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Impact of Maintenance Staffing on Availability of the Air Traffic Control Communications, Navigation and Surveillance Systems

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Abstract

More efficient allocation of maintenance resources to the more than 45,000 U.S. National Airspace System (NAS) facilities is becoming increasingly significant as the average age of the NAS increases, and air traffic continues to grow.

This paper describes a set of simulation models which can be used to derive the impact of staffing, shift staffing strategies, maintenance policies, and other maintenance management decisions on equipment availability, technician utilization, average equipment down time, equipment downtime for unscheduled maintenance, and equipment downtime for scheduled maintenance.

The results show that as technician training increases, the equipment availability increases, scheduled downtime remains the same, but the unscheduled downtime decreases by more than 1.8 hours per outage. As the mean time between failures (MTBF) decreases or mean time to repair (MTTR) increases, the equipment availability decreases, the technician utilization increases linearly, and the unscheduled outage downtime increases dramatically. When non-uniform staffing and deferred maintenance is considered, deferral of scheduled maintenance results in a significant benefit (average outage time of 20.8 hours non-deferred vs. 7.4 hours deferred).

1. INTRODUCTION

This paper describes a discrete event simulation tool which will be used to as an aid to making decisions on the allocation of maintenance resources for the U.S. National Airspace System (NAS). This methodology used in the tool estimates the impact of (a) actual repair rates, (b) number of technicians, (c) average maintenance rate per facility, (d) failure rate per facility, (e) distribution of technicians by shifts training and (f) travel time to facility -- on outage time, service availability and technician utilization. The NAS- consists of more than 45,000 individual equipment or systems supporting air traffic control which have functions as diverse as lighting to radar tracking, and which incorporate technologies ranging from backup diesel generators to networks of UNIX stations[4]. Their maintenance requires technicians trained in many disciplines deployed over the entire United States and its possessions. This maintenance workforce is managed out of a national network of cost centers. Each such cost center has limited number of technicians ("servers") who are responsible for providing scheduled maintenance and repair for the equipment assigned to that center.

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[4] The FAA's Pilot/Controller Glossary defines the NAS as: "The common network of U.S. airspace; air navigation facilities, equipment and services; airports or landing areas; aeronautical charts, information and services; rules and regulations and procedures; technical information; manpower and material. Included are system components shared jointly with the military."

A maintenance cost center can be represented by a model in which facility maintenance actions stochastically arrive at a maintenance center, and the first available qualified technician is then dispatched. The technician is then occupied for an interval determined by the repair time probability distribution, type of facility, the nature of the repair, whether or not spares are necessary, travel time, and other factors. When all available technicians are occupied, the maintenance action or repair waits until a qualified technician becomes free. Also, if spares are not available, or expert assistance is required (from a contractor or national maintenance resource), then completion of the repair is further delayed.

2. METHODOLOGY

In earlier work (1), it was shown how a cost center could be modeled by a classical Machine Repair M/M/n queuing model in which queue waiting time, technician utilization, and average number of outstanding repairs could be solved for using analytical methods and where the outages arrive from a finite population (3).

However, this analytical solution requires many simplifying assumptions, including that all facilities have the same repair rate, staffing is uniform throughout the work day, only one technician is dispatched per repair, and that the travel time to all facilities is uniform. While these simplifying assumptions may be adequate for top-level analyses, they are not accurate when applied to specific costs centers. Because one of the objectives of our model is to assist a maintenance dispatcher to assess various dispatching and scheduling alternatives and identify the best course of action, the analytical approach is not sufficient. In order to address this problem, a more accurate discrete event simulation approach is used. This paper describes the simulation modeling and its results under various scenarios investigating the impact of factors such as training, reliability, and maintenance time. The problem of optimizing assignment of technicians to different types of outages, aiming to (a) decrease the waiting time of failed equipment prior to its repair and (b) increase the technician utilization rate, is also considered.

3. SIMULATION MODELS DESCRIPTION

The simulation model has three major elements: the cost center maintenance simulation model, the service availability model, and unavailability impact model. The cost center simulation model predicts facility outage duration as a function of the resources at the maintenance cost center. The service availability model translates facility outage times to service availability. The unavailability impact model estimates the impact of services unavailability on the capacity of an airport, Terminal Control Area (TCA), en-route fix, or other element of the NAS.

3.1 Cost Center Maintenance Simulation Model

The cost center maintenance model is a discrete event simulation model that represents a cost center as a multiple server, heterogeneous queuing system.

The objects in this simulation models are: technicians, facilities, cost centers, services, and failure events. Technicians perform scheduled preventative maintenance, and unscheduled corrective maintenance to repair or restore service due to outages. Note that a *failure* is either an outage, a degradation in service or a loss of redundancy. A failure is not necessarily synonymous with an outage; a radar facility may continue to provide service if one channel has failed but a redundant channel is capable of providing service.

Facilities are the equipment and systems which are serviced by the technicians. A subset of facilities in the cost center comprise a service. For example, an Instrument Landing System (ILS), is composed of a Glide Slope (GS), Localizer (LOC), Inner Marker (IM), Middle Marker (MM), Outer Marker (OM), Distance

Measuring Equipment (DME), Runway Visual Range (RVR), and an Approach Lighting System (ALS)[5]. Technicians and facilities are grouped together into FAA-defined cost centers. Table 1 shows the specific attributes of these objects.

A failure/maintenance event is generated every time a facility requires servicing. However, facilities in a cost center are serviced by technicians assigned to the same cost center. If a facility fails and all qualified technicians are busy repairing other facilities, then the facility waits until a qualified technician becomes available. It is assumed that a technician not qualified in the equipment class which fails can not be assigned to repair the failure. The immediate results of the simulation are (a) the duration of maintenance events (i.e., the time difference between when a technician completes the maintenance action and the time when the maintenance need was generated) and (b) the time during which a technician is occupied with the event (i.e., is busy and cannot be dispatched to handle another maintenance action without interrupting work on the current maintenance action).

