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COBEM-2017-1404 EFFECTS OF DESIGN FOR MAINTAINABILITY IN COMPLEX AIRCRAFT SYSTEMS

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Abstract. Maintenance is one of the largest contributors to the expenses of the total ownership cost of complex aerospace systems. As technology is aggregated to modern systems, maintenance may become more costly and therefore more relevant when designing new aircraft. The present work investigates the cost-effectiveness of complex aerospace systems through case studies. Availability and life cycle cost are determined using commercial off the shelf optimization software package for baseline analysis as well as modifications in system maintenance design. By exploring design for RAM (Reliability, Availability and Maintainability), this research aims to reduce maintenance costs throughout the product life cycle and improve system availability while maintaining the system's capability to fulfill its operational requirements. The optimization software is also used to quantify gains in cost reduction, aspect yet to be explored in depth in recent literature.

Keywords: Design for RAM. Maintainability, Systems engineering, Life Cycle Costs.

1. INTRODUCTION

With the development of systems engineering, aircraft design have been steadily improving. However, the focus on product support still leaves some room for improvement. Since much of the cost of an aircraft is supposed to be spent in the operational phase, design for support is one of the main aspects at the time of aircraft development and acquisition.

In order to better develop new aircraft, some authors started to strike the problem where it is easier to change and would present better results: the conceptual design. Hence, the terminology "design for λ ", where λ is a characteristic of the project (e.g. reliability, maintainability, etc.), has been widespread (Pahl and Beitz, 2007). As can be seen in Blanchard (2014), the conceptual design phase is where there is the most possibility to alter the project with little investment and it is in this phase where most of the future budget will be committed.

Sassanelli et al. (2016) studied various alternatives of designs for λ in order to integrate them and improve product service supportability. For this, they analyzed the following characteristics: usability, manufacture and assembly, quality, validation, reliability, modularity and customizability, maintainability and testability. This led to a qualitative guideline for product service supportability throughout the product life cycle.

This work focuses on design for RAM (Reliability, Availability and Maintainability) addressing maintenance in a systemic way that affects not only the operator but also other stakeholders and shareholders (manufacturer, suppliers, MRO, etc.) as this directly influences cost of support and acquisition. For the operator, a product that is easier to maintain becomes more attractive. Maintenance also affects the availability of the product while the time spent during maintenance implies that the product will not be able to operate. Some other aspects considered in this regard are accessibility, ability to detect and isolate faults, weight limitations for components, dimensional limitations of components to allow them to be transported, and design requirements for components to be compatible with robots (Kuo et al, 2001).

One example of the improvements that come with design for maintainability is the Boeing 787 Dreamliner. In this case, there was a 56% reduction in scheduled labor hours for the tail section when compared to its predecessor, the Boeing 767. The 787 project also maintained the composite floor structure used in the Boeing 777, since it is known to be reliable, having zero non-routine labor hours. By simplifying the trailing edge of the wing, the lubrication points were reduced by more than half when compared to the Boeing 767 (Hale, 2008).

2. METHODOLOGY

In order to study the maintainability of a system, we will compare different simulated scenarios varying some maintainability requirements and measuring the total cost of the system for each alteration. Using real or simulated data from a legacy Brazilian Air Force system as baseline, modifications to the system will be studied through the use of a cost analysis software to verify the effects of maintainability parameters in overall costs.

These parameters will be determined by prediction models for maintenance such as RCA Method and SAE Maintainability Standard. With the results in hand, we hope to be able to determine how much is saved and how much is spent with investments as well as where to spend money to obtain the optimal return from the investments.

3. LITERATURE REVIEW

Maintenance is an ever-growing portion of product costs when considering complex aerospace systems. During the evolution of aircraft, the correct way to execute maintenance has changed as can be proved by the different maintenance philosophies present in literature. This is due to the quantity and complexity of components that make up an aircraft. As new technology is incorporated into these systems, their maintenance must also be revised.

In some cases, however, aircraft designers are not aware of the problems resulting from a design that sacrifices maintainability for performance. This could lead to a product that is extremely difficult to maintain and therefore is not economically viable to operate. With this in mind, many authors determined guidelines to be followed in order to guarantee the maintainability of the product.

