White Paper

Benefit to Cost Analysis of the Machine Condition Analysis (MCA) Program on U.S. Aircraft Carriers

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Introduction

U.S. Navy aircraft carriers are significant mobile assets that have a staff of more than 5000 personnel. Each is a self-sustained floating airport that's a sovereign U.S. territory. When deployed, they operate with their own ZIP code, post office, hospital, dental clinic, barbershops, athletic facilities and chapels. Coined as floating cities, in fact they are as much a floating industrial plant. Within the aircraft carrier's 4.5 acre footprint, are 500+ significant rotating machines that all play a part in the vessel's level of "mission readiness" otherwise known to a stationary plant engineer as its level of "plant availability". Because of the nature of the aircraft carrier's mission, unexpected downtime not only puts its own personnel at risk but impacts the security of our nation and the US interests it defends. Availability is taken extremely serious in the U.S. Navy.

The aircraft carriers have utilized machine condition analysis technologies for improved ship availability, reduced maintenance cost and targeted machine repair planning since the mid 1970s. Azima DLI, (then Diehl & Lundgaard, Inc. and subsequently DLI Engineering Corp.) played a key role in helping the Navy design and implement a very efficient **Machinery Condition Analysis** (MCA) program. On a routine basis, MCA saves the aircraft carriers potentially $10 million dollars per year, with only a small fraction of that amount invested into the program. While the true benefit is increased mission readiness, this paper will focus on all the "benefit to cost" realized by the MCA program.

Aircraft carrier maintenance planners have used information from the MCA program to define availability work packages since 1970. Azima DLI was the government's prime contractor for MCA and SFMVA from 1978 through 2006. Since 2006, Lightship Group has been the prime contractor and Azima DLI has operated as a subcontractor to Lightship Group. The specific condition of about 450 total pieces of rotating machinery on each ship is determined quarterly. The results are tracked more frequently for use in

deciding if the machine should be repaired or overhauled, or if scheduled time-based work can be deferred. This information has made the maintenance and repair planning process more accurate and cost effective, and has reduced the incidence of failures and emergent industrial work for these machines.

Contractor Conducted Surveys

Approximately six months before a shipyard repair period, a three man contractor team goes onboard the ship and works with the **Ship's Force Machine Vibration Analysis** (SFMVA) team to complete an MCA survey. Concurrently with the vibration testing, machine visual inspections are performed and operator input is obtained. A preliminary MCA report is issued onboard to the ship's engineering officers and a final MCA report which has been reviewed by key Navy engineering groups, is distributed to all ship stakeholders by the office of the Commander of Naval Air Forces (CNAF) within 23 days of the return of the contractor survey team. The CNAF maintenance planners and Type Commanders (TYCOMs) use the MCA report to reduce the scope of the machinery portion of the shipyard repair work package. Summary of Benefits item 2 (below) is the potential savings if planners follow all MCA recommendations.

After half of the shipyard repair periods, a follow up survey is conducted by a contractor team. This MCA survey provides quality assurance of the repairs performed, confirms new machinery configurations and documents machinery readiness following the availability.

Ship's Personnel Conducted Surveys

The ship's force is annually trained and provided with vibration data collectors to test their own machinery. The SFMVA collected data is analyzed onboard and the results are used to schedule Condition Based Maintenance (CBM) while underway. These results are sent to the contractor monthly, for review and inclusion in statistical studies.

FY 2008 Program Results

The MCA program conducted 7 shipyard repair availability surveys during the Navy's fiscal year (FY) 2008. The contractor tested 1,971 machines during MCA surveys and the ships' personnel tested 3,783 machines throughout the year, for a total of 5,754 machine tests.

The ships' SFMVA recommendations can be redundant with contractor MCA surveys and were not counted in this study. However, MCA reports made the following number of recommendations for non-nuclear cognizant machinery:

Repair Class \ Priority	Desirable	Important	Mandatory
Overhaul component	6	4	5
Repair specific item	39	47	7
Inspect or monitor component	Not considered in this study		

The total program cost was $925,000 including contractor costs and government administration. Consequently, the cost of conducting MCA and SFMVA was $161 per machine test.