The duration of a failure or maintenance event depends on the following attributes:

- The time needed to perform the maintenance or repair action which is in turn determined by the outage cause code (scheduled vs. unscheduled; commercial power and comm. vs. equipment or parts, etc.).
- The shift and day of the week on which the event occurred (unscheduled failures only – of significance for facilities with lower maintenance priorities which are not fixed on non-prime shifts or during weekends).
- Travel time to the affected facility (unscheduled failures only).
- Whether completion of the maintenance action or repair is pre-empted because of the need to work at a higher priority facility.

The time during which a technician is occupied with the event is determined by:

- The time needed to perform the repair action which is in turn determined by the outage cause code (scheduled vs. unscheduled; commercial power and comm. vs. equipment or parts, etc.).
- Travel time to and from the facility (for both scheduled and unscheduled outages)
- Administrative time associated with the repair (logging, post-repair site activities, etc.).

3.1.1 Simulation Model

The initial prototype model was implemented using the ARENA 3.0 discrete event simulation development tool. Figure 1 shows a graphical representation of the ARENA model's block diagram that makes up the model. A failure/maintenance dispatch report is created by a CREATE block, in accordance with the given probability distribution. The use of the exponential distribution to measure and predict outage interarrival times is a common practice (1) and was used in this model. At the ASSIGN block, the attributes of the failure/maintenance dispatch report are initialized. The FINDJ block finds the technician who has the least utilization rate and the shortest queue within his group, and is trained to repair the facility. In general, this block searches for an expression's value over a specified range of an index whose value must meet the prescribed condition.

When available, the committed technician immediately starts work on the repair as represented in the SEIZE block. Depending on the type of the Cause Code (currently limited to scheduled and unscheduled in this model), the model has slightly different treatments. The duration of a scheduled outage is only the repair (or other scheduled maintenance) time; the outage starts only when the technician reaches the site and deactivates the equipment. However, an unscheduled outage duration starts upon the failure, and includes

[5] The RVR and ALS are generally not considered part of the ILS but are necessary for low visibility landings and are therefore included in the availability model.

the time waiting for a technician, and travel time to the site as well as the actual repair time. In all cases, the technician is busy for longer than the time of the outage; there is also travel time back from the site and post-repair administrative time.

When the technician is committed, its time is marked and recorded because this measure is needed for calculation of the time technician is busy. This is done by recording the time in the first DELAY block (Administrative Time) and keeping it until a technician goes back to the center. After a facility is repaired, it is made available using the RELEASE block; the technician can travel back to the cost center.

The following statistics is derived from the simulation output:

- Number of scheduled and unscheduled failures and outages
- Duration of each failure or outage and whether scheduled or unscheduled
- Total duration of failures or outages by facility
- Time technician was busy and
- Technician utilization.

The general simulation file can be tailored for individual cost centers through the specification of attributes, variables, queues, sets, resources, tallies, and outputs. For example, it is possible to specify a cost center with 15 facilities divided into 3 types and 6 technicians. The queues defined in the simulation are facility failures waiting to be repaired by each of 6 technicians in the cost center. Results are recorded for total scheduled failure outages, total unscheduled failure outages, the scheduled and unscheduled failure times for each of the 3 facility types, and technician time busy. Counters are defined for scheduled failures and unscheduled failures. The probability distributions for the repair times of each of the technicians (assumed to be normal) and the outage times are assumed to be normal.

In this simulation model, the finite size of the queues (affecting both the number of failed units and the failure rate) is accounted for. Based on the queuing theory, the failure arrive rate should change with the number of failed facilities. Hence, the total number of facilities (NF) in this simulation model is fixed (i.e., 90) and cannot exceed the total number of failed facilities. This is because we can not assume that there is an infinite number of facilities.

3.2 Service Unavailability Model

The service unavailability model is a series of mathematical relationships which translates the set of outage durations for each facility and the technician occupied times (i.e., interval of time during which technicians are busy) into facility and service unavailabilities.

The total downtime for facility j, T_{dj}, can be determined by

$$T_{dj} = \sum_{i} t_{ij} \tag{1}$$

where t_{ij} is the outage time for each simulation maintenance of facility j determined from the cost center maintenance simulation.

The average outage time, or mean downtime (*MDT*) of facility j, given by

$$MDT_j = \frac{T_{dj}}{n_j} \tag{2}$$

where n_j is the number of outages of facility j in the simulation.

The operational availability, A_j for an individual facility

$$A_j = \frac{T_{stot} - T_{dj}}{T_{stot}} \qquad (3)$$

where T_{stot} is the total time of the simulation.

The operational availability for a service of which the facility is a part here A_s is the service string availability is given by

$$A_s = \prod_j A_j \qquad (4)$$

This is under the assumption that there is no redundancy among facilities, e.g., the ILS has only one localizer, glide slope, and DME. If there is redundancy, then more complex combinatorial relationships must be used. A more complete description of these models may be found in a related paper (5).

Technician j utilization factor r_j is defined by

$$r_j = \frac{T_{busyj}}{T_{stot}} \qquad (5)$$

where $T_{busy\,j}$ is the total time that technician *j* is occupied.

3.2 Unavailability Impact Model

The unavailability impact model translates service unavailability into the impact on capacity and delay. If the capacity of an ATC control point (fix, arrival runway, departure runway, airway, etc.) when the supporting operational services are available is C_o, and the degraded capacity when the service is not available is C_d, then the impact of availability can be stated simply as

$$C_{eff} = A^*C_o + (1-A)C_d \qquad (6)$$

where C_{eff} is the effective capacity (weighted by availability) and *A* is the availability of the service. Equation 6 can be expanded to account for multiple states of degraded service and capacity by additional terms for both availability of the state and the capacity of that state, i.e.,

$$C_{eff} = \Sigma_i A_i C_i \qquad (7)$$

where A_i is the incremental availability of service level *i* and C_i is the capacity at that level of service.

Unfortunately, in most cases, values for C_o, C_d, and C_i are not readily available. In such cases, an empirical analysis of traffic, controlling for other factors including weather and demand, must be performed. These analyses are facility-specific, and they vary by site.