3.1 Qualitative guidelines

One of the authors, Knezevic, 1997, provided an overview of design principles that make a product easily maintainable. These principles are:

- Accessibility: Any component subject to routine maintenance should be easily accessible;
- Modularity: Modules, or subassemblies, reduce the time needed to replace components and therefore maintenance time;
- Simplicity: A simpler design is obviously easier to maintain and can be achieved by taking measures such as reducing the number of parts or part varieties;
- Standardization: Using standard components assure a certain level of quality in the component, makes it easier to replace the component and also ensures a good cost effectiveness because of their ready availability;
- Fool proofing: Items that appear to be similar but cannot be used in the same function should be designed to prevent wrong assembly;
- Inspectability: Design the product so that it can be easily inspected and tested through nondestructive means.

3.2 Maintainability Prediction Methods

- Root Cause Analysis Method (Mital et al, 2008)

The RCA Method is a prediction model based on support time to measure the maintainability of the system. Support time is regarded as a function of physical design features, support requirements and personnel requirements essential to efficient maintenance. The maintainability is gauged through various sets of questions, which attribute scores to the level of maintainability attained. A linear equation was developed for support time by regression analysis of empirical data, and is given by:

$$Z = 3.54651 - 0.02512A - 0.03055B - 0.01093C \quad (1)$$

where A, B and C represent measures of the three parameters.

Table 1 shows a partial representation of the design aspects approached in this method, where each characteristic is scored between 0 and 4 depending on the supportability. The problem with this method is the fact that many objects of evaluation use terms such as adequate access, which are too subjective.

Table 1. Partial Representation of Checklist A for the RCA Method: Physical Design Features
(Modified from Mital et al, 2008)

Physical Design Features	Score
Access	
Access adequate for both visual and manipulative tasks (electrical and mechanical)	4
Access adequate for visual but not for manipulative tasks	2
Access inadequate for visual and manipulative tasks	0
Latches, fasteners, and connectors	
External latches, fasteners, and connectors are captive, need no special tools, and require only a partial turn for release	4
External latches, fasteners, and connectors meet one of these three criteria	2
External latches, fasteners, and connectors meet none of these three criteria	0

- The Federal Electric Method (Mital et al, 2008)

This method analyzes complex maintenance tasks and applies time analysis to measure the maintainability of the system. In order to apply this method, four steps must be completed to analyze an equipment:

- Identification of principal parts;
- Determination of the failure rate of each part;
- Determination of the time required for the maintenance of each part;
- Computation of the expected maintenance time for the equipment by utilizing the information obtained in the first three steps.

While the first two steps involve routine maintenance, the time aspect of the maintenance routine is the main part of this method. For that reason, the following seven actions are necessary to ascertain the maintenance time:

1. Localization: First the malfunction must be pinpointed without the use of auxiliary equipment;
2. Isolation: Next, the malfunction is located with the use of auxiliary test equipment, built-in tests or by other means;
3. Disassembly: Full or partial disassembly is essential to the removal or replacement of defective parts. A couple of very important aspects of this stage are the accessibility and ease of component removal;
4. Interchange: This process involves the substitution of a defective part for one that is in good working order;
5. Reassembly: Reassembly of the equipment involves restoring it to its original condition and is crucial that it be done properly;
6. Alignment: After the repair is completed, a check of the system must be done, involving adjustments, calibration, among other checks necessary due to repair actions;
7. Checkout: Here, a verification of the system performance is completed in order to confirm that the system is up to par with the requirements it must attend.

Standard time tables for each of these seven actions have been developed based on various repair tasks. However, before times are predicted, a functional analysis of the system is carried out. A hierarchical breakdown of the system functional levels (part, subassembly, assembly, unit group, system) is used to analyze the system functions. This breakdown structure enables sharper estimates of repair times since the level of repair directly affects the time of execution for disassembly, reassembly, alignment and checkout.

3.3 Quantitative Maintainability Indices

In this section, we will describe the main indices used to measure maintainability. These indices must be based on measurable characteristics, provide effectiveness-oriented data and must be readily obtainable from operational and applicable development testing (Conlon et al, 1982).

