MAINTAINABILITY OPTIMIZATION - THE FUTURE CHALLENGE

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Abstract

The paper describes the development of a method of optimizing airplane maintenance, using generalized network flow and mixed integer linear programming computer models. The optimization determines the best sequence of activities and best allocation of mechanics to maintenance activities involving more than one mechanic. (For single mechanic tasks the sequence and allocation optimization problem does not exist.)

In the model, maintenance tasks are divided into their elemental activities, each activity being interrelated by a precedence network. The purpose of the optimization is to minimize one or more of several objective functions such as total labor, elapsed job time, or the job total cost.

Optimization of maintenance activities raised the question of how the results should be presented to mechanics. A real time system was developed for the purpose of presenting instructions to mechanics.

Testing the computational procedure and the real time system has included several maintenance task scheduling problems, the largest of which was for removal and replacement of a Boeing 757 airplane engine.

I. Introduction

Deregulation of the U.S. airline industry is causing intense competition, absorption of small airlines by large, and a heavy emphasis on reduction of labor costs of all types. Against this background the author has been actively researching means of reducing the amount of labor required for commercial airplane maintenance operations. The research has focused on the development of data in three overlapping areas:

- Quantitative assessments of the amount of maintenance time and labor required for new airplane designs
- Economical development of maintenance plans for new airplanes
- Efficient execution of maintenance

The need to develop an accurate method of quantitatively assessing the maintainability attributes of new airplane design led the author to develop a system of predetermined time standards known as AMETS, Airplane Maintenance Engineered Time Standards. AMETS is more fully described in Reference 1 and part of a typical analysis using the AMETS system is shown in Figure 1. The use of AMETS for the analysis of new airplane designs raised several issues directly related to efficient maintenance planning and execution.

First, the maintenance task must be described in some detail so that a match can be made between elements of the work and predetermined standards. At times the analysis is made when the airplane exists only on paper. Even though the analysis is made at an early stage of design, the task description forms an accurate enough set of instructions for use by a maintenance mechanic. Since one major airline started using an AMETS analysis as a supplement to the maintenance manual an issue was whether AMETS task descriptions should be extended and supplant the maintenance manual.

Second, tasks performed by more than one mechanic in real-world maintenance must be identified so that an accurate estimate can be made of the elapsed time for the defined work as well as the amount of labor involved. When carefully performed, this process results in a work plan that is frequently better than the usual practice of leaving mechanics to their own devices. Another issue was therefore whether maintenance mechanics could and would work to a set of optimized instructions.

'Optimal' can have different connotations. For example, there may be a requirement to accomplish the same maintenance operation either in minimum elapsed time or with minimum labor costs. When the costs of airplane delays are known, scheduling and sequencing of maintenance may also be optimized for minimum total cost. However, while optimization using such objective functions as elapsed time, labor cost, or total cost was obviously desirable, the large number of alternative allocations of mechanics and possible sequences of activities (even with relatively simple maintenance tasks) magnified the problem. Several approaches were used for solving this problem and they are described in the section that follows.