4. Cost Center Maintenance Simulation Model Results

This section describes demonstrates the results that can be achieved with the simulation model. The impact of changes in the following parameters are used as examples.[6]:

- Technician Qualification
- Equipment Reliability
- Equipment Repair Time and
- Alternative Shift Staffing strategies combined with deferred maintenance action strategies.

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[6] These results are reported for cases that are simplified in order to impact to the parameters which are being varied. A large airport cost center, to which the model is now being applied, consists of more than 80 facilities, 20 technicians, and multiple levels of training and sparing.

4.1 Technician Qualification Study

The objectives of this study are to determine the impact of technician training (i.e., number of systems for which qualified) on availability, technician utilization, average equipment down time, equipment downtime for unscheduled maintenance, and equipment downtime for scheduled maintenance.

The following are the assumptions used in the simulations:

Facility Types	10
No. of Facilities of Each type	1
Techs (per shift)	2

Facility Failure Interarrival Time (All Types): Exponential dist; 46.7 hr. MTBF

(Per facility; for 10 facilities, there is a failure or maintenance action every 4.67 hours)

Repair Time (All Types)	Exponential dist.; 4.1 hr. MTTR
Proportion of Scheduled Repair (All Types)	50%
Shift Staffing	All shifts equally staffed

A total of 6 cases were analyzed. The first case assumes 2 technicians each qualified on 5 systems, these proceed up to 2 technicians each qualified on 10 systems (Table 3-1). The simulation model logic for this example is the same as that shown in Figure 1.

4.1.1 Results

The simulation results in terms of availability, technician utilization, and facility downtime are discussed. As training is increased, the equipment availability increases from approximately 0.9913 to 0.9926 (Figure 3-1). This is to be expected because as technicians become qualified to repair more systems, it is more likely that when a system fails, a technician will be available to perform the repair, and it is less likely that the outage will wait until a qualified technician becomes available.

The results also show that technician utilization is basically unchanged (approximately 43%) as training is increased (Figure 3). This result is to be expected because, technician utilization (in the case of an M/M/1 queue) is determined by

$$r = n\,l/mm \qquad (8)$$

where r is technician utilization, n is the number of facilities , l is the is the failure rate per facility, m is the number of technicians, and m is the average repair rate. Given that the number of technicians and number of facilities has not changed (even though a large proportion of available technicians is able to fix the next failure), the utilization should not change. In other words, although it is more likely that a technician (server) will be available when a failure or maintenance action arises, it is also the case that the workload is distributed across more technicians.

Scheduled downtime remains unchanged because the equipment is actually down only when a technician arrives to perform the repair. Unscheduled downtime decreases by more than 1.8 hours per outage as technician training is increased. This decrease can be explained by the fact that as more technicians are qualified on an equipment time, it is more likely that a repair technician will be available to perform the repair, and the expected time that an outage must wait for a technician to start the service will decrease (Figure 4).

4.2 Reliability Study

The objective of the reliability study was to determine changing the impact of reliability (i.e., Mean Time Between Failures, MTBF) on availability, technician utilization, average equipment down time, equipment downtime for unscheduled maintenance, and equipment downtime for scheduled maintenance.

The following are the assumptions for this study:

No. of Facility and Types	10
No. of Technicians per Shift	2
Proportion of Scheduled Repair (All Types)	50%
Shift Staffing	All shifts equally staffed

The effect of these cases is to vary the average MTBF of the cost center by 10% decrements to 50% of the baseline value (Table 3a).

The basic simulation model has been changed to create 2 different categories of facilities, one with the normal MTBF, and the second with half the MTBF (twice the failure rate). The interarrival times of the failures of each of the facilities is varied proportionately with the number of facilities. Other than this change, the model is similar to the baseline case.

4.2.1 Results

The results of the simulation in terms of availability, technician utilization, and facility downtime are derived with the following outcomes: As the MTBF is decreased (i.e., the number of facilities with ½ of the baseline MTBF is increased), the equipment availability decreases from the baseline of approximately 0.9913 to 0.9444 in a nonlinear manner (Figure 5a). This is to be expected because as more facilities require frequent service, technicians become less available, and there is a greater likelihood that an unscheduled outage can not be immediately fixed.

Figure 6a shows the technician utilization as a function of the number of facilities failing with greater frequency. The result is linear as the proportion of facilities with ½ the reliability (as measured in MTBF) increases. This is consistent with the relationship between utilization and failure rate shown in Equation 1.

Figure 7a shows the relationship between average facility downtime and the number of facilities with half the baseline MTBF. The dramatic increase in unscheduled outage time can be explained by the fact that technicians become busier as the average failure rate increases, and hence, it is less likely that a technician will be available to perform a maintenance action. The duration of scheduled downtimes remains constant because of the reasons cited in the earlier section. The average outage time is the mirror image of the availability curve (Figure 6a). This is to be expected given the relationship between downtime and availability defined in Equation 3.

4.3 Repair Time Study

The objective of this study is to determine the impact of changing repair time (i.e., MTTR) on availability, technician utilization, average equipment down time, equipment downtime for unscheduled maintenance, and equipment downtime for scheduled maintenance.

The following are the assumptions for this study:

Facility Types	10
Technician per shift	2
Facility Failure Interarrival Time (All Types):	exponential distribution
	46.7 hr. MTBF per facility
Proportion of Scheduled Repair (All Types)	50%
Qualification of Tech 1	Facility 01-05;

Qualification of Tech 2	Facility 06-10
Shift Staffing	All shifts equally staffed

The effect of these cases is to vary the average MTTR of the cost center by 10% increments to 100% of the baseline value (Table 3b).

The simulation model used for the MTTR study is similar in overall structures to that described in section 4.1. However, when the facility type is defined, an MTTR attribute is also associated with it (whereas previously, all facility types had the identical MTTR).