- Mean Time To Repair (MTTR): this indicator is determined by the total corrective maintenance down time in a specific time period divided by the number of maintenance tasks completed in the same period. Because the frequency of corrective maintenance tasks and the number of labor hours are not considered, this indicator does not provide a good measure of the maintenance burden;
- Maximum Time To Repair (MaxTTR): As its name says, this indicator is the maximum corrective maintenance down time within which 90 to 95% of all corrective maintenance tasks can be accomplished. This indicator is important when there is a limited down time requirement;
- Maintenance Ratio (MR): MR is the cumulative number of man-hours of maintenance expended in direct labor during a given time period, divided by the cumulative number of end-item operating hours during the same time. Both corrective and preventive maintenance are included as well as man-hours for off-system

repair of replaced components and man-hours for daily operational checks. This indicator is a good measure of maintenance burden associated with a system, however, it does not relate directly to maintenance cost;

- Mean Time Between Maintenance (MTBM): it is the mean of the distribution of the time intervals between maintenance actions, preventive or corrective. MTBM is a useful tool when calculating availability and statistically-oriented maintenance analyses;
- Average Number of Technicians Required: this indicator provides a quantitative means of expressing the personnel aspect of the overall maintenance concept and a good measure for converting down time into labor hours;
- Off-System Maintainability Indices: this indicator is especially useful for modular systems since in these cases the maintenance burden is transferred to off-system maintenance. These indices are system specific and therefore must be analyzed for each system in order to assess system maintainability;
- Annual Support Cost (ASC): ASC is comprised of the annual cost of maintenance personnel, repair, parts and transportation for all corrective and preventive maintenance actions. It provides another means of quantifying the maintenance burden of a system;
- Turn Around Time (TAT): is defined by the elapsed time between the induction of a component, engine or aircraft into the repair shop and the time at which the product repair is completed and the unit is certified for service;
- Availability: This indicator shows the percentage of time that the system is available versus the total time of operation and maintenance downtime.

Despite the large number of quantitative maintainability indicators, this work will focus on MTBM, TAT, Availability and ASC or in this case LSC (Life Support Cost).

4. MODEL

The model studied in this paper consists of 24 aircraft, where 12 operate from the main operating base, and 4 other aircraft operate from each of three offset operating bases. There is one regional storage unit that supplies the offset bases and one central storage unit that supplies the main base and the regional storage unit. A repair workshop attends the need for repairs coming from central storage unit. The main base can also store spare parts while the offset bases can only perform replacement of LRU's after the new part has been delivered from the regional store. Figure 1 shows a schematic representation of the model obtained from the Opus10® software.

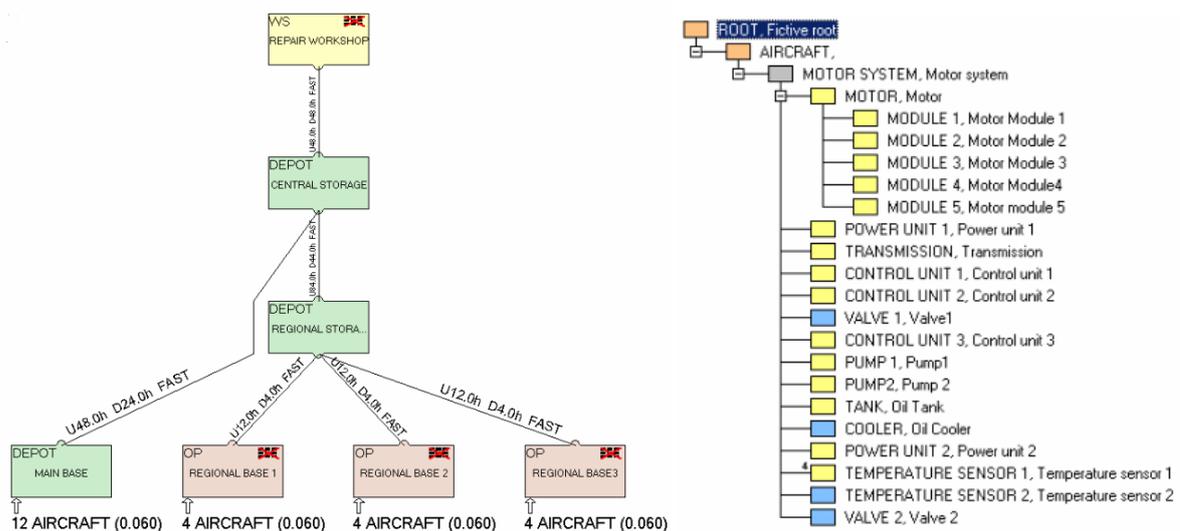


Figure 1. Station and item structure.