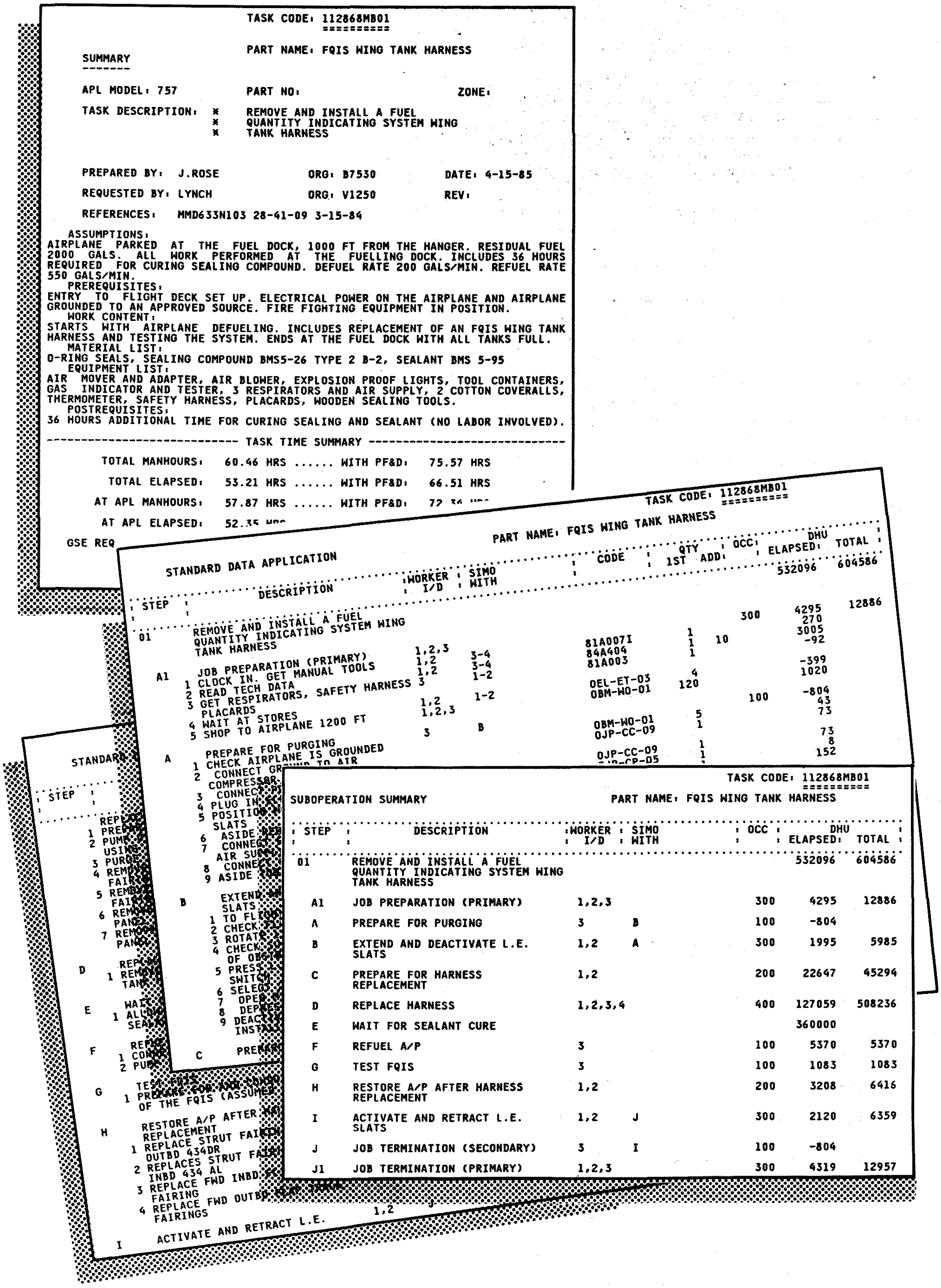
II. Multiman Task Optimization

Realization that the optimization of multiman tasks was going to be difficult came with the discovery that each time an AMETS multiman task analysis was reviewed it was possible to find a better way of allocating and sequencing the maintenance activities it contained. In fact, the enumeration of all possible alternatives for allocating M mechanics among N independent activities of a maintenance task is approximately given by expression:

$$U = N! \sum_{r=MIN}^{MAX} \frac{MAX!}{r!\,(MAX - r)!}$$

where:

U is the approximate number of alternatives
N is the number of independent activities
r is the number of mechanics used
MIN is the minimum mechanics required
MAX is the maximum mechanics possible



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                                 TASK CODE: 112868MB01
                                            ==========
                                 PART NAME: FQIS WING TANK HARNESS
    SUMMARY
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    APL MODEL: 757               PART NO:                          ZONE:

    TASK DESCRIPTION:  *         REMOVE AND INSTALL A FUEL
                       *         QUANTITY INDICATING SYSTEM WING
                       *         TANK HARNESS

    PREPARED BY:  J.ROSE              ORG: B7530           DATE: 4-15-85

    REQUESTED BY: LYNCH               ORG: V1250           REV:

