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C-141 DEPOT MAINTENANCE: USING SIMULATION TO DEFINE RESOURCE REQUIREMENTS

R. Garrison Harvey

Command Analysis Group
Air Mobility Command
Scott AFB, IL 62225

David V. McElveen

C-141 Production Division
Warner-Robins Air Logistics Center
Robins AFB, GA 31098

Peter H. Miyares

Directorate of Supply
Air Combat Command
Langley AFB, VA 23665

Thomas F. Schuppe

Department of Operational Sciences
Air Force Institute of Technology
Wright-Patterson AFB, OH 45433

ABSTRACT

The throughput of C-141 aircraft in depot maintenance was adversely affected by the addition of two major, unanticipated tasks. Many constraints existed to improving the production rate but, due to complex interrelated effects, it was difficult to determine which resource constraints were the most critical. A simulation model was developed as a policy evaluation tool to define potential throughput improvements resulting from increased resource availability. This tool provided management key insights and allowed them to focus their limited budget on adding those resources which provided the largest throughput increases.

1 INTRODUCTION

The C-141 aircraft is a four-engine jet aircraft used to haul cargo throughout the world. The aircraft is primarily used by the Air Mobility Command of the United States Air Force. The C-141 has been in service since 1965 and there are currently 275 of these aircraft in the Air Force inventory.

Approximately every sixty months each aircraft is flown to Robins Air Force Base, Georgia, to undergo Programmed Depot Maintenance (PDM). The Warner-Robins Air Logistics Center, located at Robins AFB, is one of the Air Force's major maintenance depots and is responsible for all periodic maintenance, including PDM, on the C-141 aircraft. PDM is a process that inspects and repairs as necessary mechanical, electrical, hydraulic, and structural components of the aircraft. Approximately 1500 people are dedicated to this C-141 PDM process at Warner Robins ALC.

In 1990, serious wing cracks were found in a number of C-141 aircraft. These cracks were located in a major structural member that joined the outer wing with the inner wing. It was decided that these cracks must be repaired as expeditiously as possible, for safety of flight reasons. Also in 1990, other cracks were identified in the center wing box, a major structural subassembly, approximately eight feet high, twenty-two feet long, and eighteen feet across, which connects the wings to the fuselage. Passing through the wing box are a multitude of electrical, mechanical, hydraulic, and fuel lines. Due to the severity and location of the cracks, it was decided to replace the entire center wing box rather than repair it. The center wing box, which weighs approximately 6000 pounds, was never designed to be removed from the aircraft and replaced.

When these two major structural problems were uncovered, Warner-Robins ALC was presented with a significant problem accomplishing these repairs while also completing normal PDM on the C-141 fleet. The Center was manned to handle only the PDM activity and the impact of trying to take on the wing repair and the center wing box replacement simultaneously was unknown. The Center was faced with several major management decisions. The first decision was simply defining the Center's existing capacity. It was also necessary to quantify the additional resources needed to complete both major repairs and the ongoing PDM. Resources included people, hangar space, test equipment, tooling, and, most importantly, money. Some excess capacity existed at the Center, but it was not clear how much additional capacity would be needed to accomplish these two unanticipated additional repairs that had never been planned or previously accomplished.

2 CHOICE OF SIMULATION

C-141 Depot maintenance at Warner Robins Air Logistics Center (WR-ALC) requires many resources including manpower, facilities, and equipment to successfully maintain the C-141. The complex interaction between these resources and the maintenance functions competing for them made forecasting capabilities and capacities of the system very difficult by standard analytical techniques (Haupt, 1989). Also, process and activity durations of the system are stochastic, making mathematical or heuristic evaluation techniques very difficult if not impossible to use (Sadeh, et al, 1989). Simulation was chosen as the evaluation tool for this project due to its ability to handle complex requirements for resources, as well as the stochastic processing times.

It was also recognized that resource constraints posed the major problem to substantially increasing throughput at Warner-Robins ALC. Because of this, a tool which could identify these constraints and specifically quantify the impact of varying levels of resources was needed. Once specific constraints were identified, attention could be focused on alleviating these constraints, while ignoring other non-critical areas. This approach to problem solving, known as the Theory of Constraints, has been advocated by Goldratt and Cox (1986).