The program savings and cost for non-nuclear cognizant machinery, as defined and calculated in this study, were $11,430,250 and $786,300, for a **Benefit to Cost ratio of 14.5 to 1**. This is a conservative calculation. The Summary of Benefits section below, lists several areas of program savings, most of which are difficult to accurately quantify and were not included in the cost assessment of this study.

This benefit to cost study was done, considering FY 2001 planning practices and machinery repair costs. Earlier benefit cost studies were completed, using criteria relevant to the planning processes and costs in those years. Some of those earlier benefit to cost ratios were:

	1977	1988	2000	2001	2002	2003	2004	2005
B / C	18.8 / 1	19.0 / 1	19.5 / 1	20.0 / 1	20.9 / 1	23.0 / 1	12.3 / 1	16.6 / 1

	2006	2007	2008					
B / C	28.2 / 1	12.4 / 1	14.5 / 1					

The FY 2004, 2007 and 2008 ratios are low, because only two surveys in those years addressed notional shipyard work package reductions. The FY 2006 ratio was high, only covering 6 months.

Summary of Benefits

Listed below are descriptions of eight benefits provided by the MCA program, where each item generates repair cost savings and other benefits. Items 1 and 2, but not 3, are used in this study. The remaining five benefits are positive, but difficult to objectively quantify.

1. **Prevention of progressive machine damage through early detection of problems.** Correcting problems found during the MCA surveys prevents subsequent machine deterioration and failure. Casualties and damage, which may affect operations or safety, are prevented, as well as an emergent overhaul or major repair. **Savings $657,250**

2. **Improved selection of machines for overhaul during Planned Incremental Availability (PIA) industrial periods.** There is never enough money to overhaul all machinery. The MCA report provides specific repair recommendations to be accomplished during the PIA. This information is objective and improves the accuracy of overhaul selection. It provides a financial benefit for CVN68 Class ships, by eliminating a number of Incremental Maintenance Plan (IMP) overhauls listed in the notional work package. It also eliminates unjustified work listed in the Current Ship's Maintenance Project (CSMP). **Savings $10,773,000**

3. **Improved selection of machines for overhaul during Comprehensive Overhaul (COH) or Restricted Comprehensive Overhaul (RCOH) industrial periods.** Although in-plant machines are always overhauled, some in-plant and auxiliary machines listed in the notional work package can be eliminated. **Savings N/A**

4. **Identification of specific repairs needed, in lieu of a complete overhaul.** Considerable cost savings are realized by reducing the number of complete unit overhauls and only accomplishing the recommended specific repairs. The MCA program supports this approach by addressing components and only recommending unit overhauls when they are clearly necessary. Limiting the scope of repair often allows ship's force the option of doing the work.

5. **Reduction in post-availability repairs by using machine vibration data for quality assurance during and after industrial periods.** Post-repair vibration surveys are performed by the shipyard, ship's force, and/or the contractor. All tests use vibration acceptance criteria established by the MCA program. Problems inadvertently caused during the overhaul can be discovered and corrected under warranty. Full surveys will find problems with other machines, not screened for repair, which developed immediately before or during the availability.

6. **Prioritization of machinery operation and reduction in ship's force workload.** The contractor MCA team presents a report to the ship, listing machinery condition and all recommended repairs (Class B, C and D). The report allows the ship to prioritize machinery operating hours and to follow CBM practices, only doing repairs that are within their capability. CBM extends machinery life and ultimately reduces the ship's workload. This benefit is always onboard through SFMVA.

7. **Reduction of long-term maintenance costs by identifying recurring problems that may be permanently solved.** The MCA History Report for each aircraft carrier reveals recurring and common faults over the previous 5 to 6 years. Machine class problems or systemic problems are identified and quantified. Starting with this data, the operational, maintenance and cost benefits over the remaining life of the ship can be predicted. Planners can decide whether to repair the fault or to replace entire suites of machines.

8. **Support of repair parts procurement and manpower scheduling prior to the industrial period.** When an aircraft carrier enters a shipyard repair availability, regardless of the length of time it will be there, prior knowledge of which machines will be worked on, and what work will be done, greatly improves efficiency. Having the correct parts and workers on hand greatly improves the ability to finish on time and within budget.