    REFERENCES:   MMD633N103 28-41-09 3-15-84

   ASSUMPTIONS:
 AIRPLANE  PARKED  AT  THE  FUEL DOCK, 1000 FT FROM THE HANGER. RESIDUAL FUEL
 2000  GALS.  ALL  WORK  PERFORMED  AT  THE  FUELLING DOCK. INCLUDES 36 HOURS
 REQUIRED  FOR CURING SEALING COMPOUND. DEFUEL RATE 200 GALS/MIN. REFUEL RATE
 550 GALS/MIN.
   PREREQUISITES:
 ENTRY  TO  FLIGHT DECK SET UP. ELECTRICAL POWER ON THE AIRPLANE AND AIRPLANE
 GROUNDED TO AN APPROVED SOURCE. FIRE FIGHTING EQUIPMENT IN POSITION.
   WORK CONTENT:
 STARTS  WITH  AIRPLANE  DEFUELING. INCLUDES REPLACEMENT OF AN FQIS WING TANK
 HARNESS AND TESTING THE SYSTEM. ENDS AT THE FUEL DOCK WITH ALL TANKS FULL.
   MATERIAL LIST:
 O-RING SEALS, SEALING COMPOUND BMS5-26 TYPE 2 B-2, SEALANT BMS 5-95
   EQUIPMENT LIST:
 AIR  MOVER AND ADAPTER, AIR BLOWER, EXPLOSION PROOF LIGHTS, TOOL CONTAINERS,
 GAS  INDICATOR AND TESTER, 3 RESPIRATORS AND AIR SUPPLY, 2 COTTON COVERALLS,
 THERMOMETER, SAFETY HARNESS, PLACARDS, WOODEN SEALING TOOLS.
   POSTREQUISITES:
 36 HOURS ADDITIONAL TIME FOR CURING SEALING AND SEALANT (NO LABOR INVOLVED).