Each aircraft is required to fly 525 hours per year and a 10-year scenario is run to simulate a long operating scenario. The transportation time from and to each station is detailed in figure 1. To simplify the case study, only the engine system is considered and it was simplified to 20 items. The items are divided into modules, line replaceable units (LRU), shop replaceable units (SRU) and discardable units (DU). Table 2 shows in detail each part with its cost, failure rate and item type.

Table 2. LSC gain for different man-hour variations

Item identifier	Description	Unit price [USD]	Failure rate [per million FH]	Type
MOTOR SYSTEM	Motor system			ASSY
MOTOR	Motor	550000	951	LRU
POWER UNIT 1	Power unit 1	198550	407,92	LRU
TRANSMISSION	Transmission	157150	221,1	LRU
CONTROL UNIT 1	Control unit 1	446450	32	LRU
CONTROL UNIT 2	Control unit 2	118200	126	LRU
VALVE 1	Valve1	1430	347,84	DU
CONTROL UNIT 3	Control unit 3	85700	56	LRU
PUMP 1	Pump1	10210	108	LRU
PUMP2	Pump 2	9750	65,7	LRU
TANK	Oil Tank	6500	35,71	LRU
COOLER	Oil Cooler	1160	400	DU
POWER UNIT 2	Power unit 2	58550	1864	LRU
TEMPERATURE SENSOR 1	Temperature sensor 1	2785	73,7	LRU
TEMPERATURE SENSOR 2	Temperature sensor 2	1250	68	DU
VALVE 2	Valve 2	1430	102,4	DU
MODULE 1	Motor Module 1	7750	175,92	SRU
MODULE 2	Motor Module 2	259450	72,44	SRU
MODULE 3	Motor Module 3	77100	89,12	SRU
MODULE 4	Motor Module4	77100	227,44	SRU
MODULE 5	Motor module 5	128600	386,08	SRU

In this case, there are two types of preventive maintenance, one which is performed every 200 flight hours on the entire engine system and another, which is performed every 600 flight hours on the engine and its modules. The overhaul is performed at the operational bases from which the aircraft are operating. The expected turn-around time to complete the overhaul is assumed 2 days for the engine system and requires 8 man-hours. The engine overhaul is also done at the operating bases and has an expected TAT of 3.5 hours. The engine is removed and sent to the central store where it is disassembled into modules, which takes 4 days. Finally, the modules are sent to the workshop to be overhauled, which takes 5 weeks. The replacement of engine and modules require 3.5 and 4 manhours respectively while the module overhaul requires 16 manhours. Lastly, a service life limit of 800 flight hours was imposed on the drain valve, at which point the part is discarded and replaced with a new one.

5. RESULTS AND DISCUSSION

After analyzing the model, a baseline for the system was established and used as comparison for all other scenarios. In the first scenario, the TAT is varied from 2% to 10% in intervals of 2%, decreasing the TAT gradually in order to analyze its effect on the LSC for an availability of 95%. This process was repeated for the second and third scenarios, considering manhours used and MTBM. Figures 2, 3 and 4 are outputs from the Opus10® software for each of the scenarios analyzed.

5.1 Scenario 1

After varying the TAT for the system, the following graph was obtained where a clear improvement can be seen as the TAT is reduced. For the established availability of 95%, we are able to quantify the gain compared to the baseline case. Table 2 shows the percentage gain for each decrease in the TAT. This scenario simulates a more maintainable system, where maintenance activities are completed faster.

