Operational Availability Modeling for Risk and Impact Analysis

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1. SUMMARY & CONCLUSION

Availability is a system performance parameter which provides insight into the probability that an item or system will be available to be committed to a specified requirement. Depending on the application, availability can be defined to include reliability, maintainability and logistic support information. For fleet management purposes, the ability to quantify availability in terms of all of its contributing elements is essential. This paper provides a discussion on a steady state operational availability model which can be used to assist the Canadian Air Force in its aircraft fleet management requirements.

The availability model embodies scheduled and unscheduled maintenance and allows for impact analysis using in-service maintenance data. The model is sensitive to fleet size, aircraft flying rate, frequency of downing events, aircraft maintainability, scheduled inspection frequency, and scheduled inspection duration. The predictive capability of this availability model is currently providing the Canadian Air Force with a more sophisticated maintenance analysis decision support capability.

In order for this paper to be available for general distribution, it must be unclassified. As a result, the case studies presented do not reveal the actual operational availability of any Canadian Air Force fleet. However, the level of detail provided is more than adequate to illustrate the case studies and give insight into applications of the availability model.

2. INTRODUCTION & BACKGROUND

The Canadian Air Force has initiated an R&D project directed at supportability analysis for aircraft fleets. A required element in the supportability analysis research is establishing the ability to carry out risk and impact analysis as it pertains to operational availability (Ao). The reason operational availability has been selected as a measure of interest is that the primary goal of aircraft maintenance operations is to achieve the highest Ao possible. In addition, availability is an indicator which can be used for assessing fleet capability. This paper will discuss the development and use of an operational availability model that is based on aircraft level information and parameters extracted from in-service maintenance data.

3. NOMENCLATURE

MTBDE = Mean Time Between Downing Event,
$MTTR_{DE}$ = Mean Time To Restore Aircraft After Downing Event,
MTBM = Mean Time Between Maintenance,
MDT = Mean Maintenance Downtime,
Per = Periodic Inspection Frequency (Major Hardtime Inspection),
Supp = Supplementary Inspection Frequency (Minor Hardtime Inspection),
DLM = 3rd Line Inspection Frequency (Major Structural Inspection),
MPT = Expected Time To Complete Periodic Inspection,
MST = Expected Time To Complete Supplementary Inspection,
MDLMT = Expected Time To Complete 3rd Line Inspection,
YFHPAC = Yearly Flying Hours per Aircraft (Equipment Utilization),
N = Number Of Downing Events For A Fixed Period Of Time
μ_L = Lognormal Mean
σ_L = Lognormal Standard Deviation,
TT = Total Time (For one year 8760 calendar hrs),
OT = Operating Time,
ST = Standby Time,
SDT = Scheduled Downtime,
UDT = Unscheduled Downtime.

4. MODEL DEVELOPMENT & ANALYSIS

4.1 *Availability Theory*

The definition of availability for this paper comes from MIL-STD-721 and is defined as "A measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called for at an unknown time." This by itself is inadequate and must be expanded to specifically define the availability measure of interest. For this paper, all references to availability refer to operational availability which is defined as including all possible events which cause an item to be unavailable, without restrictions. This should not be confused with inherent availability and achieved availability which are measured under ideal conditions. In addition, the calculations and derivations shown are for steady state operational availability, alternatively called the uptime ratio.

The typical method of determining availability using in-service data is to observe the equipment state over time and determine the ratio of uptime to total time. This approach is basically a measurement activity in which historical availability levels are determined. It is important to note that in this availability measuring approach there are many possible classifications of time. However, fundamentally, the item being observed is in either an available or an unavailable state. The breakdown of time associated with either of these two states can arbitrarily be assigned to a time category, as required for analysis. The division of time used by the Canadian Air Force for operational availability measurements is given in Figure 1.

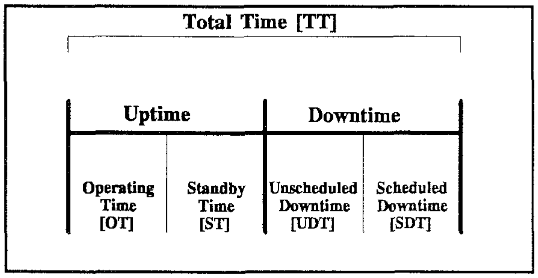

Figure 1

Using the breakdown of time given in Figure 1, Ao can be calculated using eqn (1).

$$Ao = \frac{OT + ST}{OT + ST + SDT + UDT} \tag{1}$$

Eqn (1) is very similar to other operational availability expressions, (Refs. 1- 3) with the exception that logistic and administrative delay time is incorporated in scheduled downtime (SDT) and unscheduled downtime (UDT). The reason is that the Canadian Air Force's maintenance data collection system does not categorize downtime by logistic or administrative delay.