Analyzed Data

Machine Tests Conducted

During FY 2008, a total of 5,754 machine tests were conducted by ship's force and the contractor. The total program cost divided by this number of tests equals a cost of $161 per machine test.

Vibration Surveys Conducted

Vibration results from 7 MCA surveys were analyzed.

Ship	Survey Date	Survey F/Y	PRE/POST Shipyard Availability Survey ID
CVN76	25 Jan	2008	POST-FY07 PIA1
CVN71	26 Feb	2008	POST-FY07 PIA3
CVN74	29 Apr	2008	POST-FY07 PIA2
CVN69	22 Jul	2008	POST-FY08 PIA2
CVN73	26 Sep	2008	PRE-FY09 SRA
CVN68	13 Nov	2007	PRE-FY08 PIA3
CVN75	20 Mar	2008	PRE-FY08 PIA2

The first five MCA surveys listed above were conducted for the early detection of faults, supporting daily operations, work package development or quality assurance testing. The remaining two MCA surveys were conducted to reduce the notional work packages for PIA2 or PIA3 availabilities.

Machine Groups Analyzed

There were 70 machine groups included in the benefit/cost portion of this analysis. Generally, these groups of machines include turbines, motors, fans, pumps, compressors, reduction gears, generators and centrifuges. They are not individually identified in this public white paper by request of the Navy.

Nuclear cognizant machine groups, which make up 17% of the program, are not included in the benefit/cost ratio calculations.

Benefit to Cost Ratio Analysis

Benefit Item 1 - Prevention of Progressive Machine Damage through Early Detection of Problems – Analysis Method:

Assumptions:

The following are the assumptions used in the analysis of this benefit item.

1. The early detection of machine faults is a benefit that applies to all aircraft carriers and is derived from those surveys not related to reducing shipyard work packages.
2. The machine faults resulting in repair recommendations, if not corrected, will result in a possible risk of failure of the unit. These risks are estimated as:
    a. 20% for a Desirable recommendation,
    b. 60% for an Important recommendation, and

c. 100% for a Mandatory recommendation

3. Failure of the unit is defined as the development of a machine fault serious enough to require an overhaul of one or more of the major components (pump, motor, turbine, etc.).

4. In the absence of the MCA program, the specific recommended repairs would not likely be performed because they would not be readily identified. Only complete overhauls would be accomplished, and that would be done either after failure or on a specific schedule (e.g., every other industrial period).

5. In the absence of the MCA program, a certain number of the units that would have received repair recommendations would fail in accordance with the associated estimated risk factors, resulting in corresponding, but avoidable, complete overhaul costs.

6. In the presence of MCA, 100% of the Important and Mandatory specific repair recommendations, and 25% of the Desirable recommendations, result in actual performance of the recommended repair.

7. The costs of complete overhauls are based on CVN68 Aircraft Carrier Incremental Maintenance Plan (IMP) cost estimates. The costs of specific repairs are estimated to be 10% of complete overhauls.

Calculations:

The total cost of all specific repairs recommended by the MCA program was calculated using estimated costs as noted in Assumption 7 and according to Assumptions 5 and 6. The savings generated by early detection and repair of faults, avoiding emergent overhauls, are calculated as follows:

$$S = \sum^{D} (0.25)(PC\text{-}0.1C) + \sum^{I} (PC\text{-}0.1C) + \sum^{M} (PC\text{-}0.1C)$$

Where:

S	=	**Savings generated by early detection of faults**
P	=	Probability of a unit component needing a complete overhaul of 0.2 for a Desirable recommendation of 0.6 for an Important recommendation of 1.0 for a Mandatory recommendation
C	=	Cost of a complete overhaul of a unit component
0.1C	=	Cost of a specific repair of a unit component
D	=	Desirable recommendations
I	=	Important recommendations
M	=	Mandatory recommendations

$\sum^{D} (0.25)(0.2\text{-}0.1)C$	=	0.25 x $177,800	=	$44,450
$\sum^{I} (0.6\text{-}0.1)C$	=			$514,700
$\sum^{M} (1.0\text{-}0.1)C$	=			$98,100
S	=			$657,250

Benefit Item 2 – Improved Selection of Machines for Overhaul during PIA Industrial Periods – Analysis Method:

Assumptions:

The following are the assumptions used in the analysis of this benefit item.

