	.09	.089
G	Func Clust Align	.41	.406
H	R&R Int Module	.42	.417
I	Marriage	.31	.307
J	R&R G.C.A.	.27	.267
K	Preseal	.44	.436
L	Minor Wir Rpr	.13	.129
M	Mod 5N16	.42	.417
N	IMU Cal	1.62	1.594
O	ATP	1.43	1.413
P	Dummy	.03	.028
Q	Dummy	.00	.002
R	Dummy	.05	.052
S	Dummy	.01	.010
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3199.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
NB	.034	.0306
NO	.883	.8864
OB	.089	.0801
OT	.699	.7079

TABLE 7

IMPROVEMENT OF ELECTRONIC REPAIR STAGE BY TEN PERCENT FFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.058
C	R&R G.C.A.	.27	.260
D	Electronic Rpr	.49	.435
E	Diag Clust Align	.40	.358
F	R&R Torque Motor	.09	.086
G	Func Clust Align	.41	.368
H	R&R Int Module	.42	.403
I	Marriage	.31	.282
J	R&R G.C.A.	.27	.254
K	Preseal	.44	.431
L	Minor Wir Rpr	.13	.124
M	Mod 5N16	.42	.411
N	IMU Cal	1.62	1.586
O	ATP	1.43	1.407
P	Dummy	.03	.022
Q	Dummy	.00	.002
R	Dummy	.05	.050
S	Dummy	.01	.010
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3129.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
DC	.014	.0126
DP	.057	.0513
DE	.816	.8231
FD	.144	.1296
FK	.706	.7204
GC	.018	.0162
GD	.075	.0675
G1	.756	.7653
IC	.026	.0234
ID	.110	.0990
IJ	.645	.6586
HD	.144	.1296
HK	.706	.7204
NC	.009	.0081
ND	.036	.0324
NO	.883	.8875
OC	.022	.0198
OD	.093	.0837
OT	.699	.7105

TABLE 8

IMPROVEMENT OF TORQUE MOTOR STAGE BY TEN PERCENT
EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improved Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.067
C	R&R G.C.A.	.27	.262
D	Electronic Rpr	.49	.480
E	Diag Clust Align	.40	.393
F	R&R Torque Motor	.09	.082
G	Func Clust Align	.41	.403
H	R&R Int Module	.42	.412
I	Marriage	.31	.306
J	R&R G.C.A.	.27	.267
K	Preseal	.44	.431
L	Minor Wir Rpr	.13	.127
M	Mod 5N16	.42	.411
N	IMU Cal	1.62	1.608
O	ATP	1.43	1.423
P	Dummy	.03	.027
Q	Dummy	.00	.002
R	Dummy	.05	.051
S	Dummy	.01	.010
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3196.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
DC	.014	.0126
DE	.816	.8184
DF	.010	.0090
GC	.018	.0162
GF	.014	.0126
GI	.756	.7592
IC	.026	.0234
IF	.020	.0180
IJ	.645	.6496
HF	.026	.0234
HK	.706	.7086
NC	.009	.0081
NF	.007	.0063
NO	.883	.8847
OC	.022	.0198
OF	.017	.0153
OT	.699	.7029
FD	.144	.1296
FH	.124	.1116
FQ	.026	.0234
FK	.706	.7354

TABLE 9

IMPROVEMENT OF FUNCTIONAL CLUSTER ALIGNMENT BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.070
C	R&R G.C.A.	.27	.269
D	Electronic Rpr	.49	.486
E	Diag Clust Align	.40	.396
F	R&R Torque Motor	.09	.090
G	Func Clust Align	.41	.406
H	R&R Int Module	.42	.420
I	Marriage	.31	.311
J	R&R G.C.A.	.27	.271
K	Preseal	.44	.440
L	Minor Wir Rpr	.13	.130
M	Mod 5N16	.42	.420
N	IMU Cal	1.62	1.620
O	ATP	1.43	1.431
P	Dummy	.03	.028
Q	Dummy	.00	.002
R	Dummy	.05	.052
S	Dummy	.01	.010
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3232.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
GC	.018	.0162
GD	.075	.0675
GI	.756	.7653