Air Force decision makers often place demands on the depot maintenance system without completely understanding its capacity. A prime example is the requirement to replace the center wing box on 90 C-141 aircraft by the end of FY95. The only center wing box replacement data available was from a single prototyped aircraft done in a contractor's facility. Furthermore, it was not clear how the center wing replacement process would work with other on-going repair activities. The simulation provided managers a policy evaluation tool to determine if the center wing box replacement process was achievable, and to measure center wing box replacement process effects on the schedule of aircraft requiring other maintenance. The simulation was later useful in determining the impact of gaining additional hangars on the maintenance schedule and aircraft flowtime through the system.

The demand on resources was a critical concern. Decisions on future manning levels as well future support equipment acquisitions were required. The simulation considered the complex interactions of the demands for particular resources including facilities, manpower, and equipment. A good example was the utilization of nondestructive inspection (NDI) equipment and personnel. Several procedures within the maintenance process require NDI to search for cracks within the aircraft. The simulation was used to identify the best policy in assigning a number of NDI teams to each aircraft, or to "pool" the NDI resources for better utilization and availability.

Processing and activity durations for the system are stochastic in nature. Although exact distributions for these times were not available, the most frequently expected value was estimated by experienced maintenance supervisors. High and low values for each process were gathered through discussions with management and front line supervisors within the Center. This data was combined to form triangular distributions which were used in the simulation. Rework ratios as well as fault detection rates were gathered in a similar manner, compiled, and used within the simulation.

3 MODEL DESCRIPTION

C-141 maintenance is conducted year round, except for the ten Federal holidays per year and an occasional day lost to bad weather. Two full ten-hour shifts work Monday through Thursday and a smaller ten-hour shift works Friday through Monday. In a typical year, 50 to 60 aircraft receive PDM and are repainted.

Initially a model of the current PDM process was constructed using the SLAM II simulation language (Pritsker, 1986). This model, shown in Figure 1, was a macro-view of the PDM process and grouped many smaller sub-processes into single activities. The structure, logic, and data of the model was reviewed with PDM experts from the Center. In addition, the model was exercised with nominal data. Measures of system throughput and resource utilization were reviewed to validate the model. Once the basic model was completed, additional detail was added to include the effects of incorporating the wing crack repairs (Speedline) and the center wing box replacement. These additions are shown in Figure 2. An important point to note in Figure 2 is that a single aircraft will follow only one path through this process, from

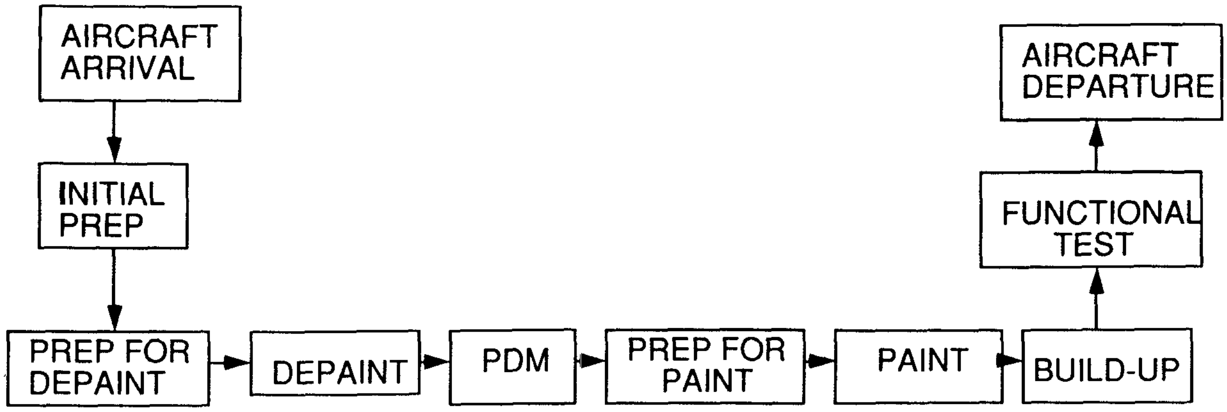

Figure 1: Initial Programmed Depot Maintenance (PDM) Process

Aircraft Arrival to Aircraft Departure.

3.1 Speedline

The speedline program calls for the inspection and repair of cracks found in the aircraft wings and the possible replacement of the wing's beam caps which are wing joint support structures. The process is called "speedline" because the Center would like to accomplish the process on each aircraft as quickly as possible. The Center has two years to complete the process on 183 aircraft. Planners and engineers arranged and organized maintenance schedules and facilities in an attempt to process each aircraft through speedline to meet this requirement. Aircraft that had not received the speedline process within two years would be grounded. In order to meet this deadline, speedline aircraft must arrive at Warner-Robins by 30 September 1993.