4.3.1 Results

The results of the simulation in terms of availability, technician utilization, and facility downtime are analyzed and the following was concluded: As the MTTR is decreased (i.e., the number of facilities with twice of the baseline MTTR is increased), the equipment availability decreases from the baseline of approximately 0.9913 to 0.9516 in a nonlinear manner (Figure 5b). This is to be expected because as more facilities require longer service, technicians become less available, and there is a greater likelihood that an unscheduled outage can not be immediately fixed.

Figure 6b shows the technician utilization as a function of the number of facilities failing with greater frequency. The result is linear as the proportion of facilities with ½ the reliability (as measured in MTBF) increases. This is consistent with the relationship between utilization and technician business time shown in Equation 1.

The dramatic increase in unscheduled outage time (Figure 7b) can be explained by the fact that technicians become busier as the average failure rate increases, and hence, it is less likely that a technician will be available to perform a maintenance action. The duration of scheduled downtimes remains constant because of the reasons cited in the earlier section. The average outage time is the mirror image of the availability curve (Figure 6a). This is to be expected given the relationship between downtime and availability defined in Equation 3.

4.4 Simulation of Shifts

Two simulation studies were performed in order to demonstrate the capability of the discrete event simulation models to simulate changes in staffing level and maintenance policies by shift. The following two simulations studies were performed:

- Impact of maintenance deferral policies on outage times and availability
- Impact of MTBF upon outage times and availability.

The following are the general assumptions for all analyses:

Number of shifts:	4, each with 42 hours;
No. of facility types	2
No. of facilities of each type	5
Repair Time (All Types)	exponential distribution
	4.1 hr. MTTR

In this model, technicians were assigned to make a repair only if they were on the shift on which the maintenance action occurred (Figure 8). This assumption resulted in the construction of the “Choose” and “Assign” blocks shown at the top of the figure. Shifts were defined as occurring in 42-hour segments of a 168-hour (1 week) cycle. The first shift run to 42 hours, the second between 43 and 84 hours, the third between 85 and 126 hours, and the final, between 127 and 168 hours (inclusive). The remainder of the model is similar to that which has been described previously.

4.1.1 Non-Uniform Staffing and Deferred Maintenance Strategy Study

In this study, 10 technicians were distributed among 4 shifts. Two shifts are lightly staffed, two are fully staffed. The MTBF of each facility was assumed to be 46.7 hours. It was also assumed that there were no administrative or travel delays.

The following staffing profile was assumed:

Shift 1: Tech 1;

Shift 2: Tech 2;

Shift 3: Tech 3, 4, 5, 6;

Shift 4: 7, 8, 9, 10

There were assumed to be 2 facility types. Technician qualifications were assumed to be as follows:

Qualified Tech for Facility Type 1: 1, 2, 3, 4, 7, 8

Qualified Tech for Facility Type 2: 1, 2, 5, 6, 9, 10

Two cases were considered:

1. *No deferral:* All technicians, either on lightly staffed or the main shifts, are responsible for performing both scheduled and unscheduled maintenance actions.
2. *Deferral of scheduled maintenance:* Technicians on the main shift perform both scheduled and unscheduled maintenance, but those on the lightly staffed shifts perform only corrective maintenance.

Deferral of scheduled maintenance results in a significant benefit (average outage time of 20.8 hours non-deferred vs. 7.4 hours for deferred) because the single technicians on the off-shift are less busy (Table 4a). Thus, an unscheduled maintenance action can be handled.

4.1.2 MTBF Impact in the Presence of a Deferred Maintenance Strategy

In this study, the staffing and qualifications were identical to the deferred maintenance cases described above, but an additional administrative and travel delay of 1 hour were added. MTBFs were varied from the nominal 46.7 hours per facility to half (average of 23.7 hours per facility) to double (93.4 hours per facility)

The results show (Table 4b) that outage time decreases with increasing reliability in a manner similar to those shown in section 4.1. These results show that reliability can have an impact on facility availability and outage time even though staffing and maintenance deferral strategy can also impact the results.

5. SUMMARY AND CONCLUSIONS

This paper has described a set of simulation models which can be used to derive the impact of staffing, shift staffing strategies, maintenance policies, and other maintenance management decisions on service availability, technician utilization, average equipment down time, equipment downtime for unscheduled maintenance, and equipment downtime for scheduled maintenance.

Among four studies that were conducted, the Technician Qualification Study gave us the impact of technician training (i.e., number of systems for which qualified). As technician training increased, the equipment availability increased from approximately 0.9913 to 0.9926. Scheduled downtime remained the same, but the unscheduled downtime decreased by more than 1.8 hours per outage. In Reliability Study, the impact of reliability (i.e., MTBF) was determined. As the MTBF decreased, the equipment availability decreased, the technician utilization increased linearly, and the unscheduled outage downtime increased dramatically. The Repair Time Study showed that as the MTTR decreased, the equipment availability decreased, technician utilization increased, and the unscheduled outage time increased dramatically. In the Shift Study, when non-uniform staffing and deferred maintenance was considered, deferral of scheduled maintenance resulted in a significant benefit (average outage time of 20.8 hours non-deferred vs. 7.4 hours deferred). In the case of the MTBF impacts in the presence of a deferred maintenance strategy, it was found that the outage time decreased with increasing reliability.

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List of Tables

List of Figures

Table 1. Objects in N-RPM Simulation

Object	Attributes
Facility	• Specialization class (communications, navigation, surveillance, and automation). • Facility designation (class, type, and facility code, Source: FMF) • Probability Distribution Function of the failure or maintenance rate (for scheduled and unscheduled maintenance actions – Source: empirical analysis of the National Airspace Performance Reporting System, NAPRS, data) • Probability Distribution Function and parameters of the repair time (for outages of all significant cause codes. Source: NAPRS data) • Travel and associated administrative time in minutes, Source: FMF) • Maintenance staffing priority code or Restoration Code (i.e., number of shifts during which facility will receive service – Source: FMF) • ATC priority code
Technician	• Identification of technician • List of equipment on which qualified • Days of week when working • Shifts to which assigned
Cost Center	• Identification of cost center • List of facilities in cost center • List of technicians
Service	• Identification of service • List of facilities making up a service
Failure/ Maintenance event	• Identification of Failed Facility • Shift on which outage occurred (day, swing, graveyard) • Day of week of outage (Weekday, Weekend) • Severity (outage, degradation, loss of redundancy)