To solve for availability in eqn (1), operating time (OT) and standby time (ST) must be known. Using a maintenance data collection system to collect information can pose a problem, since equipment downtime, rather than uptime, is recorded. This results in the requirement for availability to be estimated by using one (100% available) minus the unavailability. Unavailability can be calculated using eqn (2).

$$\overline{Ao} = \frac{SDT + UDT}{OT + ST + SDT + UDT} \tag{2}$$

Although this approach does allow for operational availability to be calculated, it is restricted in usefulness. The impact of changes to those factors which impact Ao can not be predicted; they can only be measured. In fact, the factors which actually impact on Ao are not identifiable in eqns (1) and (2). For this reason, operational availability models have been developed which allow for Ao to be calculated as a function of mean time between maintenance (MTBM) and mean maintenance downtime (MDT). MDT is usually defined to include downtime associated with all forms of maintenance and includes logistic and administrative delay. The standard expression found in literature for Ao as a function of MTBM and MDT (Refs. 3- 4) is given in eqn (3).

$$Ao = \frac{MTBM}{MTBM + MDT} \tag{3}$$

Again there are variations of eqn (3), which may or may not expand MDT into maintenance, logistic and administrative components. Of interest is that the time domain must be consistent across all parameters. Often one will see MTBM expressed in operating hours and MDT expressed in man hours. The problem with eqn (3) is that both unscheduled and scheduled maintenance are grouped together, even though each has a different maintenance downtime and time to maintenance requirement distributions. In fact, scheduled maintenance is not random at all and should not be linked with unscheduled stochastic events. In addition, the transformation from operating hours to calendar or clock hours is not readily apparent.

Markov availability modeling can be used to obtain the point availability, A(t). However, there are several reasons why this approach has not been explored. Markov models are easily solved with exponential failure and repair time distributions, but are much more complex when distributions such as Lognormal must be incorporated (Ref. 5). This is significant, since none of the repair time distributions used in this paper are exponential. Finally, point availability estimates derived from Markov analysis are not required for steady state risk assessment. What is required for in-service data analysis within the Canadian Air Force is that the method used for predicting availability be simple to understand and easy to implement. An availability model meeting this requirement has been developed. The model used is simply a further derivation of eqn (2) in which scheduled and unscheduled downtime (SDT and UDT), as a function of utilization, are predicted.

4.2 *Unscheduled Downtime*

Downtime as a result of unscheduled maintenance is a function of two parameters: the rate at which maintenance is required and the amount of time required to restore the system to a serviceable state. When considering the availability of an aircraft fleet, it is necessary to determine the downing rate, or the rate at which the aircraft is made unserviceable, regardless of the number of maintenance demands the aircraft has for each downing event. This downing event can, therefore, be caused by the failure of a component, a perceived failure, the requirement for a removal of a time expired item, a configuration change, the embodiment of a modification or any combination of these listed activities. What this does not include is the requirement for a scheduled preventive maintenance inspection. The parameter used to express the occurrence of unscheduled maintenance demand is the mean time between downing events (MTBDE), which becomes a measure of the entire system's in-service reliability. Research into quantifying MTBDE from in-service data has determined that for Canadian Air Force fleets MTBDE is exponentially distributed. Therefore, MTBDE can be estimated by dividing the total airframe or flying hours by the total number of unique downing events which occur during a stated period of time, as given in eqn (4).

$$MTBDE = \frac{\textit{Total Flying Hours For Period}}{\textit{Total Number Of Downing Events}} \tag{4}$$

For every downing event, there is a corresponding time required to restore the aircraft to an available state. The mean time to restore the aircraft ($MTTR_{DE}$) is the expected time, in calendar hours, for which an aircraft was unavailable and could not fly due to a downing event. Because there is a possibility that an aircraft may have several maintenance actions (MA) charged against it, all of which may have been opened and closed at different times, it is necessary to determine the earliest date and time at which any of the MAs were opened, and the latest date and time at which any of the MAs were closed. The difference between these two times becomes a time to restore observation which can be used to estimate a time to restore distribution. An analysis was carried out for all Air Force fleets which confirmed that the time to restore distribution is Lognormally distributed. As a result, $MTTR_{DE}$ must be estimated using the Lognormal distribution. This is done by finding estimators for the Lognormal mean (μ_L) and standard deviation (σ_L) from the time to restore data and then using the Lognormal parameters to determine $MTTR_{DE}$. Eqn (5) gives this standard transformation (Ref. 6).

