Comparison of Reliability and Maintainability of Space Stations versus Products Used on Earth

Yizhak Bot - CTO
BQR Reliability Engineering Ltd
e-mail: bot@bqr.com

Abstract

This article demonstrates a comparison of a Reliability Model and Maintenance Concept for an Air-Conditioning System in a Space Station versus an Air-Conditioning System in a Chemical Plant on Earth.

1 General

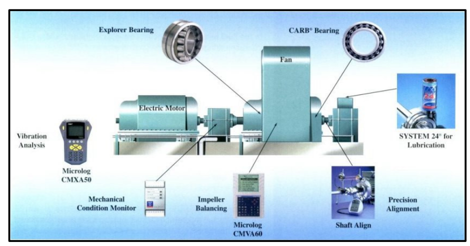
On Earth, system maintenance activities can take place at any time versus product used in Space, where maintenance cannot be provided or is very expensive to provide maintenance to.
Both systems are critical, when in Space Stations the air-conditioning system must operate continuously to enable life while in Chemical Plants the air-conditioning system cools the environment of ovens that operate at 900 deg. Celsius.
If the air-conditioning system stops in the Space Station, human lives will be lost.
In Chemical plants a possible explosion can occur which endangers the nearby environment.
In the Chemical Plant the production process can be stopped allowing air-conditioning systems to be stopped as well – in this case the plant will have financial loss due to the stop of the production process.
These parameters and others, which characterize each and every system, need to be taken into consideration in order to perform an Availability and Maintainability models.
The Reliability and Maintainability Module in this case influences directly the architecture of the system and its environment in a way that enables to influence the implementation, cost, weight and volume.
For example: the cost in a Space Station is not critical but in a Chemical Plant it is.
On the other hand, the weight and volume are critical for a Space Station but are not critical for a Chemical Plant.
This article presents an Optimization Process and Mathematical Models that will take into consideration all aspects and will suggest alternatives and give the designer the ability to choose the best option.
The Article will give detailed components list of the different air-condition systems, the probability of failure of every component including distribution & failure modes.
We will build a failure tree from which we will conclude about the different maintenance tasks, including: Tools, Automatic Test Equipments, Man Power and Transportation.

Finally, we will define different options and tolerances for every parameter. The different options are based on the Multi-Parameter behavior.
The Logic optimization process will be described allowing calculation of a closed solution list from which solutions can be chosen in a graphical way.

As output we will present all options on a Graph allowing the designer to choose the most optimal option.
In this article we will also present examples from the systems to point out the size & complex in search of solutions.

2 Fan assembly in a Chemical Plant

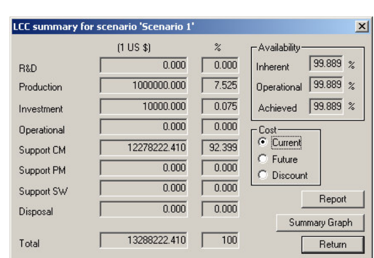
The fan assembly was installed in the production line enabling to cool down the chamber.



Picture 1: Fan Assembly Scheme

2.1 Initial Maintenance Strategy before optimization

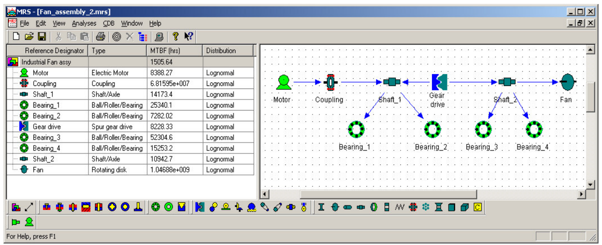
The Maintenance concept will be Corrective, remove and install a new Fan assembly after each failure. No repairs to be done on internal parts. Life Cycle is 10 years.
One Fan assembly cost is 1M$.
During the life cycle, the Fan assembly was replaced~12 times. Initial LCC = 13,288M$ for 10 years.