Table 2. Qualification Study Simulation Case Descriptions

Case	Facility Types for which Tech 1 qualified	Facility Types for which Tech 2 qualified
1	1, 2, 3, 4, 5	6, 7, 8, 9, 10
2	1, 2, 3, 4, 5, 6	5, 6, 7, 8, 9, 10
3	1, 2, 3, 4, 5, 6, 7	4, 5, 6, 7, 8, 9, 10
4	1, 2, 3, 4, 5, 6, 7, 8	3, 4, 5, 6, 7, 8, 9, 10
5	1, 2, 3, 4, 5, 6, 7, 8, 9	2, 3, 4, 5, 6, 7, 8, 9, 10
6	all	all

Table 3. Reliability Study Simulation Case Descriptions

3a. Case Descriptions with ½ MTBF

Case	No. of Facilities with Baseline MTBF (46.7 hours)	No. of Facilities with Half the Baseline MTBF
1	10	0
2	8	2
3	6	4
4	4	6
5	2	8
6	0	10

3b. Case Descriptions with 2 MTBF

Case	No. of Facilities with Baseline MTTR (4.1 hours)	No. of Facilities with Twice Baseline MTBF (8.2 hours)
1	10	0
2	8	2
3	6	4
4	4	6
5	2	8
6	0	10

Table 4. Shift Staffing Study Results

4a. Deferred Maintenance Results

Study Cases	Availability	Tech Util	Average Outage Time	Scheduled Outage time	Unscheduled Down Time
No deferral	0.967534	44.37208	20.81582	4.1251	37.550
Deferral	0.988515	26.63272	7.364840	4.1920	10.539

4b. MTBF Summary Results

Study Cases	Availability	Technician Utilization	Average Outage Time	Scheduled Outage Time	Unscheduled Outage Time
½ MTBF	0.943455	52.42752	18.137305	4.1529	32.039
Nominal MTBF	0.980900	35.78528	12.232613	3.9962	20.628
1.5 MTBF	0.994077	17.46312	5.738469	4.1969	7.2944
Twice MTBF	0.995820	13.15947	5.339518	4.1705	6.5442