$$MTTR_{DE} = \exp^{\mu_L + \frac{\sigma_L^2}{2}} \tag{5}$$

Eqns (4) and (5) describe how in-service data are used to obtain MTBDE and $MTTR_{DE}$. However, what is required is an expression which incorporates both MTBDE and $MTTR_{DE}$ to predict unscheduled downtime in calendar hours based on utilization. To do this, MTBDE must be normalized on calendar hours. This is done by incorporating a utilization factor (YFHPAC) to determine the number of downing events (N) for a fixed period of time (one year) as shown in eqn (6).

$$N = \frac{YFHPAC}{MTBDE} \tag{6}$$

The unscheduled downtime can now be found using eqn (7):

$$UDT = N \times MTTR_{DE} \tag{7}$$

This equation can be further expanded to incorporate MTBDE as eqn (8).

$$UDT = \frac{MTTR_{DE} \times YFHPAC}{MTBDE} \tag{8}$$

Eqn (8) can now be used to estimate the total unscheduled downtime for an aircraft using $MTTR_{DE}$, MTBDE and YFHPAC. To illustrate this calculation, let MTBDE = 10 flying hours and be $MTTR_{DE}$ = 30 calendar hours. If the utilization for a year is 1000 hours per aircraft, then the unscheduled maintenance downtime is predicted at 3000 calendar hours per year, or 3 calendar hours for every flying hour.

4.3 *Scheduled Downtime*

Scheduled downtime can be calculated by estimating the number of scheduled maintenance events and multiplying each event by its expected completion time. For Canadian Air Force aircraft maintenance, there are essentially three types of scheduled maintenance events: supplementary inspection which is similar to a civilian aviation "A" check, a periodic inspection which is more in depth than an "A" check but less in depth than a civilian aviation "C" check, and a major structural inspection which is similar to a "C" check. When a periodic inspection is carried out, it counts as both a supplementary and periodic inspection. On some Canadian Air Force fleets, when a major structural inspection is carried out it counts as both a periodic and structural inspection. In addition, each aircraft type in the Canadian Air Force has different frequencies of scheduled inspections and expected inspection completion times.

The inspection frequencies are established based on a Reliability Centered Maintenance program. The actual inspection durations used in the model are estimated from in-service time to complete inspection data. Analysis of this data for all Canadian Air Force fleets has established that the scheduled downtime durations are normally distributed. Thus, the expected time to complete an inspection is obtained using an arithmetic mean of the inspection completion time data.

The estimation of the number of scheduled maintenance inspections required to support an aircraft is a function of aircraft utilization. The number of periodic inspections required is given by eqn (9).

$$\textit{Number Of Periodic Inspections} = \frac{YFHPAC}{Per} \tag{9}$$

If the completion of a structural inspection includes the completion of a periodic inspection, then the number of period inspections required is given by eqn (10).

$$\textit{Number Of Per Insp} = \frac{YFHPAC}{Per} - \frac{YFHPAC}{DLM} \qquad (10)$$

The contribution to scheduled downtime from periodic inspections, assuming periodic inspections are not carried during a 3rd line inspection, is given by eqn (11).

$$\textit{Periodic Downtime} = \frac{YFHPAC}{Per} \times MPT \qquad (11)$$

Using this same approach, the contribution of supplementary inspections to scheduled downtime is given by eqn (12), and the contribution of structural inspections to scheduled downtime is given by eqn (13).

$$\textit{Supp Downtime} = \left(\frac{YFHPAC}{Supp} - \frac{YFHPAC}{Per}\right) \times MST \qquad (12)$$

$$\textit{Structural Downtime} = \frac{YFHPAC}{DLM} \times MDLMT \qquad (13)$$

The downtimes for each inspection type as a function of utilization (YFHPAC) can be combined into eqn (14) to give the expected downtime for an aircraft due to scheduled inspections.

$$SDT = \left[\frac{1}{Per} \times MPT + \left(\frac{1}{Supp} - \frac{1}{Per}\right) \times MST + \frac{1}{DLM} \times MDLMT\right] \times YFHPAC \qquad (14)$$

To illustrate how eqn (14) can be used, consider the aircraft inspection data contained in Table 1. If we use a utilization factor of 1000 flying hours per calendar year the scheduled downtime per aircraft per year can be calculated directly at 861 calendar hours per year. This is 0.861 calendar hours of scheduled maintenance for every flying hour.