1. This benefit applies to only CVN68 Class aircraft carriers, because these ships have an Incremental Maintenance Plan (IMP) which projects the number of complete overhauls anticipated to be accomplished during each PIA for most machine groups.

2. Between 0% and 30% of the machines in each of the machine groups are scheduled for overhaul during an upcoming availability.

3. The MCA program improves the accuracy of the selection process, so that we anticipate no class B overhauls will be done in the absence of a firm need for an overhaul.

4. The overhaul costs for the CVN68 Class machines were extracted from the Class IMP where available.

5. To be conservative in the estimate of savings, we assume that every recommendation would be done as a complete overhaul. This increases the anticipated cost of the program, but the approach eliminates the possibility of under-stating costs and inflating benefits. For example, if the recommendation is to replace motor bearings, at a cost of $5,000, we use the $15,000 cost of a complete overhaul of the motor.

Calculations

The savings due to improved selection represents the amount of money saved by not doing unnecessary overhauls. It represents savings realized by eliminating machines that will perform reliably until the next availability. The savings are calculated as follows:

S = A – R

Where:

S = Estimated savings due to improvement in overhaul selection

A = Anticipated planned cost of overhauls based on PIA (IMP) numbers

R = Recommended cost of overhauls from specific and overhaul recommendations

A	=	$12,009,000
R	=	($1,236,000)
S	**=**	**$10,773,000**

Total Benefit Savings and Program Costs – Analysis Method:

Assumptions

The following are the assumptions used in combining these items.

- The Benefit Item 1 savings are calculated as the cost of complete overhauls less the cost of the specific repair recommendations from one pre and four post availability MCA surveys.
- The Benefit Item 2 savings are calculated as the cost of the planned complete overhauls, less the cost of complete overhauls for all specific and overhaul repair recommendations from two pre-availability surveys.
- The Benefit Item 1 and 2 savings can be summed.
- The MCA program costs are the FY 2008 funded task amounts used by the contractor and an estimated $50,000 for CNAF contract administration.
- The total program cost is conservatively reduced by 15% (65 of 375 machines each survey is 17%) to remove nuclear cognizant machine test costs, the benefit savings of which are not considered in this study.

Calculations

The benefit/cost ratio for the non-nuclear cognizant portion of the program is then calculated as follows:

$$B/C = \frac{\text{(Benefit Item 1) + (Benefit Item 2)}}{\text{(0.85) (Contractor Cost + Admin Cost)}}$$

Then:

Benefit 1 Savings	=	$657,250
Benefit 2 Savings	=	$10,773,000
Total Program Benefit	**=**	**$11,430,250**
Cost of Contractor	=	$875,000
Cost of Admin	=	$50,000
Total Program Cost = (0.85) ($925,000)	=	**$786,300**

2008 Program Benefit to Cost = $11,430,250 / $786,300 = **14.5 / 1**

Closing

The aircraft carrier MCA program is one of the world's largest and longest running machine condition monitoring programs. Since its inception in the 1970's, its benefit to cost has been proven through studies such as this paper describes and has encouraged the Navy in its move from time-based maintenance to condition-based maintenance. The experience gained by implementing this scale of condition monitoring over such a long period of time has resulted in the development and implementation of highly efficient methodology and software automation that is used in commercial industry today by Azima DLI and its entire commercial customer base.

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About the Author

Loren Cleven holds a B.S. Engineering Science and Applied Physics degree, is a licensed Professional Engineer; Mechanical Engineering and holds Category III certification, Vibration Institute (1996). Loren has been with Azima DLI for 37 years and has been MCA Program Manager in the Government Services Division since 1997. His current technical duties include managing the machinery condition analysis program for US Navy aircraft carriers, performing machinery and mechanical system condition assessments based on vibration analysis, instructing students in vibration analysis and reviewing reports prepared by other Azima DLI engineers.

About Azima DLI

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