Picture 2: LCC Summery before optimization

Since the company used to replace the whole Fan assembly, there is no field failure data collection of internal components.

In this case we used the MRS (Mechanical Reliability Simulation) to get the Time To Failure distribution, MTBF and basic failure modes pf the internal comments.



Picture 3: Fan Assembly break down in MRS

A FMECA (Failure Mode & Criticality Analysis)

Failure Modes Criticality Matrix (Quantity for Internal Causes only)							
PROBABILITY		Criticality Range	SEVERITY				
Group	Range		V	IV	III	II	I
a	b	c	d				
A	0.200000 - 1.000000	> 223144	0	0	0	0	0
B	0.100000 - 0.200000	105361 - 223144	0	0	0	0	0
C	0.010000 - 0.100000	10050.3 - 105361	0	0	4	13	0
D	0.001000 - 0.010000	1000.5 - 10050.3	0	0	1	3	0
E	0.000000 - 0.001000	0 - 1000.5	0	0	1	1	0

RefDes	Function	FRb	FRc	Crit
Industrial Fan assy	Ventilation of the plant room		665.1	0.487364
Bearing_1	Shaft constraint	39.46	39.46	0.0217046
Bearing_2	Shaft constraint	137.3	137.3	0.0755282
Bearing_3	Shaft constraint	19.12	19.12	0.0105149
Bearing_4	Shaft constraint	65.56	65.56	0.036058
Coupling	Torque transmission from motor to shaft	0.01467	0.01467	1.4671e-005
Fan	Ventilation of the plant room	0.0009552	0.0009552	9.55224e-007
Gear drive	Torque transmission from Shaft 1 to Shaft 2	121.5	121.5	0.12153
Motor	Power source	120.1	120.1	0.0600749
Shaft_1	Torque transmission from Coupling to Gear	70.55	70.55	0.070554
Shaft_2	Torque transmission from gear to fan	91.39	91.39	0.091385

LibrName	Prob
Modes for Function 'Motor'	
Open winding	
Fan no rotation	1.000000
Overheating	
Shorted winding	
Fan no rotation	1.000000
Overheating	
Wear of bearings	
Excessive vibration and noise of fan	1.000000
Contamination with high hardness part...	
Misalignment	

Picture4: Fan Assembly break down in FMECA

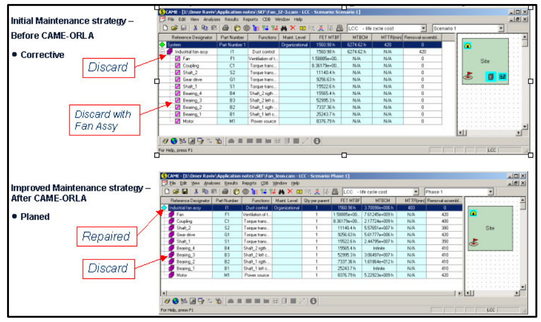
Also a FTA (Fault Tree Analysis) was preformed to calculate system's failure probabilities.

Event name	Description
System Failure	Phase: Phase 1
Industrial Fan assy	Fan no rotation
Motor	Shorted winding
Internal Cause	Overheating
Coupling	Torsion Fatigue crack
Internal Cause	Excessive vibrational load
Shaft_1	Bending Fatigue crack
Internal Cause	Excessive vibrational load
Gear drive	Bending Fatigue crack
Internal Cause	Excessive vibrational load
Internal Cause	Misalignment
Bearing_4	Seizure
Internal Cause	Overheating
Shaft_2	Bending Fatigue crack
Internal Cause	Excessive vibrational load
Motor	Open winding
Internal Cause	Overheating
Gear drive	Contact fatigue crack
Internal Cause	Excessive vibrational load
Internal Cause	Misalignment
Bearing_4	Fatigue crack
Internal Cause	Excessive vibrational load
Internal Cause	Bearing select not properly
Shaft_2	Torsion Fatigue crack
Internal Cause	Excessive vibrational load

Picture 5: Fan Assembly FT break down

2.2 First optimization step

ORLA (Optimal Repair Level Analysis), CAME-ORLA recommends to Remove/Replace Internal components instead of discarding the whole Fan assembly.