Table 1 - Aircraft Inspection Data	
Supp	450 flying hours
MST	75 calendar hours
Per	900 flying hours
MPT	300 calendar hours
DLM	3600 flying hours
MDLMT	1600 calendar hours

4.4 *Steady State Operational Availability Model*

Now that both scheduled and unscheduled downtime can be calculated directly, a final equation for operational availability can be represented by eqn (15).

$$Ao = 1 - \left(\frac{SDT + UDT}{TT}\right) \qquad (15)$$

Using the values for scheduled downtime (SDT) and unscheduled downtime (UDT) previously calculated in the paper in eqn(15) results in a predicted steady state operational availability of 56%.

To validate the model, the predicted steady state Ao can be compared to the actual observed availability for some fixed time period. This was done by calculating a predicted operational availability for all Canadian Air Force Fleets and comparing these values to the actual measured operational availability for each fleet in 1993. This validation exercise consistently gave predicted results which were within $\pm 10\%$. Differences in results between observed and predicted Ao can be attributed to the variability in the statistical estimators of the model parameters. In addition, there is no evidence to suggest that the observed operational availability for a one year time period should be exactly representative of the steady state Ao.

The real value of the model is not only to provide an estimation of availability, but also to provide a risk analysis tool. Changes in any of the 9 parameters which are evaluated to solve eqn (15) can be measured in terms of their impact on Ao. To further illustrate the applicability of this model, three additional examples will be solved. All case studies are real with actual results provided. However, some of the input parameters required to duplicate the calculations have been omitted so that the true operational availability of the discussed fleets is not revealed.

5. OPERATIONAL AVAILABILITY EXAMPLES

5.1 *Case 1*

Case 1 provides an example of how aircraft utilization impacts availability. The Canadian Air Force uses Lockheed Hercules (C-130) as their primary air transport vehicle. Two of the operational bases that operated this aircraft type in 1993 were 8 Wing Trenton, Ontario and 18 Wing Edmonton, Alberta. Given that these two bases have similar roles and maintenance practices, one would expect them to have comparable steady state operational availabilities. In fact, this is not the case: the observed Ao at these two bases is consistently dissimilar. Prior to the research associated with the development of an Ao model, a persistent difference between bases was attributed to other factors, like better maintenance practices of one base over the other. However, this is incorrect. Trenton's aircraft utilization from Apr 93 to Mar 94 was approximately 250 flying hours per aircraft higher than Edmonton's utilization. Using the methodology given in this paper and each base's aircraft utilization as input parameters, it was found that there should be a steady state difference in Ao of approximately 10%. What in the past was viewed as a problem, should instead be accepted as normal, based on the differences in aircraft utilization.

The fact that availability is a linear function of utilization is intuitive. If an aircraft is not flown, then the expected availability should be 100%, and conversely the more an aircraft is used, the lower the anticipated availability.

5.2 *Case 2*

Case 2 provides an example of how differences in aircraft reliability can impact availability. The F-18 Hornet is used as a fighter aircraft by the Canadian Air Force. One of the operational units which operate this aircraft identified a possible problem with the level of effort required to maintain the initial production lot (Lot 5) of aircraft received by the Canadian military from McDonnel Douglas. Analysis of in-service data confirmed the concern raised by the operational squadron. The maintenance person hours per flying hour (MPH/FH) for Lot 5 F-18 aircraft was statistically higher than the rest of the fleet (10.2 vs 6.1 MPH/FH). This difference in maintenance burden is attributable to a reliability cause factor. The reliability difference can be seen by a comparison of MTBDE parameters. Lot 5's MTBDE is 2.8 flying hours and the MTBDE for non-Lot 5 aircraft is 3.6 flying hours.

The impact of this difference in aircraft reliability on availability can be predicted using the model discussed in this paper. Assuming all other parameters are the same across all aircraft lots, then the difference in aircraft reliability will result in an availability difference of approximately 8% based on current utilization levels. This information is critical to the decision making process because the impact of no change can be quantified and used in a cost benefit analysis.

5.3 *Case 3*

Case 3 provides an example of how changes in a scheduled inspection program can be translated into availability. The Canadian Air Force operates the Sea King helicopter (CH124) as its primary naval support aircraft. One of the activities undertaken by the Air Force in support of this fleet is scheduled inspection rationalization. Using the Ao model the impact of changes in inspection schedule can be quickly quantified. Consider the CH124 which has just undergone a change in periodic inspection frequency, from 400 to 500 flying hours. This change in frequency was input into the model, with the resulting improvement in steady state operational availability predicted at 4.5%.