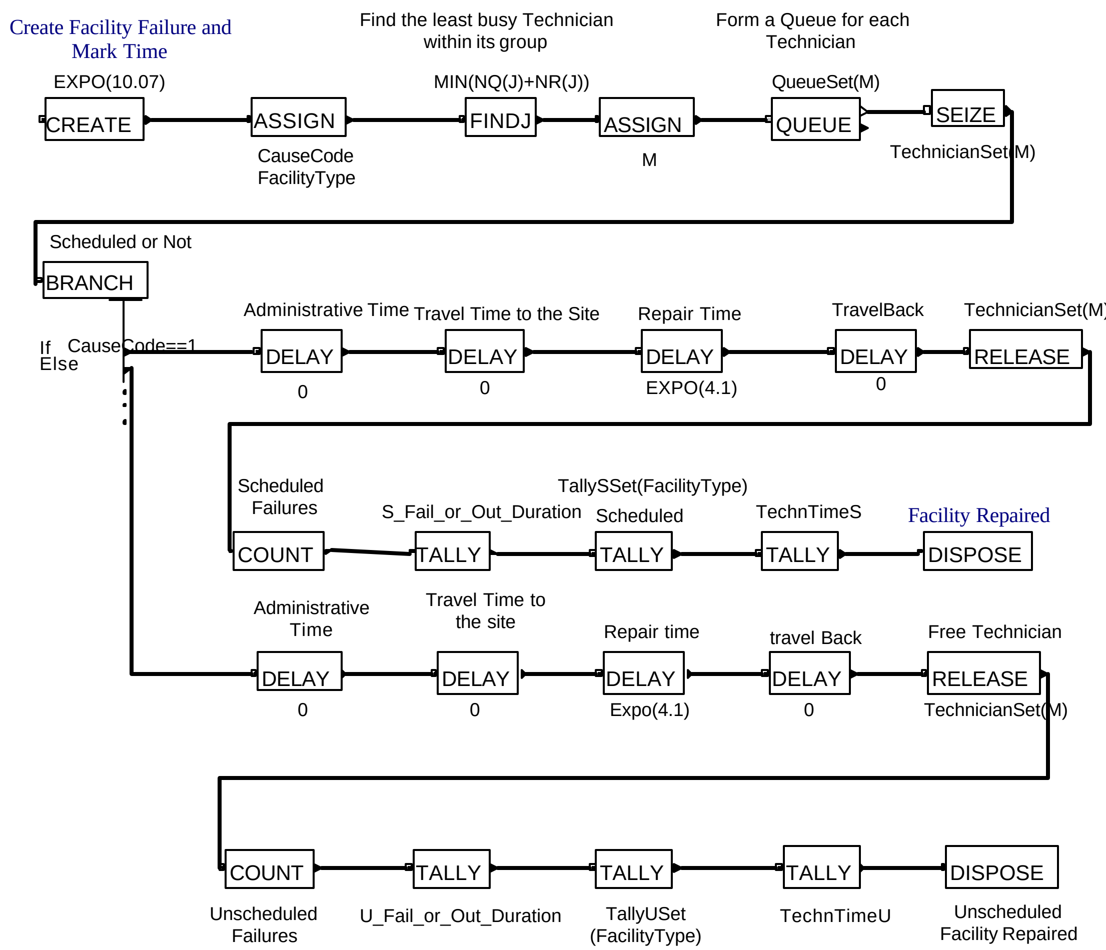


Figure 1. General Maintenance Cost Center Simulation Model

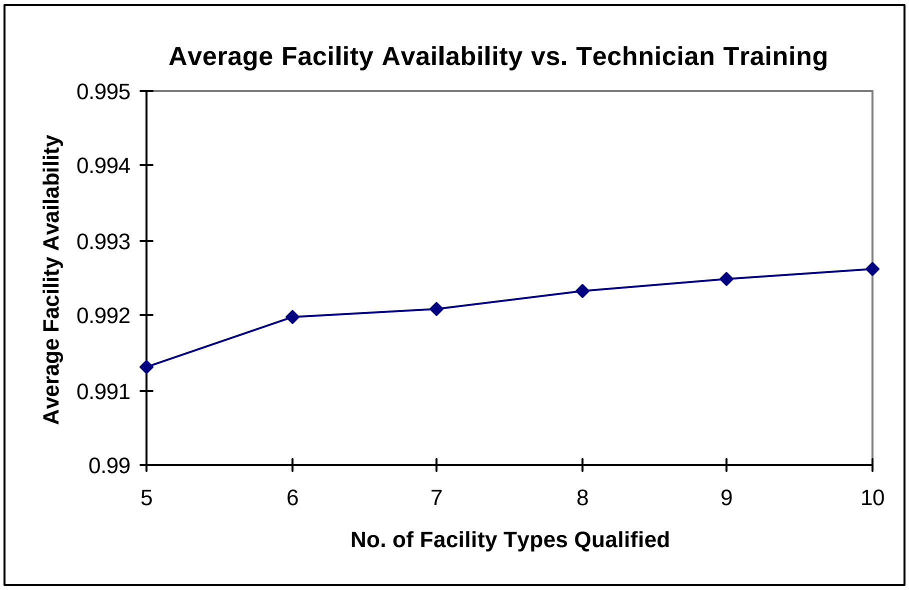


Figure 2. Average Facility Availability vs. Technician Training