TABLE 10

IMPROVEMENT OF INTERNAL MODULE STAGE BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.065
C	R&R G.C.A.	.27	.261
D	Electronic Rpr	.49	.474
E	Diag Clust Align	.40	.390
F	R&R Torque Motor	.09	.087
G	Func Clust Align	.41	.399
H	R&R Int Module	.42	.378
I	Marriage	.31	.305
J	R&R G.C.A.	.27	.265
K	Preseal	.44	.408
L	Minor Wir Rpr	.13	.120
M	Mod 5N16	.42	.389
N	IMU Cal	1.62	1.590
O	ATP	1.43	1.410
P	Dummy	.03	.027
Q	Dummy	.00	.002
R	Dummy	.05	.042
S	Dummy	.01	.009
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3095.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
DC	.014	.0126
DH	.049	.0441
DE	.816	.8223
FH	.124	.1116
FK	.706	.7184
GH	.065	.0585
GC	.018	.0162
GI	.756	.7643
IC	.026	.0234
IH	.094	.0846
IJ	.645	.6570
NC	.009	.0081
NH	.031	.0279
NO	.883	.8870
OH	.080	.0720
OC	.022	.0198
OT	.699	.7092
HK	.706	.7184
HR	.124	.1116

TABLE 11

IMPROVEMENT OF MARRIAGE STAGE BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.069
C	R&R G.C.A.	.27	.268
D	Electronic Rpr	.49	.485
E	Diag Clust Align	.40	.395
F	R&R Torque Motor	.09	.090
G	Func Clust Align	.41	.405
H	R&R Int Module	.42	.419
I	Marriage	.31	.307
J	R&R G.C.A.	.27	.272
K	Prescal	.44	.439
L	Minor Wir Rpr	.13	.129
M	Mod 5N16	.42	.419
N	IMU Cal	1.62	1.620
O	ATP	1.43	1.431
P	Dummy	.03	.028
Q	Dummy	.00	.002
R	Dummy	.05	.052
S	Dummy	.01	.010
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3228.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
IC	.026	.0234
ID	.110	.0990
IJ	.645	.6586

TABLE 12

IMPROVEMENT OF PRESEAL STAGE BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.070
C	R&R G.C.A.	.27	.269
D	Electronic Rpr	.49	.489
E	Diag Clust Align	.40	.399
F	R&R Torque Motor	.09	.090
G	Func Clust Align	.41	.408
H	R&R Int Module	.42	.421
I	Marriage	.31	.308
J	R&R G.C.A.	.27	.302
K	Preseal	.44	.424
L	Minor Wir Rpr	.13	.115
M	Mod 5N16	.42	.373
N	IMU Cal	1.62	1.620
O	ATP	1.43	1.431
P	Dummy	.03	.028
Q	Dummy	.00	.002
R	Dummy	.05	.052
S	Dummy	.01	.009
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3232.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
LK	.615	.5535
LM	.385	.4465
KG	.023	.0207
KM	.818	.7362
KJ	.159	.2431

TABLE 13

IMPROVEMENT OF MOD 5N16 STAGE BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.070
C	R&R G.C.A.	.27	.269
D	Electronic Rpr	.49	.490
E	Diag Clust Align	.40	.399
F	R&R Torque Motor	.09	.090
G	Func Clust Align	.41	.409
H	R&R Int Module	.42	.421
I	Marriage	.31	.309
J	R&R G.C.A.	.27	.268
K	Preseal	.44	.430
L	Minor Wir Rpr	.13	.112
M	Mod 5N16	.42	.403
N	IMU Cal	1.62	1.620
O	ATP	1.43	1.431
P	Dummy	.03	.028
Q	Dummy	.00	.002
R	Dummy	.05	.052
S	Dummy	.01	.009
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3233.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
ML	.309	.2781
MS	.024	.0216
MN	.667	.7003

TABLE 14

IMPROVEMENT OF IMU CALIBRATION BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.062
C	R&R G.C.A.	.27	.267
D	Electronic Rpr	.49	.478
E	Diag Clust Align	.40	.390
F	R&R Torque Motor	.09	.088
G	Func Clust Align	.41	.400
H	R&R Int Module	.42	.411
I	Marriage	.31	.302
J	R&R G.C.A.	.27	.263
K	Preseal	.44	.430
L	Minor Wir Rpr	.13	.127
M	Mod 5N16	.42	.411
N	IMU Cal	1.62	1.599
O	ATP	1.43	1.431
P	Dummy	.03	.027
Q	Dummy	.00	.002
R	Dummy	.05	.051
S	Dummy	.01	.010
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3191.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
NB	.034	.0306
NC	.009	.0081
ND	.036	.0324
NF	.007	.0063
NH	.031	.0279
NO	.883	.8947