What is interesting in this example is that when inspection intervals are projected beyond 500 flying hours as shown in Figure 2, the marginal benefits gained in operational availability decrease as the inspection interval increases. To illustrate this, consider the fact that the cumulative improvement in operational availability from changing the inspection interval from 200 hours to 500 hours is

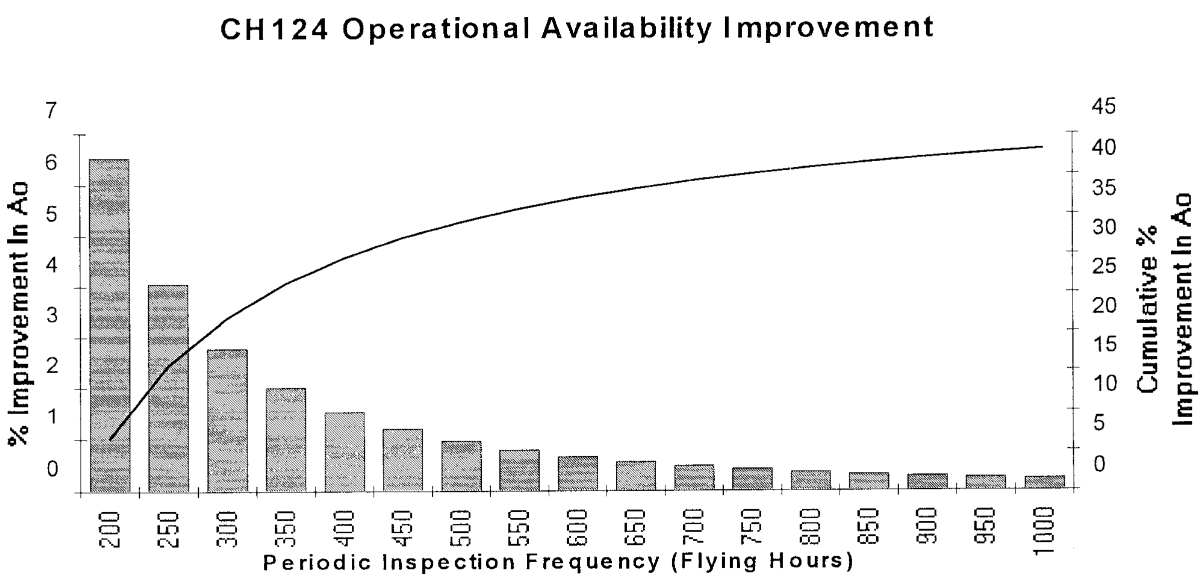

Figure 2

approximately 30%. A further 300 hour increase to 800 hours only results in a predicted cumulative improvement of 10%. This means that availability as a function of increasing periodic inspection interval is asymptotic to some limiting steady state availability value. The difference between this limiting availability and 100%, is the level of unavailability attributable to all other parameters in the model. This is important since any decision to increase the inspection interval beyond 500 hours should not be based on potential improvements in availability, but instead on reductions in maintenance costs.

6. FINAL DISCUSSION

This paper has illustrated an application of using in-service maintenance data to construct a risk analysis availability model. This analysis capability can be of significant value in predicting availability and performing impact assessment on those parameters which affect availability. The discussion provided shows that there are alternative approaches to modeling availability, however, the methodology used here allows for the separation of scheduled and unscheduled maintenance parameters within a single availability model. There is no reason why this approach can not be used by other industries to analyze in-service availability.

The final test for this model will be in its acceptance throughout the Canadian Air Force as a valid and effective analysis tool. An interactive risk analysis tool has been programmed in PASCAL which will provide for Ao risk analysis sessions for all current Canadian Air Force fleets. At this time, the program is in the Beta test stage awaiting endorsement from the Air Force aerospace engineering community.

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BIOGRAPHY

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Captain David J. Hurst is currently a member of the Canadian Armed Forces and is employed at the Aerospace Maintenance Development Unit in Trenton Ontario Canada. He received a BEng degree in Engineering and Management from the Royal Military College of Canada in 1987 and his MSc in Reliability Engineering from the University of Arizona in 1993. Capt. Hurst is currently employed as a Reliability Engineer on a supportability analysis R&D project. His current research responsibilities involve aircraft maintainability monitoring and assessment, aircraft inspection analysis and operational availability modeling for risk and impact analysis. Prior to his post graduate training, Capt. Hurst had tours as an Aircraft Maintenance Officer for a Search and Rescue Squadron and as an Aircraft Maintenance Control and Records Officer.