 --------------------------- TASK TIME SUMMARY ----------------------------

        TOTAL MANHOURS:    60.46 HRS ...... WITH PF&D:   75.57 HRS

          TOTAL ELAPSED:   53.21 HRS ...... WITH PF&D:   66.51 HRS

       AT APL MANHOURS:    57.87 HRS ...... WITH PF&D:   72

         AT APL ELAPSED:   52.35

   GSE REQ
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                                                          TASK CODE: 112868MB01
                                                                     ==========
                                       PART NAME: FQIS WING TANK HARNESS
   STANDARD DATA APPLICATION
 ......................................................................................
 : STEP :        DESCRIPTION           :WORKER : SIMO  :   CODE   :  QTY  : OCC:    DHU         :
 :      :                              :  I/D  : WITH  :          : 1ST ADD:    : ELAPSED: TOTAL :
 ......................................................................................
                                                                               532096   604586
  01      REMOVE AND INSTALL A FUEL
          QUANTITY INDICATING SYSTEM WING
          TANK HARNESS                                                    300    4295    12886
   A1     JOB PREPARATION (PRIMARY)      1,2,3                                    270
        1 CLOCK IN. GET MANUAL TOOLS     1,2     3-4    81A007I    1             3005
        2 READ TECH DATA                 1,2     3-4    84A404     1   10         -92
        3 GET RESPIRATORS, SAFETY HARNESS 3      1-2    81A003     1
          PLACARDS                                                               -399
        4 WAIT AT STORES                 1,2     1-2    OEL-ET-03  4             1020
        5 SHOP TO AIRPLANE 1200 FT       1,2,3          OBM-WO-01  120    100    -804
                                                                                  43
   A      PREPARE FOR PURGING            3       B      OBM-WO-01  5              73
        1 CHECK AIRPLANE IS GROUNDED                    OJP-CC-09  1              73
        2 CONNECT GR                                                               8
          COMPRESS                                      OJP-CC-09  1             152
        3 CONNECT
        4 PLUG IN
        5 POSITIO
          SLATS
        6 ASIDE
        7 CONNEC
          AIR SU
        8 CONNE
        9 ASIDE
   B      EXTEND
          SLATS
        1 TO FL
        2 CHECK
        3 ROTAT
        4 CHECK
          OF OB
        5 PRES
          SWITC
        6 SELEC
        7 OPE
        8 DEP
        9 DEAC
          INST
   C      PRE
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   STANDAR
 : STEP  :
          REP
   A1   1 PRE
        2 PUM
          USI
        3 PUR
        4 REM
          FAI
        5 REM
          FAI
        6 REM
          PAN
        7 REM
          PAN
   D      REP
        1 REM
          TAN
   E      WAI
        1 ALL
          SEA
   F      RE
        1 CO
        2 PU
   G      TEST FQIS
        1 PREPARE FOR AND COND
          OF THE FQIS (ASSUME
   H      RESTORE A/P AFTER
          REPLACEMENT
        1 REPLACE STRUT FAI
          OUTBD 434DR
        2 REPLACES STRUT F
          INBD 434 AL
        3 REPLACE FWD INBD
          FAIRING
        4 REPLACE FWD OUTB
          FAIRINGS
   I      ACTIVATE AND RETRACT L.E.      1,2
```

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                                                         TASK CODE: 112868MB01
                                                                    ==========
 SUBOPERATION SUMMARY                          PART NAME: FQIS WING TANK HARNESS

 .................................................................................
 : STEP :          DESCRIPTION           :WORKER : SIMO  :  OCC :        DHU       :