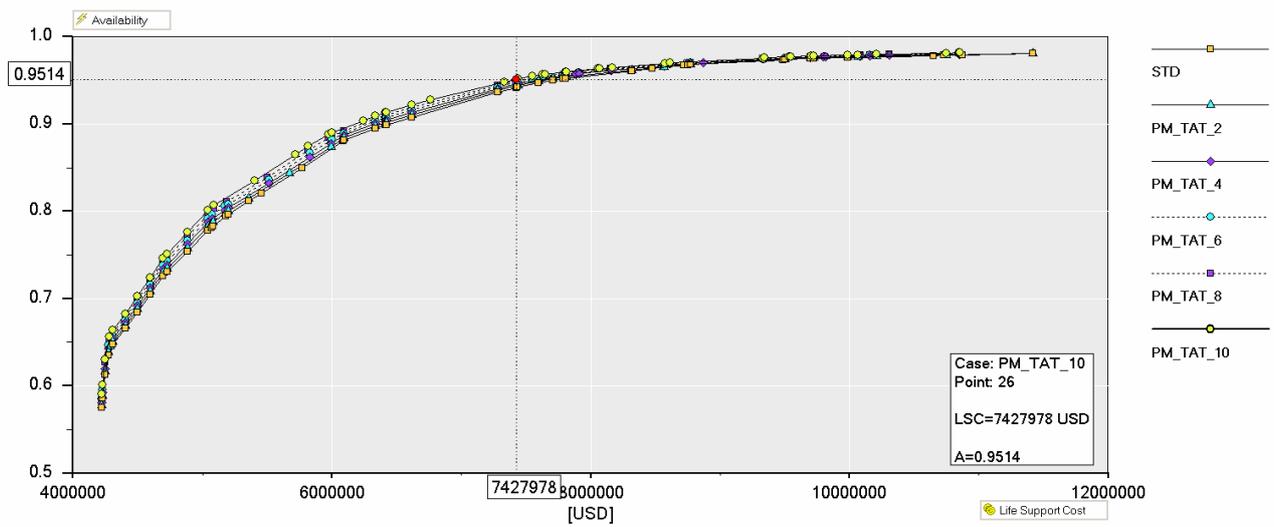


Figure 2. LSC x Availability for variation of TAT.

As can be seen in table 3, the variation in LSC is not constant despite the variation of the TAT having a constant rate. This is likely due to fact that changes in the TAT imply variation of supply stocks and therefore different stock combinations are considered for each state. However, this scenario does present an improvement in the LSC as the TAT decreases.

Table 3. LSC gain for different TAT variations

PERCENTAGE	AVAILABILITY	LSC (USD)	LSC GAIN
Baseline	95,01	7706133	
2%	95,16	7706133	0,00%
4%	95,04	7598293	1,40%
6%	95,08	7546813	2,07%
8%	95	7438973	3,47%
10%	95,14	7427978	3,61%

5.2 Scenario 2

In this scenario, the manhours used was varied for the system, and thus the graph in figure 3 was obtained, where a clear improvement can be seen as the manhours used are reduced. This scenario simulates an improvement in maintenance design, making it easier and faster to perform maintenance tasks. For the established availability of 95%, we are able to quantify the gain compared to the baseline case. Table 3 shows the percentage gain for each decrease in the manhours used.

As can be seen in table 4, the variation in LSC is almost constant following the variation of the manhours used. This is likely due to fact that changes in the manhours used do not imply variation of supply stocks but in the overall costs with personnel. Since this scenario does not affect the stocks, the availability maintains the same for each state.

Table 4. LSC gain for different man-hour variations

PERCENTAGE	AVAILABILITY	LSC (USD)	LSC GAIN
Baseline	95,01	7706133	
2%	95,01	7659303	0,61%
4%	95,01	7612473	1,22%
6%	95,01	7565643	1,82%
8%	95,01	7518813	2,43%
10%	95,01	7471983	3,04%