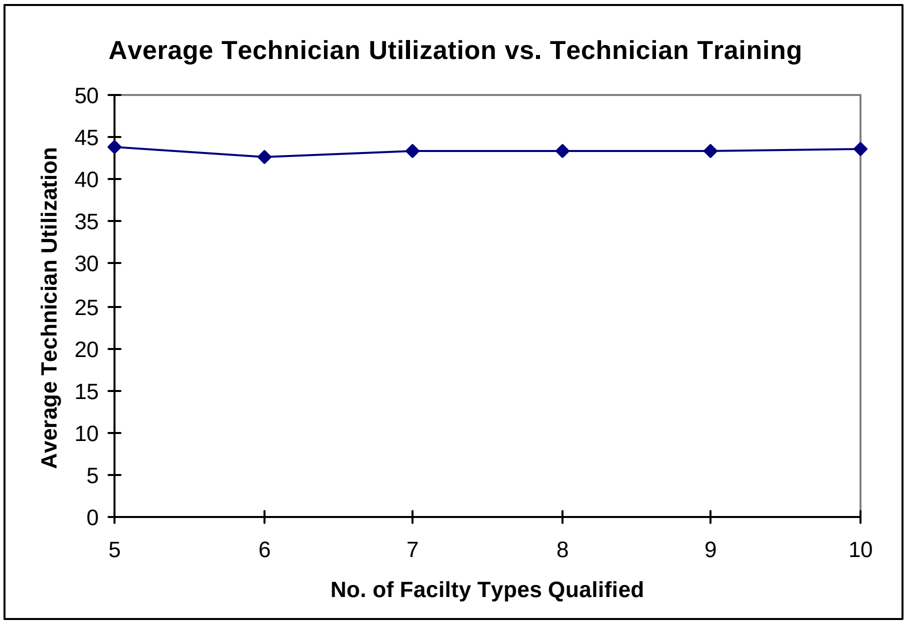


Figure 3. Average Technician Utilization vs. Technician Training

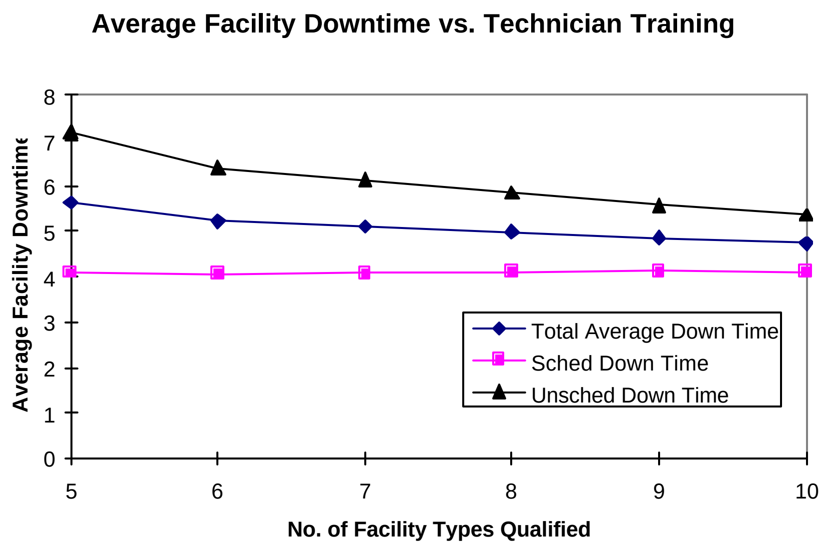
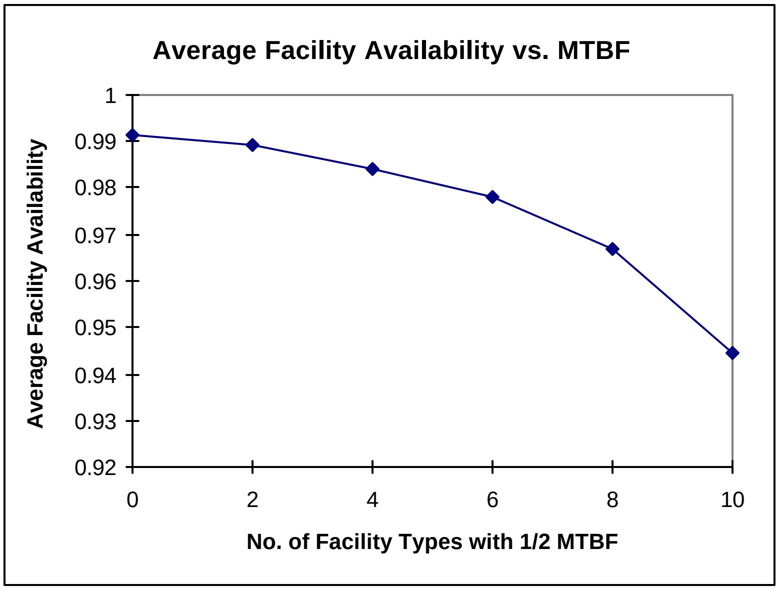
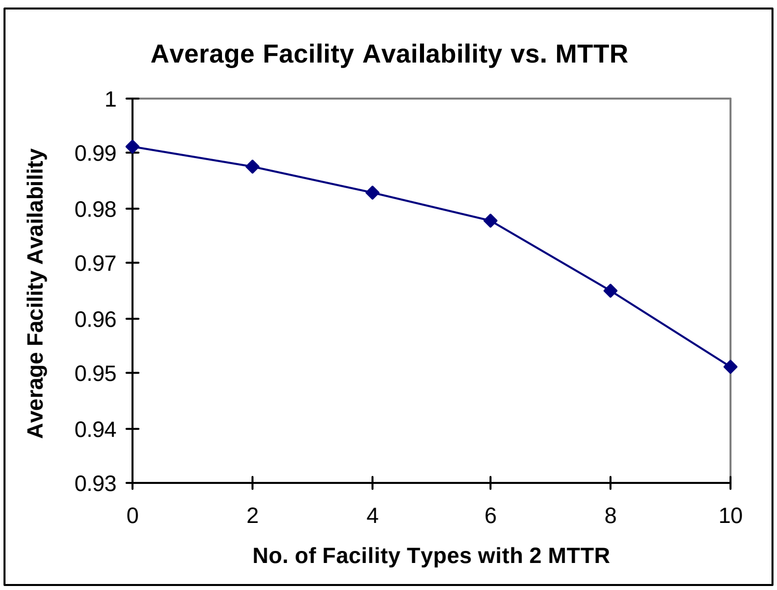