 :      :                                :  I/D  : WITH  :      : ELAPSED: TOTAL :
 .................................................................................
   01     REMOVE AND INSTALL A FUEL                                 532096   604586
          QUANTITY INDICATING SYSTEM WING
          TANK HARNESS

   A1     JOB PREPARATION (PRIMARY)         1,2,3            300      4295    12886

   A      PREPARE FOR PURGING               3        B       100      -804

   B      EXTEND AND DEACTIVATE L.E.        1,2      A       300      1995     5985
          SLATS

   C      PREPARE FOR HARNESS               1,2              200     22647    45294
          REPLACEMENT

   D      REPLACE HARNESS                   1,2,3,4          400    127059   508236

   E      WAIT FOR SEALANT CURE                                     360000

   F      REFUEL A/P                        3                100      5370     5370

   G      TEST FQIS                         3                100      1083     1083

   H      RESTORE A/P AFTER HARNESS         1,2              200      3208     6416
          REPLACEMENT

   I      ACTIVATE AND RETRACT L.E.         1,2      J       300      2120     6359
          SLATS

   J      JOB TERMINATION (SECONDARY)       3        I       100      -804

   J1     JOB TERMINATION (PRIMARY)         1,2,3            300      4319    12957
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FIGURE 1. Example of a manually sequenced AMETS analysis showing the manner in which up to four mechanics are assigned to various activities.

For an unusually simple task with only four activities and from two to four mechanics, an evaluation of up to 264 different alternatives is necessary in order to find the optimum case for a given objective function. A more typical task analysis using up to four mechanics and consisting of perhaps ten independent activities produces many millions of alternatives. Given that there is also a precedence relationship between P of the activities, there are P(P-1)/2 alternative paths between the start and end of the work. Such an analysis is not only beyond the extent of anyone's patience, but an exact solution is beyond the capabilities of current computers.

Moreover, it seemed reasonable to assume that if finding a mathematically optimum method of performing airplane maintenance was so difficult, then the real world was unlikely to achieve an optimal state by means of evolution, particularly since much airplane maintenance is nonrepetitive. This hypothesis was subsequently shown to be true.

Several different methods of computer optimization based on converting the problem to one of network flow were tried. Each method required division into a set of job activities, each activity with its own task time. The minimum and maximum numbers of mechanics possible for each activity are also provided. The order in which job elements are to be performed is loosely defined by a "precedence" network, as illustrated in Figure 2.

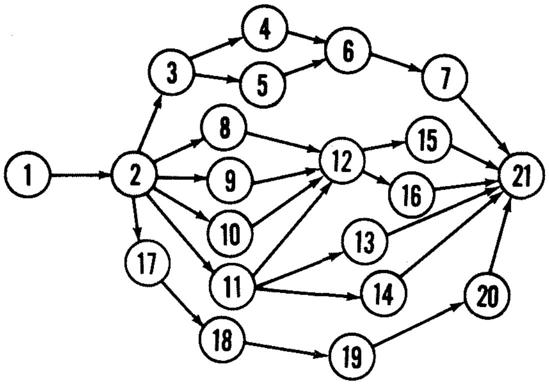

FIGURE 2. Typical Precedence Network

The example used for this network is a part of the task of jacking up a 747 airplane which requires coordination and communication between a minimum of five mechanics. In the network, job activities are represented by numbered nodes while the arcs indicate the sequencing requirement. For example, work on job element number 6 can only begin after both job elements 4 and 5 have been completed.

Each person assigned to a maintenance task is given an activity consistent with the sequencing constraints expressed by the precedence network. The problem is to determine a schedule for each task that both satisfies the precedence constraints and optimizes one of several possible objective functions:

1. Minimize the task completion time.
2. Minimize the total labor required.
3. Minimize the number of persons required to do the task.