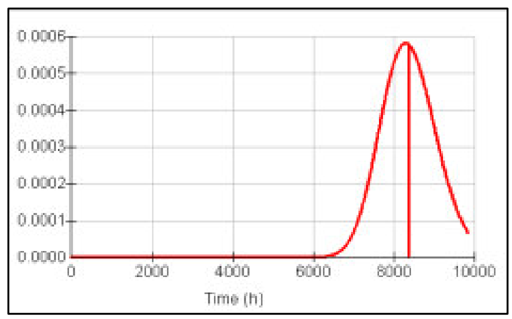
Picture 6: Fan Assembly break down Before & After ORLA

2.3 Second optimization step

The fact that the plant is shut down every 600 hours regularly (PMU) has been taken into consideration. certain components having increasing failure rate versus time.

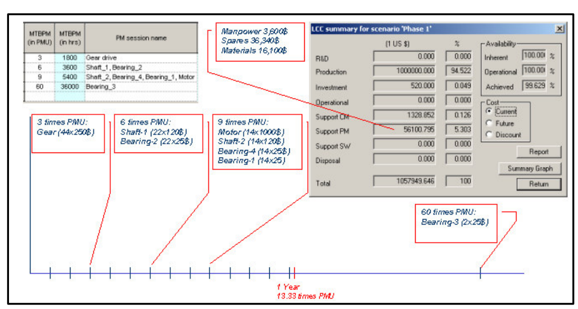
MTBPM (in PMU)	MTBPM (in hrs)	PM session name
3	1800	Gear drive
6	3600	Shaft_1, Bearing_2
9	5400	Shaft_2, Bearing_4, Bearing_1, Motor
60	36000	Bearing_3

Picture 7: First PMO recommendations



Picture 8: "Motor" Failure Distribution

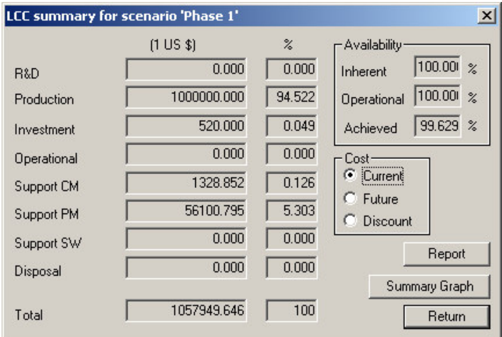
After the two-optimization steps, the components were assigned Preventive Maintenance tasks, (Repair tasks) which increase the MTBF (mean time between failure) of the Fan assembly and in the same time save a great amount of money.



Picture 9: first PM schedule

2.4 LCC first Summery

The total LCC for the 10 years was reduced to: 1.057 M$.
The initial LCC was 13,288M$.



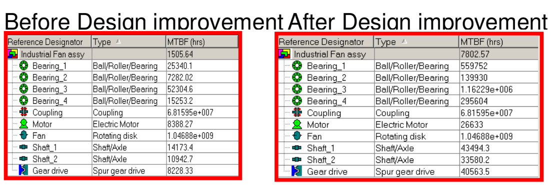
Picture 10: LCC Summery **After** first optimization

2.5 Improving mechanical design

New mechanical design improvements were made to increase the MTBF of the mechanical components & to reduce the cost of the system during the 10 years.