Figure 4. Average Facility Downtime vs. Technician Training

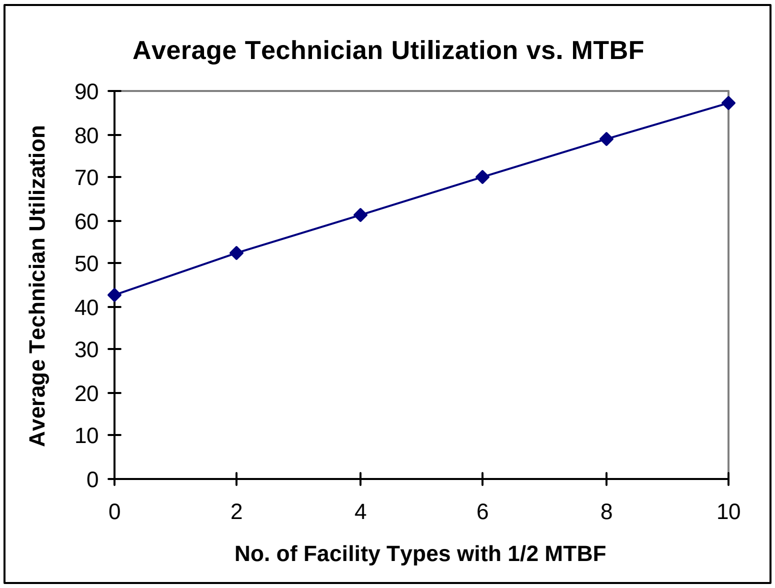


5a. Average Facility Availability vs. MTBF

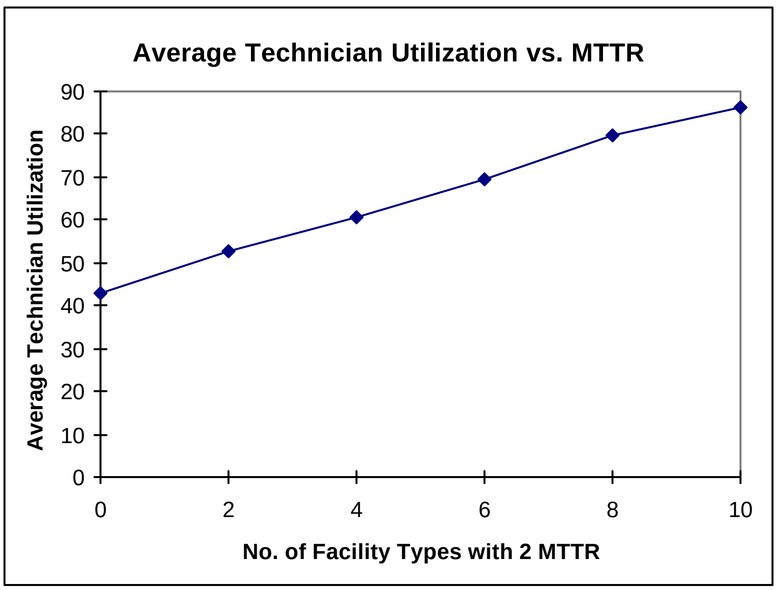


5b. Average Facility Availability vs. MTTR

Figure 5. Average Facility Availability

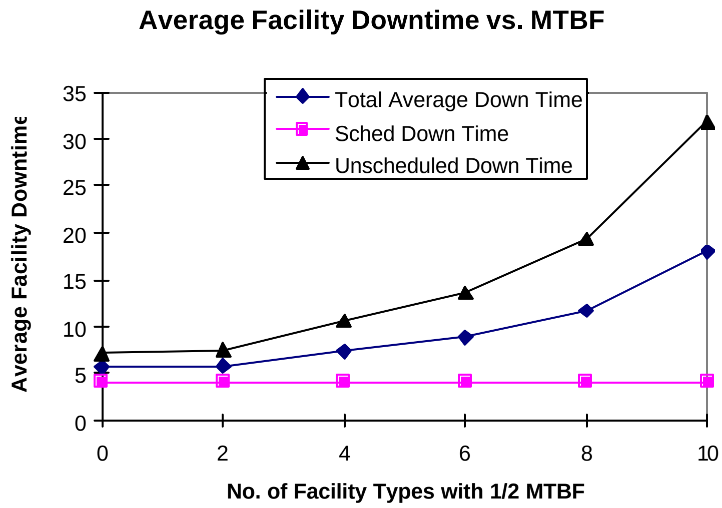


6a. Average Technician Utilization vs. MTBF

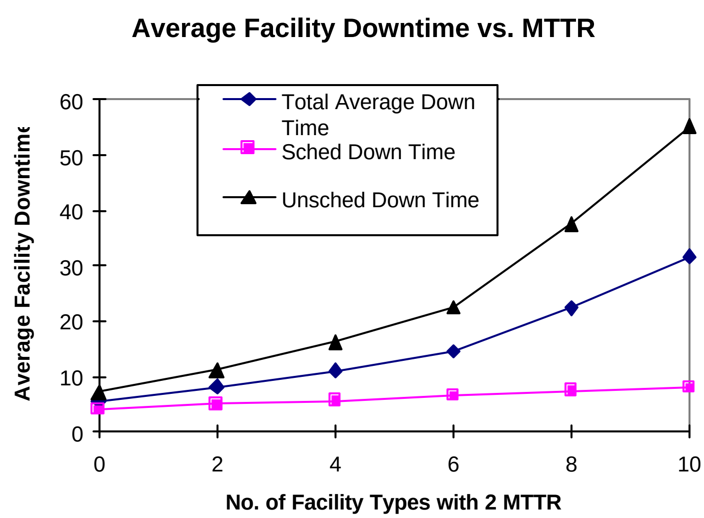


6b. Average Technician Utilization vs. MTTR

Figure 6. Average Technician Utilization



7a. Average Facility Downtime vs. MTBF



7b. Average Facility Downtime vs. MTTR

Figure 7. Average Facility Downtime

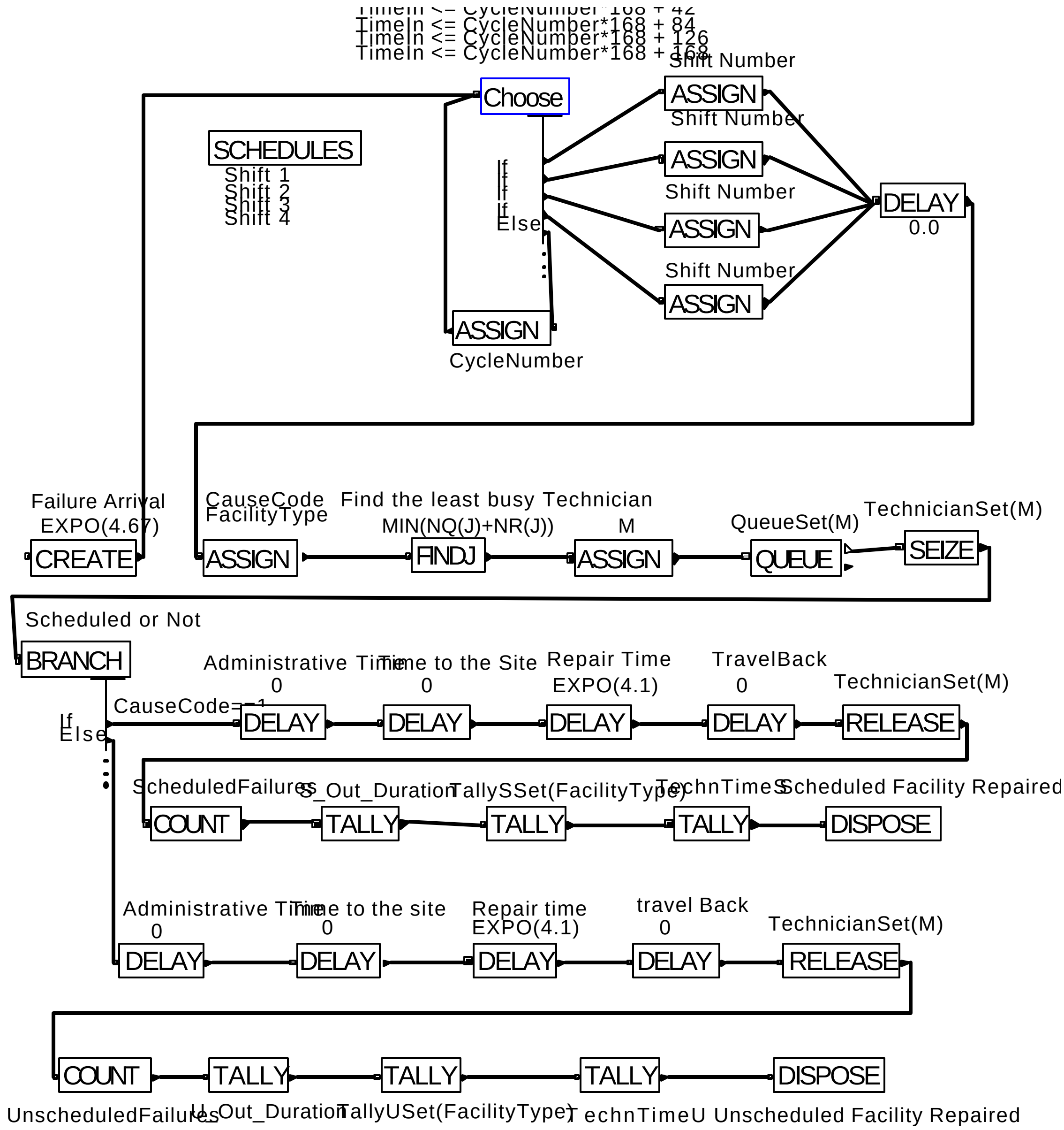


Figure 8. Staffing Simulation Model