Some of the aircraft going through speedline are also to receive PDM and/or be repainted. When the speedline program is completed at the end of FY93, the normal PDM process will continue at Warner-Robins.

3.2 The Speedline Process Flow

After an aircraft bound for speedline arrives at the Center, it receives an initial inspection and initial preparation, as shown in Figure 2. In addition, if the aircraft is going to be painted following speedline, the existing coat of paint must be removed shortly after arrival in a process called "depainting". The aircraft then receives additional preparatory work for speedline which varies depending on whether the aircraft is going to be painted and/or receive PDM.

Once prepared, the aircraft is towed to one of several hangar positions where the actual speedline process is conducted. If no hangar positions are available, an aircraft must wait until one is available.

The speedline process itself is conducted on eight separate sections of the wings: the right and left, upper and lower portions of the forward and aft sections. The first phase of the process is a nondestructive inspection (NDI) of all the rivet holes on a wing. All holes that do not pass this inspection must be redrilled and then reinspected. Prior to the reinspection, the wing undergoes two possible repairs. The first is the repair and replacement of cracked wing panels, required on about 90% of the lower forward sections. The second is the replacement of beam caps, which is required on about 12% of the lower aft sections.

Following these repairs and reinspection of the rivet holes, every aft section receives a gorilla fitting (a reinforcement for the wing joints) while additional wing work is conducted on the forward sections. Once this work is complete, the aircraft is prepared for and processed through PDM, if required. Then the aircraft is "built up", a process of reinstalling any systems or equipment removed during any part of the maintenance operation. Finally, the aircraft is functionally tested to ensure it is ready to be returned to service. Those planes requiring paint are then repainted.

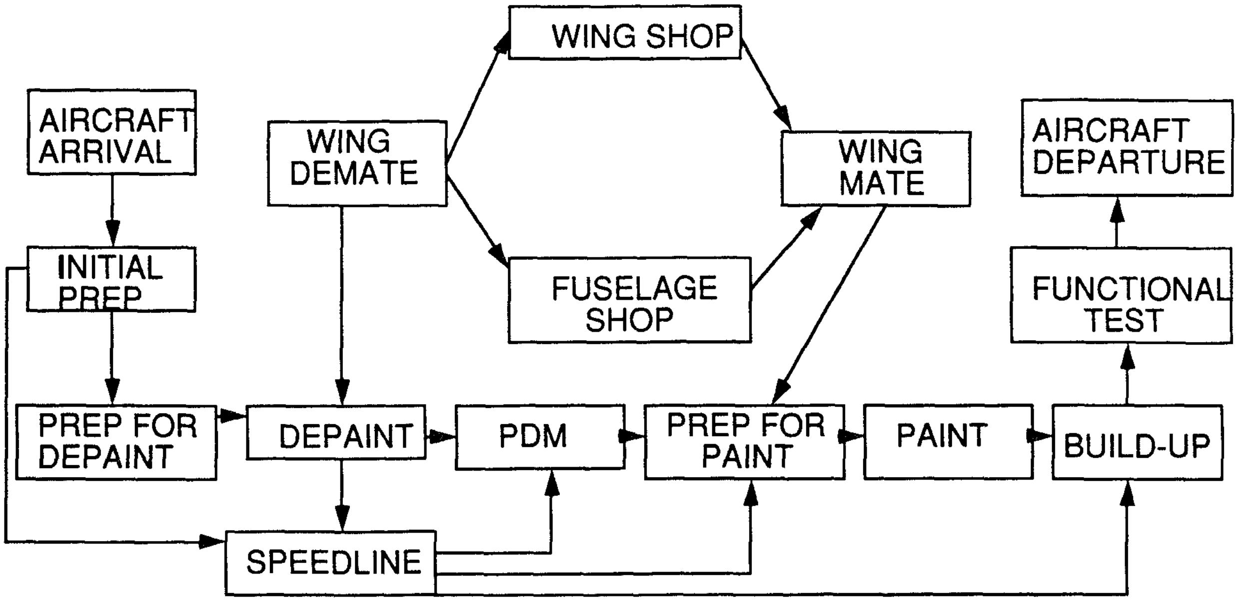

Figure 2: Programmed Depot Maintenance (PDM) Process with Speedline and Center Wing Box Replacement Included

3.3 Center Wing-Box Replacement

The center wing-box replacement program calls for the replacement of the C-141's center wing-box, a structural support which attaches the wings of the aircraft to the fuselage and acts as part of the spine of the fuselage. Originally, the program called for 124 aircraft to receive new center wing-boxes over the next four years, but the program has since been scaled back so that as few as 17 aircraft may receive new center wing-boxes.