4. Minimize the sum of labor and lateness penalty costs.

A combination of these objectives may also be required. For example, objective 3 may be given the highest priority, while 1 or 2 is used as a secondary optimization criteria. Thus, if there are a number of different ways to schedule a task, all of which have the same minimum personnel requirements, then among them, the one with the minimum completion time or the minimum labor is to be selected. Another alternative is to replace one of the objective functions with an equivalent input constraint and optimize the schedule of labor with respect to one or more of the remaining functions.

One method chosen to solve the multiperson task scheduling problem was to express it as a generalized network flow problem. For example, a worker who has completed job number 2 in the example problem of Figure 2 may then proceed to work on any one of the following job elements, assuming each element is within the worker's skill: 3, 8, 9, 10, 11 or 17. This type of decision is conveniently portrayed by the network in Figure 3. (The network of Figure 3 should not be confused with the network of Figure 2 which represents the constraints on the sequence in which work must be performed). The solution involves more than just job element sequencing decisions since each element may have two or more logical starting times. Selection of the appropriate starting times can also be expressed as a part of the generalized network. Figure 4 represents two different starting times for each of the job elements.

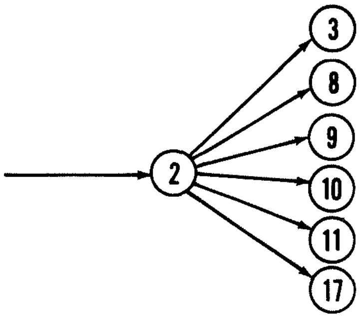

FIGURE 3. Subnetwork for allocation of mechanics to available activities

For the purpose of optimization, delay times associated with each connecting arc can be used as costs. Having translated the multiman task-scheduling problem into a generalized network flow, the first approach attempted a solution using a standard linear programming package(2) with mixed integer capability.

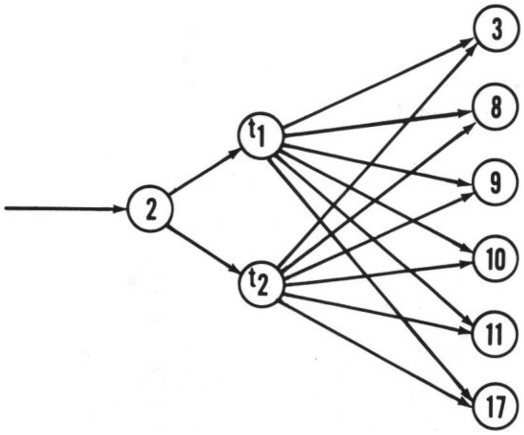

FIGURE 4. Expanded subnetwork showing a choice of two starting times, t_1 and t_2

The first analysis using computer optimization was for jacking a 747 airplane. The analysis had been previously completed by hand and thus provided a good basis for comparison. The computer solution to the problem provided a theoretical reduction of about 9% in both maintenance labor and elapsed time compared with the manual analysis.

There were two other consequences of the analysis. First, the cost of arriving at a computer solution was rapidly eroding our research budget, and second, a way was needed to stop the computer from making "smart" moves--such as having one mechanic put on all five communication headsets in its attempt to minimize walking. The problem of computational cost was solved using generalized network flow algorithms, namely those suggested by Glover, Hultz and Klingman(3), and Adolphson(4). In addition, constraints were added on the elements of the work that should or should not be performed by the same worker. The headset incident was not repeated.

III. Optimization Application

The new technique allowed us to rapidly evaluate and optimize the maintainability characteristics of new airplane design; it represented a significant advance over the manual method which involved one or two cycles of trial and error optimization in an attempt to minimize maintenance crew idle time. However, for the computerized optimization the unanswered question was whether or not airline mechanics could be directed to follow what might appear to be an otherwise illogical sequence and allocation of their work. An experiment was therefore arranged based on the removal and replacement of a 757 airplane engine. For control purposes, normal maintenance procedures were used for removal of the left engine. Four mechanics then followed preoptimized sets of individual instructions for a right-hand engine removal and are shown in Figure 5.