TABLE 15

IMPROVEMENT OF ATP STAGE BY TEN PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Number	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.044
C	R&R G.C.A.	.27	.263
D	Electronic Rpr	.49	.453
E	Diag Clust Align	.40	.370
F	R&R Torque Motor	.09	.083
G	Func Clust Align	.41	.379
H	R&R Int Module	.42	.390
I	Marriage	.31	.287
J	R&R G.C.A.	.27	.256
K	Preseal	.44	.408
L	Minor Wir Rpr	.13	.120
M	Mod 5N16	.42	.389
N	IMU Cal	1.62	1.553
O	ATP	1.43	1.372
P	Dummy	.03	.026
Q	Dummy	.00	.002
R	Dummy	.05	.048
S	Dummy	.01	.009
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3069.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
OB	.089	.0801
OC	.022	.0198
OD	.093	.0837
OF	.017	.0153
OH	.080	.0720
OT	.699	.7291

APPENDIX C

RESULTS - IMPROVEMENT OF TWO STAGES BY TWENTY PER CENT

TABLE 16

IMPROVEMENT OF INERTIAL MODULE STAGE BY TWENTY PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improve Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.06
C	R&R G.C.A.	.27	.254
D	Electronic Rpr	.49	.459
E	Diag Clust Align	.40	.380
F	R&R Torque Motor	.09	.084
G	Func Clust Align	.41	.389
H	R&R Int Module	.42	.337
I	Marriage	.31	.300
J	R&R G.C.A.	.27	.261
K	Preseal	.44	.376
L	Minor Wir Rpr	.13	.111
M	Mod 5N16	.42	.359
N	IMU Cal	1.62	1.56
O	ATP	1.43	1.39
P	Dummy	.03	.026
Q	Dummy	.00	.002
R	Dummy	.05	.033
S	Dummy	.01	.009
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $2961.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
DC	.014	.0112
DH	.049	.0392
DE	.816	.8286
FH	.124	.0992
FK	.706	.7308
GH	.065	.0520
GC	.018	.0144
GL	.756	.7726
IC	.626	.6208
IH	.094	.0752
IJ	.645	.6690
NC	.009	.0072
NH	.031	.0248
NO	.883	.8910
OH	.080	.0621
OC	.022	.0176
OT	.699	.7194
HK	.706	.7308
HR	.124	.0992

TABLE 17

IMPROVEMENT OF ELECTRONICS REPAIR STAGE BY TWENTY PERCENT

EFFECT ON RELATIVE FREQUENCIES

Stage	Name	Original Relative Frequency	10% Improved Relative Frequency
A	Receiving	1.0	1.0
B	R&R Ext Module	1.07	1.046
C	R&R G.C.A.	.27	.250
D	Electronic Rpr	.49	.384
E	Diag Clust Align	.40	.318
F	R&R Torque Motor	.09	.083
G	Func Clust Align	.41	.328
H	R&R Int Module	.42	.386
I	Marriage	.31	.254
J	R&R G.C.A.	.27	.238
K	Preseal	.44	.420
L	Minor Wir Rpr	.13	.124
M	Mod 5N16	.42	.401
N	IMU Cal	1.62	1.551
O	ATP	1.43	1.384
P	Dummy	.03	.017
Q	Dummy	.00	.002
R	Dummy	.05	.048
S	Dummy	.01	.010
T	Shipping Prep	1.0	1.0

New Average Variable Cost = $3024.

INPUT PROBABILITY DATA

Transition Prob	Original Value	10% Improve Value
DC	.014	.0126
DP	.057	.0513
DE	.816	.8231
GD	.075	.0[illegible]5
GC	.018	.0162
GI	.756	.7653
IJ	.645	.6586
ID	.110	.099
IC	.026	.0234
ND	.036	.0324
NC	.009	.0081
NO	.883	.8875
OT	.699	.7105
OC	.022	.0198
OD	.093	.0837
HD	.144	.1296
KF	.706	.7204
FD	.144	.1296
FK	.706	.7204

SELECTED BIBLIOGRAPHY

A. REFERENCES CITED

1. Burke, Thomas E. "Analysis of Multi-Output Sequentially Phased Systems Using Markov Chains." Master's Thesis, Texas A&M University, May, 1969.

2. Burt, John N., Lt Col., USAF and Lt. Robert T. Denbow. "G200 Bearing: An Analysis Concerning the Reliability of an Inexpensive Part and its Effect on Depot Level Repair Cost." Unpublished Master's Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 16 January 1974.

3. Chase, Richard B. and Nicholas J. Aquilano. Production and Operations Management - A Life Cycle Approach. Homewood, Illinois: Richard D. Irwin, Inc., 1973.

4. Genet, Russell M., Chief, Industrial Engineering Support Division, AGMC, Newark Air Force Station, Newark, Ohio. Personal interview, 10 December 1973, 7 January 1974, 11 February 1974, and 18 March 1974.

