Modeling Multiple Preventative Maintenance Actions in a RAMS Analysis

Jack Olivieri, Lead Multi- Discipline Systems Engineer, MITRE Corporation

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SUMMARY & CONCLUSIONS

This paper describes how multiple preventative maintenance (PM) activities can be modeled in the availability and reliability analyses of complex systems, using popular off the shelf software. This is a necessary and critical step for an understanding of the downtime implications of certain electromechanical subsystems and systems, but is not always easy to model with all software packages.

Quite often, maintenance and service related actions are an afterthought in reliability and availability calculations. This is because most electronic systems require minimal maintenance of electronic circuit boards, components and sub systems. Dust filter replacement, inspection (and perhaps calibration) are the primary activities usually needed. As a result, many find it prudent to ignore these activities because they are second or third order effects. In most cases, they do not even require downing the system.

However, electromechanical devices and assemblies are different. There are many situations where several maintenance activities on an ongoing, repeatable schedule are required in order to prevent premature faults and extend the useful life of the device. This is especially true of engines, motors, generators, cooling fans and any device that includes bearings or mechanical movement. In addition, downing of the system is usually necessary to perform the needed maintenance.

This paper discusses an actual example of a radar power plant reliability block diagram (originally consisting of over 1000 blocks) with redundant gensets that shows how the maintenance dominates the down time and how failure rates play a lesser role in the availability of the power plant.

1 INTRODUCTION

Maintenance and service related actions are often an afterthought in reliability and availability calculations. However, downtime due to preventative maintenance and overhaul activity can be the dominant factor in the determination of system availability, especially for electromechanical subsystems.

During the design of large ground based military radar with potentially multiple sites, several analyses were performed to assess the overall operational reliability (Ao) of the system. One subsystem modeled was a large power plant required for the operation of the radar which will be constructed by a defense contractor. The power plant subsystem is of critical importance to the overall program in order to meet the system Key Performance Parameters (KPP). This paper focuses on the details of the power plant subsystem and the modeling of the preventative maintenance attributes contained within.

Ultimately, the model analysis and results will be used to 1) assess and understand the final design, 2) provide a baseline for further modifications and tradeoffs and 3) review the detailed availability and maintainability characteristics of the power plant as part of the entire system.

2 RADAR POWER PLANT DETAILS

The power plant consists of multiple diesel engines coupled to generators (motor-generators or gensets). The overall power plant will provide ~10 Megawatts (MW) of power to support each radar site and will require significant effort to maintain. For this exercise, it is assumed that there will be initially 5 prime generators and 2 backups, each with an output of 2 MW. The final number of generators, including backups will depend on the analysis results. The analysis will also determine the impact of the preventative maintenance (PM) actions to the Ao of the power plant subsystem and the overall system and to determine an optimum approach to those activities.

Moreover, into order to meet the Ao goal, we needed to know which parameters could be traded off and which redundancy configuration (N+1,N+2,etc.) would be appropriate for the cost and manpower constraints.

2.1 *Maintenance Activities*

There are several categories of maintenance; corrective maintenance (CM), preventative maintenance (PM) and Overhauls (OH) that are relevant to gensets. CM occurs when a failure has occurred or (in some cases) when an imminent failure is about to occur. PM is regularly scheduled or planned maintenance based on the manufacturer's recommendations. The OH activity is based on hours of run time or fuel consumption of the genset. In this analysis, we will be concerned primarily with PM and OH activities.

2.1.1 PM Assumptions

The following assumptions were made during the analysis and were incorporated in the model:

- Only PM activities which contribute to downtime are counted and PM time is assumed to be a fixed constant. Therefore, while changing the oil in an engine is counted as downtime, routine inspections (e.g. inspecting engine mounts, water pumps, leaks, etc.) are not counted because the genset is not taken off line for the particular inspection.
- All engines are of equal reliability and power output and will require the same maintenance schedule.
- When performing PM on a given engine, maintenance actions can be performed simultaneously while the engine is out of service. For example, when an engine is down for 4000 hour service, the services usually performed at every 250, 500, 1000 and 2000 hours can also be performed during that downtime. In this case the total downtime would be (8+8+16+16+12= 60 hrs). This only works in the calculations if the intervals are even multiples of the higher maintenance interval.
- No PM for electronic Line Replaceable Units (LRU) modules is considered. This PM is considered to be negligible compared to the engine PM and Overhaul
- Generator maintenance is considered to be minimal due to sealed bearings, brushless construction and only minor inspections of wiring.