FIGURE 5. Four mechanics and the AMETS analyst, still on speaking terms after a computer optimized removal of an engine.

After accounting for experience gained on the left engine, the right engine was removed in 21% less time. Admittedly the sample size was small, but the difference between non-optimization and optimization could be readily observed. The difference can be seen by comparing Figure 6, in which, typically, one out of two mechanics is working, with Figure 7, in which the computer had sequenced and allocated the work so that not only was there work to be done most of the time but discussion as to who did what was eliminated.

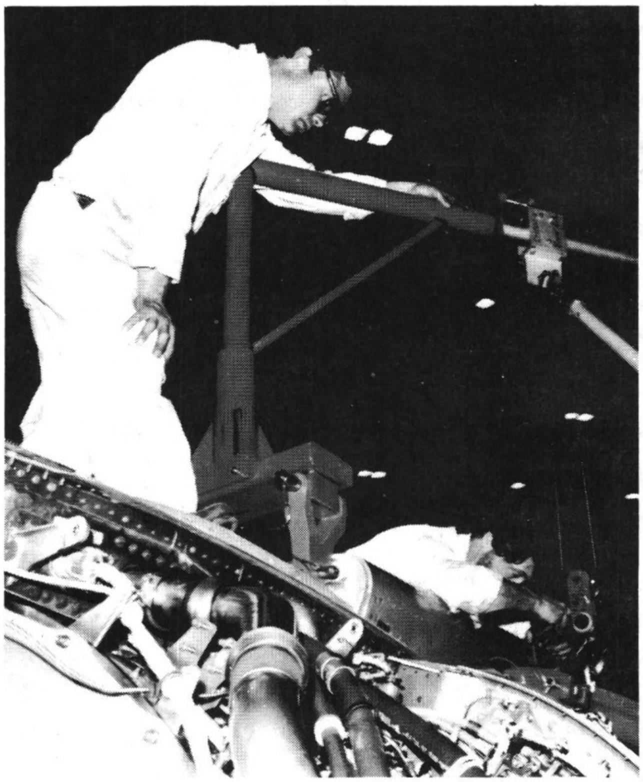

FIGURE 6. A typical unoptimized scene. One mechanic works, the other waits for instructions.

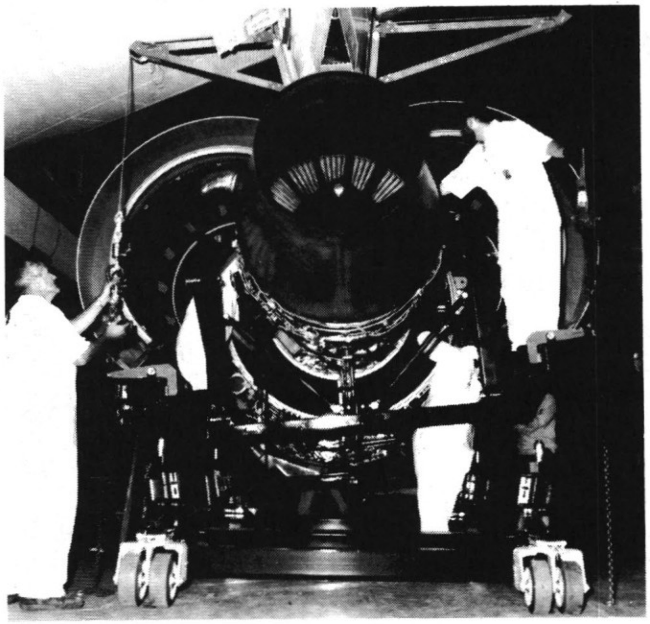

FIGURE 7. Four mechanics following a computer pre-optimized set of instructions—each with a job to do.

The engine removal experiment was not without its problems, however. First, whenever one of the four mechanics experienced a delay, the three remaining mechanics had to remain idle to keep the computer-optimized work in sequence, even though alternate work was possible. Second, when individual activities took more or less time than the estimates on which the computer-optimization was based, it was not practicable to change instructions either in content or sequence in order to man-load the newly created critical path through the network of remaining activities. Those problems accounted for a loss of only a few percent in efficiency, but had more serious implications from the standpoint of user friendliness and acceptability of the method. It was therefore decided to develop a real-time system that used feedback of progress data from the mechanics to continually re-optimize the tasks remaining. Other features were also incorporated into the real-time system. One feature made it possible for the number of mechanics on a given task to fluctuate. Another feature permitted a mechanic to refuse a given task, or to quit in the middle of a task.

We also devised a heuristic algorithm that could be implemented on an IBM PC. This algorithm does not attempt to obtain the global optimum but instead performs a series of sequential suboptimizations. It is based on the concept of viewing workers as being in one of three possible states: working on an activity, being on standby, or waiting for assistance. Every time there is a change in a worker's state, the algorithm evaluates all possible moves and selects the best one. The heuristic algorithm produced results that were adequate for experimentation at much less computational cost than the more comprehensive mixed integer linear programming models. However, we may ultimately reinstall the more comprehensive model if the resulting improvement is economically justifiable.

The most recent series of experiments were run with teams of three mechanics removing and replacing a Boeing 737 airplane's brakes. The interface between the computer and the mechanics was that shown in Figure 8. While the interface is very rudimentary, it proved to be a valuable learning experience. In a survey that followed the experiment, all the mechanics either agreed, or strongly agreed that it was easy to understand what was required. Unsolicited comments were also received that the technique should reduce maintenance discrepancies and rework.

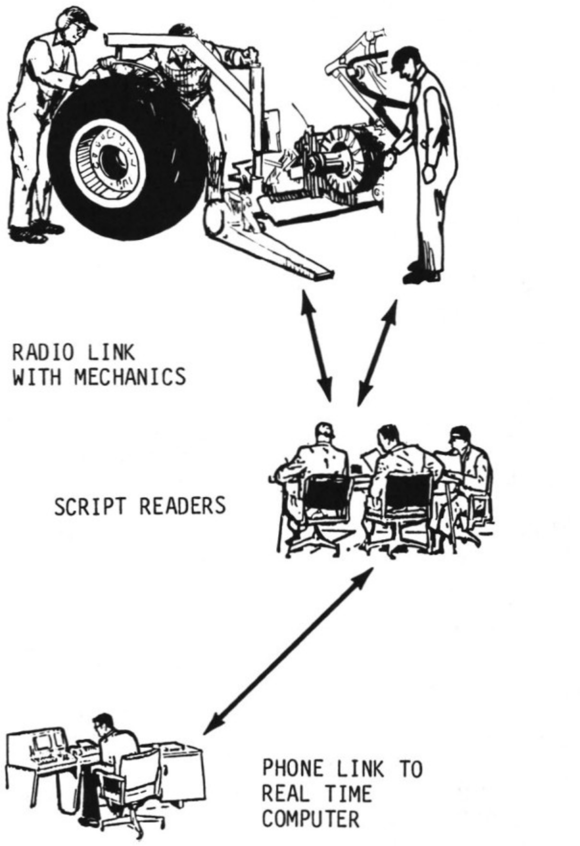

FIGURE 8. Simulation of a real-time optimization of a wheel and brake removal.

IV. Future Developments