The remaining 107 wing-boxes will be replaced either at the Center or by a civilian contractor. All center wing-box aircraft processed at Warner-Robins will be repainted and most will receive PDM.

3.4 The Center Wing-Box Process Flow

Figure 2 also illustrates the center wing-box replacement process flow. Aircraft arriving at Warner-Robins to receive a new center wing-box will also receive an initial inspection, initial preparation, and be depainted. After additional preparatory work, the wings are removed from the aircraft. The fuselage receives a new center wing-box while the wings receive the same repairs conducted in the speedline process. However, the speedline process associated with the center wing-box replacement program is independent of the other speedline process and is accomplished with its own facilities, personnel, and most of its own equipment. The majority of PDM is also accomplished while the center wing-box is being replaced. This PDM work is also conducted by different personnel and equipment than the PDM conducted following the speedline process. Once all repairs are complete, the wings are reinstalled onto the aircraft and the remainder of PDM is conducted. The aircraft is then built up, tested, and painted.

3.5 Resource Sharing Within and Between Processes

It is important to note that the speedline and center wing-box replacement processes share very few resources. The aircraft are painted and depainted in the same facilities and by the same personnel. The depaint facilities are also used to wash and prepare aircraft for painting. The processes share a few pieces of equipment and the initial inspection, initial preparation, and functional testing activities are all conducted by the same set of personnel regardless of which major repair processes an aircraft undergoes.

Resources are also shared with processes outside of center wing-box and speedline. The build-up of the aircraft is conducted by the same personnel who accomplished the preparatory work or by the PDM crew in the case of a speedline aircraft that received PDM as well. If a problem is detected during functional testing, personnel from the process who completed that repair are called upon to fix it.

3.6 The Simulation Model

The simulation model of all C-141 maintenance activity at Warner-Robins Air Logistics Center was created using SLAM II and some additional FORTRAN subroutines. The model simulates the operation and flow defined above over a planning horizon of four fiscal years. Its level of detail focuses on major repair activities as defined by the C-141 Production Division.

Some of the repair activities can be completed in parallel, while others must be completed in series. Most activities are order-dependent and cannot begin until one or a group of other activities are completed. Although the Center had been accomplishing PDM repair activities for over twenty years, no records were kept at the appropriate level of detail to define activity time distributions. Therefore, the duration of each activity was estimated, based on a triangular distribution whose median is the planned duration time in work days provided by the Production Division. The simulation model assumes that most of these activities can be completed up to 20% ahead of schedule or 30% behind schedule, based on information provided by the Production Division. For modeling simplicity, some minor activities which must be accomplished in series are treated as a single large activity, if the resources required for the combined activity are the same as for the individual activities. For example, two half-day activities are treated as one full-day activity, if there are no changes in resource requirements.

The model processes each aircraft scheduled to enter the system over a planning horizon of four fiscal years (FY92-FY95) based on the type of repair required. This information is stored in an input data file and is accessed by the simulation model using a brief FORTRAN program. The input file contains two data elements for each aircraft, the planned work day of arrival and the type of work required. The day of arrival ranges from 1 to 1416 based on the assumption that maintenance will occur 354 days a year over the four years of the program. The type of work required is classified by the following categories:

1. Speedline only (81 aircraft)
2. Speedline/paint (33 aircraft)
3. Speedline/PDM/paint (46 aircraft)
4. Center wing-box/PDM/paint (62 aircraft)
5. PDM only (46 aircraft)
6. Speedline/PDM (23 aircraft)

The model does not allow speedline aircraft to enter the system after 30 September 1993, but work on all the aircraft already in the system by that date will continue. PDM aircraft do not arrive to the system until 1 October 1993, while center wing-box aircraft enter the system throughout the four years of planned operations.