A typical PM schedule is shown for a single genset in Figure 1 (downtimes are engineering estimates and are fixed times).

Genset			
Preventive Maintenance Interval	Number per year	Downtime per occurrence (hours)	Estimated Downtime per year (hours)
Every		Hours	Hours
250 Service Hours	35.0	8	280.3
500 Service Hours	17.5	8	140.2
1000 Service Hours	8.8	16	140.2
2000 Service Hours	4.4	16	70.1
4000 Service Hours	2.2	12	26.3
8000 Service Hours	1.1	16	17.5
16000 Service Hrs	0.5	16	8.8
Total PM hours per year			683.3

Figure 1 – Typical Preventative Maintenance Schedule for Genset

As an example, the types of PMs at 250 hours include[1]:

- Battery Electrolyte Level - Check
- Belts - Inspect/Adjust/Replace
- Cooling System Supplemental Coolant Additive
- Engine Oil Sample - Obtain
- Fan Drive Bearing - Lubricate
- Hoses and Clamps - Inspect/Replace
- Radiator - Clean

2.1.2 *Overhauls Assumptions*

In addition to regularly scheduled PM, each engine in a genset must undergo periodic overhauls. These overhauls are critical to preventing premature failures or an early end of life. There are two types of overhauls, minor and major. Minor overhauls are sometimes call top end overhauls and require less “teardown” than a major overhaul which can be quite extensive. Some gensets require 2 minor overhauls before a major overhaul. In this example, only one minor overhaul is assumed before a major overhaul. See Figure 2 for a typical genset overhaul schedule. Since these figures are estimates, a Case A and Case B were entered that should bracket the actual downtimes.

When the minor and major overhauls are multiples of each other, the clock should not start at 0 for each. One should be delayed (e.g. minor overhauls clock should start at 15,000 hrs here). This prevents the system from having both a 30,000 major overhaul and a 15,000 minor overhaul at the same time.

Overhauls – Genset Type A	Interval (hrs)	Downtime per Occurrence (hrs)
Case A		
Minor / Top End Overhaul	15000	1344
Major Overhaul	30000	2016
Case B		
Minor / Top End Overhaul	15000	1848
Major Overhaul	30000	2352

Figure 2 – Typical Preventative Maintenance Schedule for Genset Type A

2.1.3 *Resources*

Obviously, manpower plays a major role in the amount of downtime incurred for both PM and overhauls. It was agreed to have two crews (resource teams) available at any one time, one for PMs and one for OHs. The resource teams are considered to be on site and the size of the teams (number of individuals) will be adjusted to implement a “reasonable” downtime, based on industry standards.

Only one engine should be downed for PM at a given time and only one should undergo an overhaul at any given time. Therefore, the maximum number of intentionally downed gensets at any time is a maximum of 2. However, if one genset is down for PM and another genset is down for overhaul, a third genset could potentially go down due to a failure.

The implications of 2 resource teams are:

1. The PM team is dedicated to work on PMs only; the same is true for the OH team
2. If a 4000hr PM is due, the PM will be completed and the 250hr, 500hr, 1000hr and 2000hr PMs will be completed as soon as the resource becomes free
3. There can be efficiencies of scale; i.e. a 4000hr PM may take less time than expected due to the genset being already unassembled in certain areas which make it easier and faster to do a 250 or 500 hr PM.
4. There may be not enough time to complete all PMs or Overhauls and still adhere to the manufacturer's recommendations. (See Figure 3 for a schedule of major overhaul times based on 14 week durations.) This shows that the durations and spacing of major overhauls for 7 gensets prevents the overhauls from being performed on time. In fact, genset 7 will not see it's 30,000 overhaul until after 44,000 hrs of operation, which could have warranty implications

    a. In these cases, early overhauls may be necessary on the the first several gensets to minimize the overdue time on the later ones. Also, since durations (downtime) of the overhauls are very important, it may be necessary to increase the size of the OH team. Figure 4 shows the effect of reduced downtimes (10 weeks) and early (by 6000 hrs) overhaul implementation. Instead of starting the overhaul at 30,000hrs, it is started at 24,000 hrs. The same strategy would apply to minor overhauls.

    b. Also, if not all gensets need to be running (as "hot" spares) then more time is available since operating hours would not accumulate as rapidly.