One of the interesting parts of any research project is conjecture about the future course of the emerging technology. Fortuitously, the development of a system such as that shown in Figure 9 is now within reach. Many options are possible with such a system, but considerable work is still required to define and evaluate the alternatives. For example, mechanics could receive optimized instructions from an on-board airplane computer or a remote ground-based system could coordinate the efforts of several mechanics working on a single task or a team of mechanics working on many tasks. The optimizing system could also be tied into a larger centralized computer with an expert system capacity for particularly difficult troubleshooting. A centralized computer can also be used for updating local data bases. In fact, one large computer company has already equipped its national team of field service representatives with such a system based on hand-held computers connected by a radio link to regional offices and from each office to a mainframe computer in San Francisco.

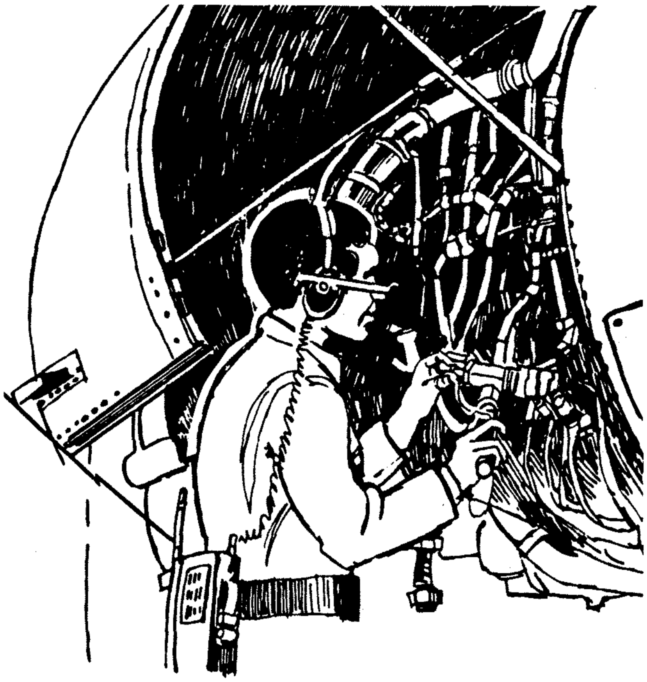

FIGURE 9. Mechanic with a head-up display and radio/voice communication to an optimizing computer.

Other experiments with even more sophisticated equipment have been sponsored by DARPA, the Defense Advanced Research Project Agency(5). This DARPA concept uses video disc technology for the presentation of illustrations and maintenance instructions using a miniature TV receiver attached to a mechanic's hard hat. The system also uses voice interactive two-way radio communication with a twenty word vocabulary of commands to the data presentation device. The system is not currently capable of coordinating the activities of several mechanics but could obviously be extended for this purpose.

The potentially low investment required for multiman task optimization makes it an alluring prospect. Assuming the system is supportable on the basis of the benefits of multiman optimization, with a minimum of additional cost it can be extended to encompass some other facilities such as:

- Automatic generation of maintenance and inspection records
- Airplane configuration control
- Spares control

Each of the above facilities can be added at little more than the expense of software development. Integration of record-keeping functions would of course require regulatory approval. Configuration control and spares control might be enhanced by supplementing the mechanics hardware with a bar code, magnetic-card, or other type of reader. A further approach to a totally integrated system(6) suggests the use of remote test equipment. Clearly the advantages of minimizing the need for costly test equipment either on board an airplane or on the ground is very significant. Some of the same hardware and software as that required for multiman optimization is used.

We are in the middle of an exciting period of technological development where techniques such as multiman optimization have become feasible for the first time. The remaining challenge is to perfect the application of optimization by better defining real-world requirements and using natural language processing methods emerging from the artificial intelligence field. Of course it remains to be proved that the now-feasible system can also be provided with the data it requires at an economically viable cost.

References

(1) John Rose, J. A. Davolt, "Increased Productivity with Predetermined Time Standards", Proc. Annual Reliability and Maintainability Symposium, January 1981, pp 193-198.

(2) "APEX III Reference Manual" Control Data Corporation, Minneapolis, 1979.

(3) F. Glover, J. Hultz, D. Klingman, "Improved Computer-Based Planning Techniques" Research report CCS283, University of Texas, February 1977.

(4) D. L. Adolphson, "A Network Based Linear Optimization System". Institute of Business Management, BYU, Provo, May 1984.

(5) Philip J. Klass, "Technique Benefits Novice Technicians", Aviation Week, October 11, 1982, pp 133.

(6) Richard G. DeSipio, "Avionics Maintenance - A Perspective, Proceedings IEEE of the 5th Digital Avionics Systems Conference, October 31, 1983 pp 15.3.1.