Embedded in the model is an assumption that one work day is no different from another. It assumes any loss of work-time due to worker non-availability is embedded in the triangular distribution of the activity durations, that is, worker non-availability is not explicitly programmed into the model, but is part of the reason the expected duration is sometimes exceeded by up to 30%. Also embedded is an assumption that most equipment and resources not explicitly modeled are always available to conduct work, or delays due to waiting for them are embedded in the duration distributions.

The resources and equipment explicitly modeled are the hangars for depainting and painting of an aircraft, the speedline process, and the center wing-box replacement process; the facilities to conduct PDM and functional testing; and equipment to no-load, water pick, and conduct nondestructive inspections (NDI) on the aircraft. An aircraft requiring these resources must wait until that resource is available before proceeding with processing.

Hangars and facilities: For this system, maintenance hangars and painting facilities are the most critical resources. The C-141 maintenance operation has access to one depaint hangar and one paint hangar. However, both of these hangars are shared with C-130 and F-15 aircraft which are also maintained at Warner-Robins Air Logistics Center. The depaint facility is also used to wash and prepare an aircraft prior to painting.

The speedline process has six hangar positions, but because of spatial constraints, two of these hangar positions have to be filled and emptied at the same time. Aircraft can not enter either of these positions unless both positions are free, and could not leave unless both were ready. This spatial constraint was included in the SLAM simulation model. On 1 October 1992, two additional speedline hangar positions were to be available. These two hangar positions will not be spatially constrained.

The center wing-box replacement process has two hangar positions in which wings can be removed or attached, and the facilities to repair four pairs of wings and six fuselages simultaneously. On 1 October 1993, the process will receive additional hangar space to process two additional pairs of wings and two additional fuselages. The PDM process can accommodate six aircraft at the same time and functional testing can process four aircraft.

Imbedded in the model are the assumptions that, based on assurances from management, all necessary material, personnel and equipment resources are available to conduct the particular maintenance operations at each position. The only exceptions follow.

No-load equipment: The no-load equipment is used to install and calibrate supports under the aircraft and wings in both the speedline and center wing-box processes. Only one set of equipment is available and it is used on a first-come, first-served basis.

Water picking equipment: The water picking equipment is used to clean speedline aircraft that also require PDM. Only one water pick is available and it is used on a first-come, first-served basis.

NDI equipment: NDI equipment is used to inspect rivet holes in the speedline, center wing-box replacement, and PDM processes. The number of NDI equipment sets available depends on the number of qualified technicians available to operate the equipment. Availability of qualified personnel varies by shift (ten sets/day shift, six sets/swing shift, four sets/weekend shift). Because the simulation model does not take shift differences into account, an average figure of seven sets of NDI equipment is used. The actual numerical average of 6.7 sets is rounded up because more work is generally accomplished during the day shift. Priority for this equipment is given to speedline aircraft first, then center wing-box aircraft, and finally PDM aircraft.

Within the speedline process, NDI equipment remains with an aircraft until all inspections, repair work, and re-inspections are completed on the rivet holes of each of the eight wing sections. The only exception is when a wing requires new wing panels and/or beam caps. If these repairs, which occur prior to reinspection, are required, the NDI equipment is used to reinspect the unaffected areas and is then released for use on other aircraft until these conditional repairs are complete. The aircraft is then allocated the first available set of NDI equipment to complete the reinspection process of the affected areas.

The model can also restrict the number of aircraft in the entire system as well as the number of aircraft processed through each operation at the same time. This is used to model a management policy of not removing too many aircraft from the active flight inventory at any one time, to control the flow in each process ensuring that a constraint is never left idle, and to reduce the amount of time an aircraft waits to enter any phase of the maintenance process.

4 MAJOR FINDINGS

4.1 Schedule Impacts

There are six possible paths a plane can take through the system. While there are many common nodes all planes pass through, and many separate nodes that compete for resources, this project concentrated on two aspects. Aircraft must go through either the speedline or the center wing box replacement, but not both. While individual aircraft may require special activities, the schedule is driven by the need to complete 90 center wing box replacements in four years and 183 speedline aircraft in two years. Because of safety of flight considerations these schedules must be met; if these schedules cannot be met then the overflow will be sent to a commercial subcontractor.

The number of aircraft on the ground at any given time also impacts the throughput. The Air Mobility Command allows only a fixed number of aircraft to be in scheduled maintenance at any given time. Therefore, lack of a backlog or queue of waiting aircraft can have a dramatic effect on the throughput by creating idle time along the critical path.