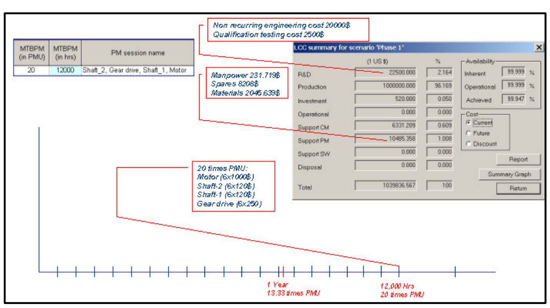
The new mechanical design improvements:

- Gears: Induction hardened: change from 40 to 50HRC
- Shafts: Low stress concentration: Keyway handled with disk milling cutter instead of finger milling cutter
- Motor: Use motor with longer life: 8,388 to 26,633 Hrs
  - Bearing 1&2: Use CARB toroidal roller bearing instead of standard bearing
- Bearing 3&4: Use Explorer quality spherical roller bearing instead of standard bearing



Picture 11: MTBF of Mechanical Parts, for the 2 designs

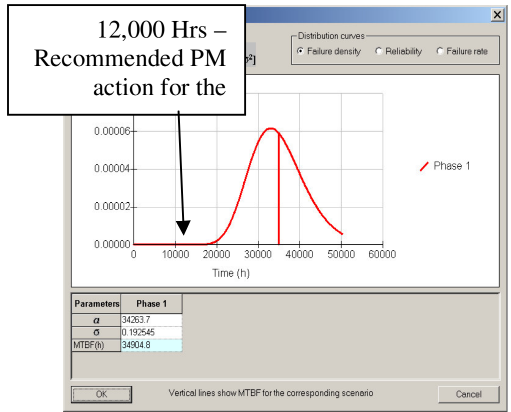
After the new mechanical improvements were implemented & the MTBF were updated we run again the PMO to get wider preventive maintenance intervals. It means; less PM actions = Less cost.



Picture 12: second PM schedule

MTBPM (in PMU)	MTBPM (in hrs)	PM session name
20	12000	Shaft_2, Gear drive, Shaft_1, Motor

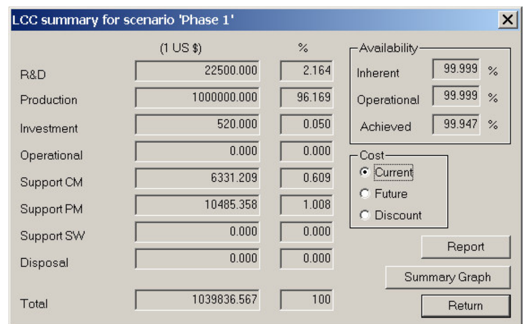
Picture 13: Second PMO recommendations



Picture 14: "Motor" improved Failure Distribution

2.6 LCC second Summery

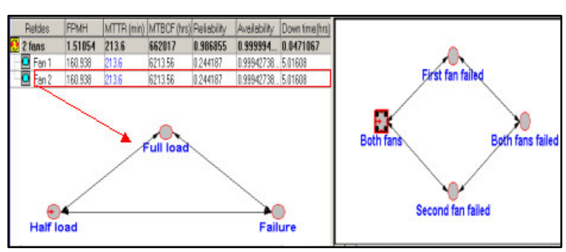
The initial LCC was 13,288M$.
The second LCC was 1.057 M$.
The third LCC for the 10 years was reduced to: 1.039 M$.



Picture 15: Last LCC Summery for

3. Fan assembly in a Space Station

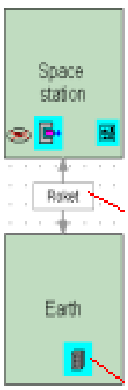
Unlike the Chemical Plant on Earth, preventive maintenance actions are impossible (or expensive) to perform in space.
On ground we can schedule maintenance tasks when system is down. In space the Fan Assembly must operate all time and we can't shut down the Fan for maintenance actions.
So a different maintenance approach is needed.
To solve this problem we will use 2 Fan's working in Parallel, each in half load, if one fails the other is switched to full load.
By implementing this approach we will improve the availability of the Fan Assembly while reducing the maintenance cost.