Genset	Start Time	Duration	Overdue Times
Major1	30000	2352	0
Major2	32352	2352	2352
Major3	34704	2352	4704
Major4	37056	2352	7056
Major5	39408	2352	9408
Major6	41760	2352	11760
Major7	44112	2352	14112

Figure 3 – Normal Overhaul Schedule

Logistics assumptions used in the models include the following:

- A spare part(s) is required to conduct the PM or Overhaul; this may not always be the case for PMs (such as when the cleaning of a component is needed)
- A failure does not refresh the genset to "new"; only the failed component is replaced; other components in the genset are not replaced
- A major overhaul refreshes the genset to "new" for end of life calculations; a PM or minor OH does not
- PM or Overhaul is delayed until spares or resources are available.

Genset	Start Time	Duration	Overdue Times
Major1	24000	1680	-6000
Major2	25680	1680	-4320
Major3	27360	1680	-2640
Major4	29040	1680	-960
Major5	30720	1680	720
Major6	32400	1680	2400
Major7	34080	1680	4080

Figure 4 – Overdue Schedule – Early Overhauls with reduced duration

3 MODELING DETAILS

3.1 Incorporating PM and OH

There were several software packages which were tried in the modeling efforts. They all used Monte Carlo simulations in order to evaluate the inputted reliability block diagram. The first package only allowed one PM or one OH. Despite several attempts to determine if there was a workaround, no response was received to queries for support. The second software package did have provisions for multiple PMs or OHs but had additional non-PM related issues.

In order to overcome these limitations, a new approach was developed to generate a reliability block diagram with a wide range of software tools. Each genset was broken down into several blocks (see Figure 5 for Genset 1). In the reliability block diagram shown, the first block represents the failure rate (FR) and Mean Time to Repair (MTTR) metrics, but no PM/OH information.

This first block also contains the failure rate distributions (usually exponential for failures and lognormal for repairs). The next several blocks contain the PM information (frequency, duration, distribution type, resources). There should be 1 PM block for each PM activity. After the PM blocks, there is one block for major overhauls and one block for minor overhauls. The information in the overhaul blocks is similar to the PM blocks. Neither the PM or Overhaul blocks contain FR or MTTR data.

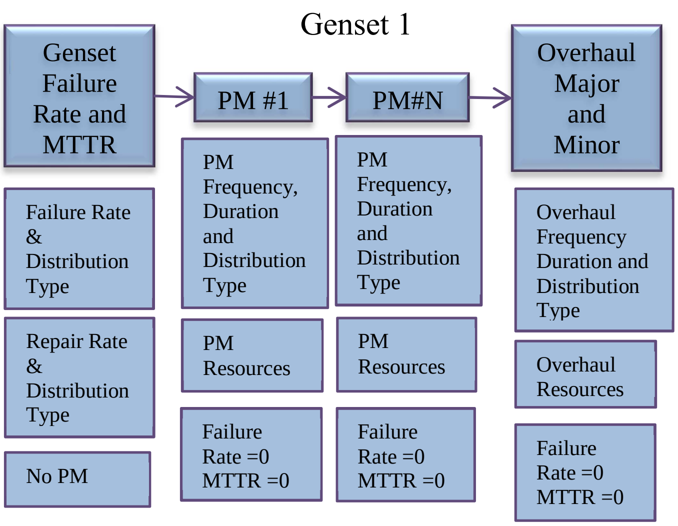

Figure 5 – Genset Block Expansion Workaround

These blocks are then combined in a classic x out of n block diagram along with other required power plant subsystems (controls, scrubbers, air handlers, etc.) for evaluation by the software tool (see Figure 6).

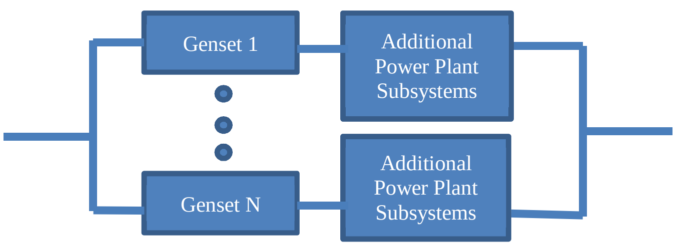

Figure 6 – Typical x/n Redundant Configuration

3.2 *Overlap Considerations*

It is useful to produce a map of PM and OH events as in Figure 5. This not only shows the PMs, but will identify conflicts in OH times. As mentioned earlier, if the PMs are even multiples of some number, they can be combined.