4.1.1 Center Wing Box Replacement

Over multiple runs, the simulation averaged 25 aircraft throughput per year. In 90% of the runs the required number of aircraft finished within two months of the schedule--an acceptable completion rate. The simulation indicates the proposed schedule is probably achievable. At the time of this project only one center wing box aircraft had been completed at the Center. It is reasonable to expect improvements in the process as the workforce becomes more proficient at this task.

4.1.2 Speedline

Over multiple runs of the simulation an average of 128 aircraft were completed in two years. The goal of 183 aircraft completed in two years was never reached. Average throughput per year was estimated to be 64 aircraft. With this level of throughput we estimated WR-ALC will fall short of its goal by 41 aircraft. This short-fall could be met by sending the unfinished aircraft to a commercial firm. The next step is to look for a way to increase the throughput, validate the improvement through simulation, and decrease the number of planes sent to a contractor.

4.2 Hangars and Manpower

Aircraft scheduled for center wing box replacement go through a de-mate facility that separates the wings from the fuselage. The wings are sent to hangars for maintenance (six pairs of wings total capacity). Similarly, the fuselages are sent to hangars (six fuselages total capacity). The simulation showed that maintenance on a set of wings is completed much faster than the work on its paired fuselage. Because of these unequal rates, one pair of wings' position could be eliminated. The position and manpower from this position could be given to either the fuselage shop or allocated to a new speedline position to increase throughput.

The simulation verified the initial estimate that the paint/depaint hangars would be bottlenecks. Eight day delays were common waiting for the paint hanger and delays three times this amount were common at the depaint hanger. These results underscore the need to improve the scheduling of the paint and depaint hangars.

4.3 Equipment

Non-destructive inspection (NDI) equipment was initially identified by the Center as critical and more equipment was being considered for purchase. The simulation indicated NDI equipment caused only minimal delay. Also, results indicated that NDI allocation could be improved by dedicating NDI equipment to individual aircraft instead of checking out equipment as needed. Purchasing more NDI equipment is no longer considered a desirable option and the new allocation strategy is being investigated.

The water pick equipment was also initially considered to be critical. The simulation showed that the current equipment caused no significant delay.

5 SUMMARY

The simulation model was constructed to provide the Center's management a tool to obtain a better understanding of their maintenance system. Simulation was chosen due to its capability to model complex interactions between resources and the random nature of activity durations. The model was used to determine the achievability of present aircraft throughput goals to identify bottlenecks within the system.

For aircraft throughput, the model demonstrated that under given assumptions, speedline aircraft throughput goals could not be achieved. This information was particularly helpful because it allowed management sufficient lead time to procure additional resources or initiate action to subcontract the excess demand. However, center-wing aircraft goals were achievable. The model also identified the paint/depaint facilities as a constraint on the system and showed NDI and water pick equipment levels to be adequate for desired throughput goals. The model further identified a possible area to improve throughput by reallocating hangar space used for wing repairs from center-wing aircraft.

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AUTHOR BIOGRAPHIES

R. GARRISON HARVEY is an analyst with the U.S. Air Force working with the Command Analysis Group at Scott Air Force Base, IL. He received a B.S. degree in mathematics from the U.S. Air Force Academy in 1988, and an M.S. degree from the Air Force Institute of Technology in 1992. His research interests are in optimizing airlift systems through simulation and statistical analysis.

DAVID V. MCELVEEN works within the newly created Operations Research and Management Information Office of the C-141 Production Division, Warner-Robins Air Logistics Center, Robins AFB, Georgia. He received a B.S. in electrical engineering technology from Georgia Southern College and an M.S. in operations research from the Air Force Institute of Technology.

PETER H. MIYARES is Chief of Weapons Systems Assessments, Directorate of Supply, DCS Logistics, Headquarters Air Combat Command. He received a B.S. in mathematics from the University of New Hampshire and an M.S. in operations research from the Air Force Institute of Technology. His primary research interests are in modeling the effects of logistic procedures, systems, and resources on Air Force combat capability.

THOMAS F. SCHUPPE is the Head, Department of Operational Sciences, Air Force Institute of Technology, Wright-Patterson AFB, Ohio. He received a B.S. in mechanical engineering from the University of Wisconsin, an M.S. is systems engineering from the Air Force Institute of Technology, and a Ph.D. in operations research from The Ohio State University. His primary research interest is in simulation modeling of complex man-machine systems. He is currently a member of ORSA and the Military Operations Research Society.