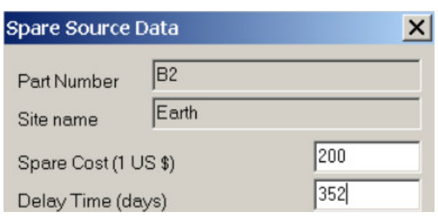
Picture 16: Reliability Block Diagram of 2 motors

Once a year a rocket is sent to replace the crew, in the same time we can send spares.
The purpose is to know how many spares to sent with installation and each time, and when to schedule a planned maintenance to replace components.
S2A (Sparing to Availability) calculates, for each part number, the quantity of spares needed in each stock location to provide the required availability.
During calculating the S2A takes into consideration the restoration time of each sub block.
S2A also takes into account repair time and delay, spare purchase delay, transportation time and stock delay.
In this scenario we should calculate the numbers of spares needed.

Some facts on the maintenance circumstances:
The only way to pass Spares to the space station is by a Rocket, which is flying to the space station once a year.
Each spare costs: 200$.
The Cost to ship a spare is defined by its weight:
1000$ per Kg.



Picture 17: The Maintenance sites



Picture 18: Spare Source data

Transportation Type	Source-Stock	Stock-Assembly	Transport cost per 1 kg
Roket	☑	☑	10000

Picture 19: Transportation data

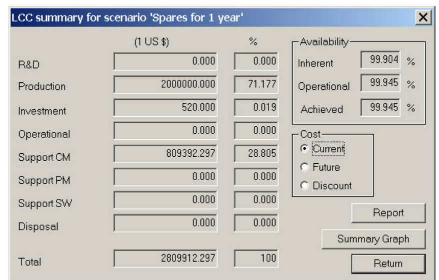
3.1 Initial Maintenance Strategy before optimization

We run S2A to calculate numbers of spares needed before conducting the PMO Optimization phase.

RefDes	Initial spares	Spares over life time
Bearing_1	0	0
Bearing_2	3	2
Bearing_3	0	0
Bearing_4	1	0
Coupling	0	0
Fan	0	0
Gear drive	2	1
Motor	4	10
Shaft_1	0	0
Shaft_2	0	0

Table 1: Initial Spares before PMO

Initial LCC = 2.8M$ for 10 years.



Picture 20: LCC Summery before optimization

3.2 First optimization step

Now we will run the PMO to know when is the best time to replace & to use a spare.
And upon the PMO results the S2A will find the optimum number of spares to send each year to achieve high Availability, Reliability & low costs.

MTBPM (in PMU)	MTBPM (in hrs)	PM session name
10	6000	Gear drive, Motor
30	18000	Bearing_2
70	42000	Bearing_4

Picture 21: PMO recommendations

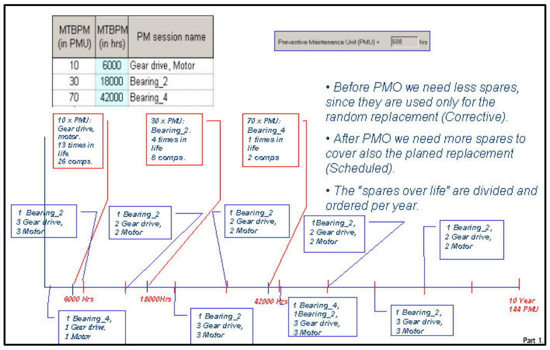
3.3 Second optimization step

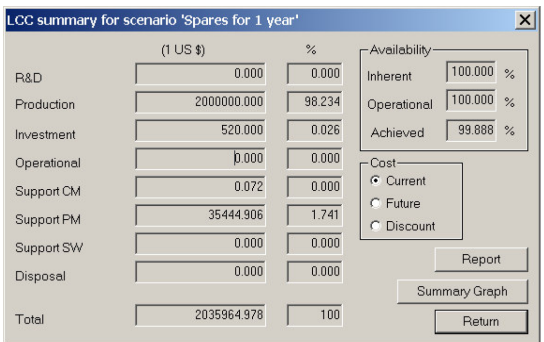
Now after calculating the best PMO intervals,
We will run the S2A for optimum results:

RefDes	Initial spares	Spares over life time
Bearing_1	0	0
Bearing_2	0	8
Bearing_3	0	0
Bearing_4	0	2
Coupling	0	0
Fan	0	0
Gear drive	0	26
Motor	0	26
Shaft_1	0	0
Shaft_2	0	0

3.4 LCC Summery for second Scenario

After the two-optimization steps, the total LCC for the 10 years was reduced to: 1.9 M$.