5. Genet, Russell M. and Patrick R. Handley. Rebuild VS Repair - A Logistics Analysis. AGMC, Newark, Ohio, undated.

6. Genet, Russell M. "The Application of Operations Analysis to Achieve Major Cost Savings in the Repair Process at AGMC. AGMC, Newark, Ohio, 10 July 1970.

7. ________. "An Introduction to the Theory and Improvement of Multi-Level Tests in Repair Processes." AGMC, Newark, Ohio, 20 June 1972.

8. ________. "An Introduction to Repair Engineering and its Application at Special Repair Facilities. AGMC, Newark, Ohio, 10 November 1969.

9. ________. "Results of a Logistical Analysis of the Depot Level Repair of Air Force Inertial Guidance Systems. AGMC, Newark, Ohio, 10 March 1971.

10. Hillier, Frederick S. and Gerald J. Leiberman. Introduction to Operations Research. San Francisco, Calif.: Holden Day Inc., 1967.

11. Howard, Ronald A. Dynamic Programming and Markov Processes. Cambridge, Mass.: MIT Press, Institute of Technology, March 1966.

12. ________. Dynamic Probabilistic Systems. Vol. 1. New York: John Wiley and Sons, Inc., 1971.

13. Jones, R., Lead Technician, Industrial Engineering Department, MABE, AGMC, Newark, Ohio. Personal interview, 11 February 1974.

14. Kemeny, John G. and Laur.e J. Snell. Finite Markov Chain's. Princeton, N.J : D Van Nostrand Company, Inc., February, 1963.

15. Miller, H., Engineering Technician, Industrial Engineering Department, MABE, AGMC, Newark Air Force Station, Newark, Ohio. Personal interviews, Newark, Ohio, 10 December 1973, and 7 January 1974.

16. Price, Howard, Program Analyst, MAWNF, AGMC, Newark, Ohio. Personal interview, 18 March 1974.

17. Rogge, R., Reliability Engineering Section, AGMC, Newark Air Force Station, Newark, Ohio. Personal interviews, Newark, Ohio, 10 December 1973, and 18 March 1974.

18. Sisco, William, Production Supervisor KT-73 Repair Shop, AGMC. Personal interviews, Newark, Ohio, 7 January 1974, and 11 February 1974.

19. Sims, Robert L., Major, USAF. Associate Professor of Management Science, Air Force Institute of Technology, Air University. Various personal interviews from 1 April to 14 June 1974.

20. ________. "Cost Moments at Mean Flow Stochastic Network Outputs." Unpublished paper, U.S. Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio.

21. Walden, Ralph, Engineering Department, AGMC. Personal interview, Newark, Ohio, 7 January 1974.

22. ________. Flowchart of the KT-73 Repair Process. Unpublished document prepared by Production Planning Department, AGMC, Newark Air Force Station, Newark, Ohio, 16 November 1973.

B. RELATED SOURCES

Bharucha, Reid A.T. Elements of the Theory of Markov Processes and Their Applications. New York: McGraw-Hill Book Company, 1960.

Cox, D.R. and H.D. Miller. The Theory of Stochastic Processes. London: Melhuen & Company, Ltd., 1970.

Elmaghraby, Salah E. The Design of Production Systems. New York: Rienhold Publishing Company, 1966.

Genet, Russell M. "Evaluating Inertial Guidance Acceptance and Performance Tests." AGME, Newark, Ohio, 16 February 1970.

Genet, Russell M. and Patrick R. Handley. "The Application of Latin Squares to the Determination of the Primary Cause of Test Unreliability." AGMC, Newark, Ohio, 20 December 1970.

Genet, Russell M. "Gyroscope Measurement and Classification: A Purely Empirical Approach for Application to the Use/Repair Cycle." AGMC, Newark, Ohio, 16 September 1969.

Genet, Russell M., Richard R. Martin, and Roosevelt R. Besteda. "An Assessment of Cost and Reliability Changes in the LN-12 Inertial Platform." AGMC, Newark Air Force Station, Newark, Ohio, 30 May 1973.

Genet, Russell M. "Depot Level Reliability Analysis of the KT-73 Inertial Measurement Unit." AGMC, Newark Air Force Station, Newark, Ohio, 19 October 1972.

Hohn, Franz E. Elementary Matrix Algebra. New York: The Macmillan Company, 2ed., 1964.

Kemeny, John G., Laurie J. Snell, and Anthony N. Knapp. Denumerable Markov Chains. Princeton, N.J.: D Van Nostrand Company, Inc., 1966.