4 *MODEL RESULTS*

Several configurations were run to compare different redundancies and determine the effects of PM and OH on genset availability. (The set of input parameters for the model is shown in Appendix A.)

Since the ancillary equipment for all the configurations are the same, only the gensets were considered in the first pass. This allowed much faster processing initially. The individual blocks in the reliability block diagram included failure rates, repair rates, PMs and OHs for the gensets as shown in Figure 5. Also, a separate set of runs were performed with no failure rate (or repair) for the genset in order to see the sensitivity of the output to PMs and OHs. This column in the table (With Genset FR) shows the availabilities for just the PMs and OHs where the entry is "N".

The results are shown in Figure 7. These data show that genset failure rate does not make a large difference in the overall availability of the genset. When the ancillary equipment is added to the genset, the contribution of the genset failure rate is even less.

Config.		Ao	Genset FR included ?
5 out of 6	N+1	0.7854	Y
5 out of 7	N+2	0.9964	Y
5 out of 8	N+3	0.99995	Y
5 out of 6	N+1	0.7917	N
5 out of 7	N+2	0.9999	N
5 out of 8	N+3	>.99999	N

Figure 7 – Ao Results

The full power plant subsystem was calculated (per Figure 6) with all additional equipment necessary for power plant operation. The results for a 5 out 7 configuration are shown in Figure 8. Also shown is the availability using Case B duration times (1848/2352) for overhauls.

Ao	Minor/Major OH Durations (hrs)	Genset FR included?
0.9914	1344 /2015	Y
0.9959	1344 /2015	N
0.9900	1848 /2352	Y

Figure 8 – 5 out of 7 – Results - Full Power Plant Subsystem

A weak link analysis was also performed to show the biggest contributors to the unavailability of the system. The results are sorted from worst to best availability and are shown in Figure 9.

Block	Ao
Major Overhaul	0.940
Minor Overhaul	0.960
250 hr PM	0.969
500 hr PM	0.984
1000 hr PM	0.984
2000 hr PM	0.992
4000 hr PM	0.997
8000 hr PM	0.998

Genset Failure Rate	0.998
16000 hr PM	0.999

Figure 9 – Weak Link Analysis

5 CONCLUSIONS

The analysis shows that to get a reasonable availability in this situation, a minimum N+2 configuration is needed and preferably N+3. In addition, overhaul durations (especially major overhauls) are a significant factor in the determination of Ao. Consideration must also be given to providing adequate time for PMs and overhauls for all gensets without violating the warranty or reducing the life of the genset. While adding gensets may help the Ao, more gensets makes the implementation of timely PM and OH more difficult.

Preventative maintenance and overhaul activities are not always a trivial consideration in the calculation of availability. Many software programs do not make it obvious on how to handle several PMs and OHs. This paper has shown an approach to inputting data and analysis of the results, while considering several aspects of the issue.

REFERENCES

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BIOGRAPHY

Jack Olivieri is a Lead Multi-Discipline System Engineer with the MITRE Corporation in the Center for National Security (CNS) where he is responsible for support of the reliability specifications and analyses efforts on various defense projects for the Air Force. Previously, he worked at Alcatel-Lucent from 1998-2009 as a Reliability Tech Manager and performed DFR activities on ATM/IP switches, media gateways, and optical platforms. He holds a BA in Mathematics from Boston College and an M.S.S.E. from the University of Massachusetts.

Email:jolivieri@mitre.org

APPENDIX A

Model Parameters	
MTBF (expon. distrib.)	10,000 hrs
MTTR (lognormal distrib.)	24hrs
Spares, number	As required (infinite)
Spares needed PM,OH?	Required for PM, OH
Minor Overhaul at	15,000hrs
After Minor OH	Do not refresh as new
Major Overhaul at	30,000hrs
After Major OH	Refresh as new
Simulation Time	100,000 hrs
Simulation Runs	100