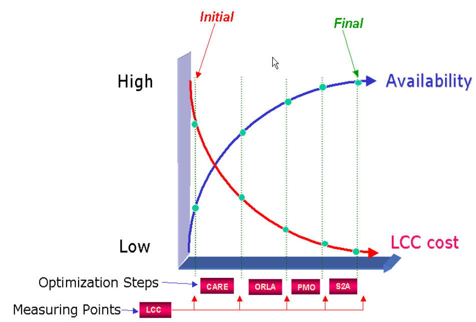


Picture 23: LCC Summery after optimization

After the two-optimization steps, the total LCC for the 10 years was reduced to: 2.03 M$.
The initial LCC was: 2.8M$.
Before PMO we need less spares, since they are used only for the random replacement (Corrective).
After PMO we need more spares to cover also the planed replacement (Scheduled).
The "spares over life" are divided and ordered per year.

4. Summary

In the last decade, BQR has developed a new technology that combines traditional methods as well as innovative ideas and algorithms, to help increase the availability of high-tech systems, while reducing their maintenance cost. Many companies that attempt to reduce maintenance operating cost fail to address all aspects of the issue. For example, companies may optimize the required number of spares needed for a system, without optimizing repair, repair level or disposal of the part. Other companies try to perform conditioning based maintenance, without combining tasks despite the risk of delaying certain tasks or limiting other tasks which could lead to a money loss. BQR's integrated tools provide solutions for reliability and maintenance issues and enable users to make decisions regarding the system as early as the design phase. BQR technology is also suitable once the system is produced and is operating out in the field. BQR's unique technology uses standard GUI (Graphic User Interface) and databases that can be interfaced and integrated with other IT systems BQR technology includes: CARE® - Computer Aided Reliability Engineering, CAME® - Computer Aided Maintenance Engineering and CAfdE® - Computer Aided Field Data Engineering (C^3).



4.1 CARE®

CARE is used for analyzing possible failures in electronic and mechanical parts and calculates all failures, causes and their effect on the system's operating ability. The database includes stress and redundancy, failure time distributions, failure detection and isolation degree with Built-In-Tests, effects of inspections and any critical parts that could affect the safety and critical operation of the system. CARE is used under the designer CAD/CAE and offers solutions in real time and enables any necessary modifications in the system more efficiently before manufacturing.

4.2 CAME®

CAME is used for optimizing the maintenance concept to help reduce the total life cycle cost of the product. This is achieved by applying several optimization steps such as: Optimal Repair level Analysis, Preventive Maintenance Optimization (Conditioned Monitoring), Sparing to Availability, Reliability Centered Maintenance and MSG-3. Calculating LCC following each optimization step, demonstrates how the maintenance cost is reduced while availability is increased. CAME presents a full maintenance plan including applied tasks, required personnel and skills, support equipment, materials and facilities, types of resources used for each maintenance site and a field failure diagnostics database. In addition, CAME features the IETM

(Interactive Electronic Technical Manual), with drawings, schemes, instructions, user written texts, as well as database. CAME is applicable under any ERP/CRM system and offers solutions in real time to enable any necessary modifications in the system more efficiently

4.3 CAfde®

CAfde is used for analyzing field data and for providing reliability and maintainability measures for the system, its assemblies and parts. The results are then applied to CARE and CAME and the data is used on operating systems to predict subsequent failure occurrences, to correct PM schedule times and provide health monitoring for each system. In addition, CAfdE provides recommendations for any necessary modifications in the design concept. For example: Is a total overhaul required for the system, or should it be replaced with new produced or developed parts?