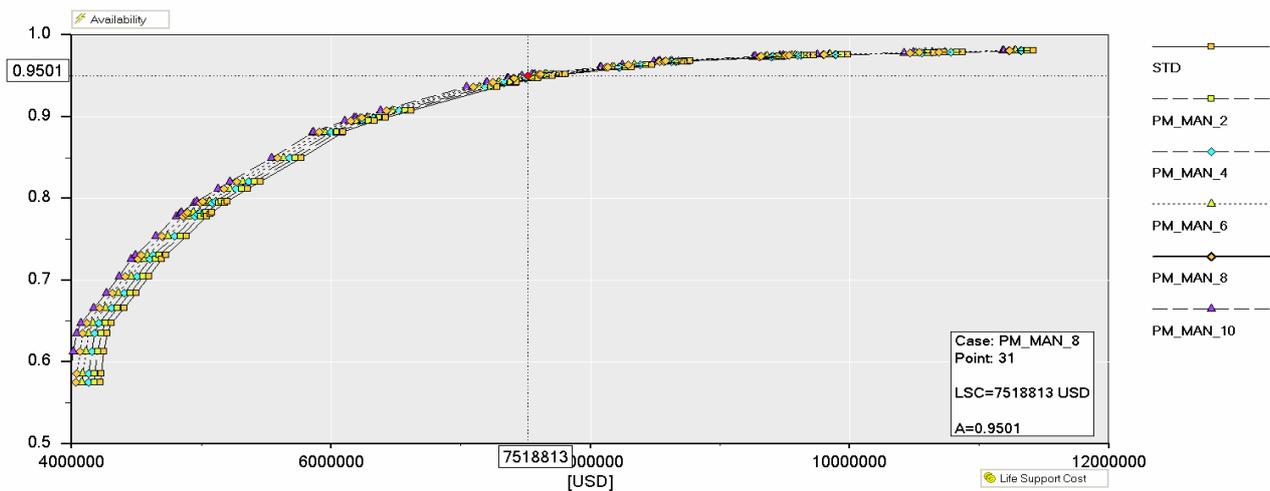


Figure 3. LSC x Availability for variation of manhours used.

5.3 Scenario 3

For the third scenario, the MTBM was altered and the LSC was analyzed for an availability of 95%. This scenario showed to have the most influence on the LSC as can be seen in figure 4. This scenario aims to simulate an improvement in product design, where less reliable and specialized parts are switched for more reliable and standardized parts.

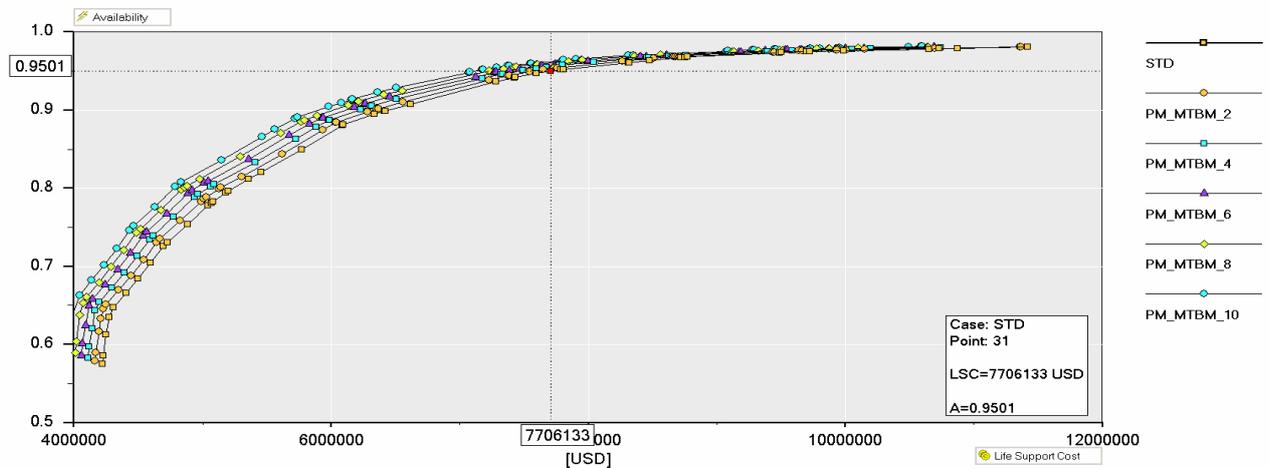


Figure 4. LSC x Availability for variation of MTBM.

Table 5 shows that the variation in LSC is not constant like in the previous scenario. This is likely due to fact that changes in the MTBM imply variation of supply stocks and therefore different stock combinations are considered for each state. As the MTBM decreases, the need for stocks also decreases and therefore the costs with spare parts is also lower.

Table 5. LSC gain for different MTBM

PERCENTAGE	AVAILABILITY	LSC (USD)	LSC GAIN
Baseline	95,01	7706133	
2%	95,18	7650669	0,72%
4%	95,08	7489497	2,81%
6%	95,13	7386698	4,15%
8%	95,02	7218445	6,33%
10%	95,22	7176683	6,87%

5.4 Analysis

As can be seen in figure 5, the approximation of the obtained data gives us a quantifiable relationship between LSC, TAT, manhours used and MTBM. Being that the most influential factor for this model is MTBM. For this indicator there is a gain of approximately 0.7909% in LSC for every 1% of reduced MTBM. The same pattern follows for TAT and manhours used. These indicators present a gain of approximately 0.4643% and 0.3038% in LSC for every 1% of improvement in the respective indicator.

Although this is a reduced model, it is still expressive of what is to be expected from such improvements in product design for maintainability.

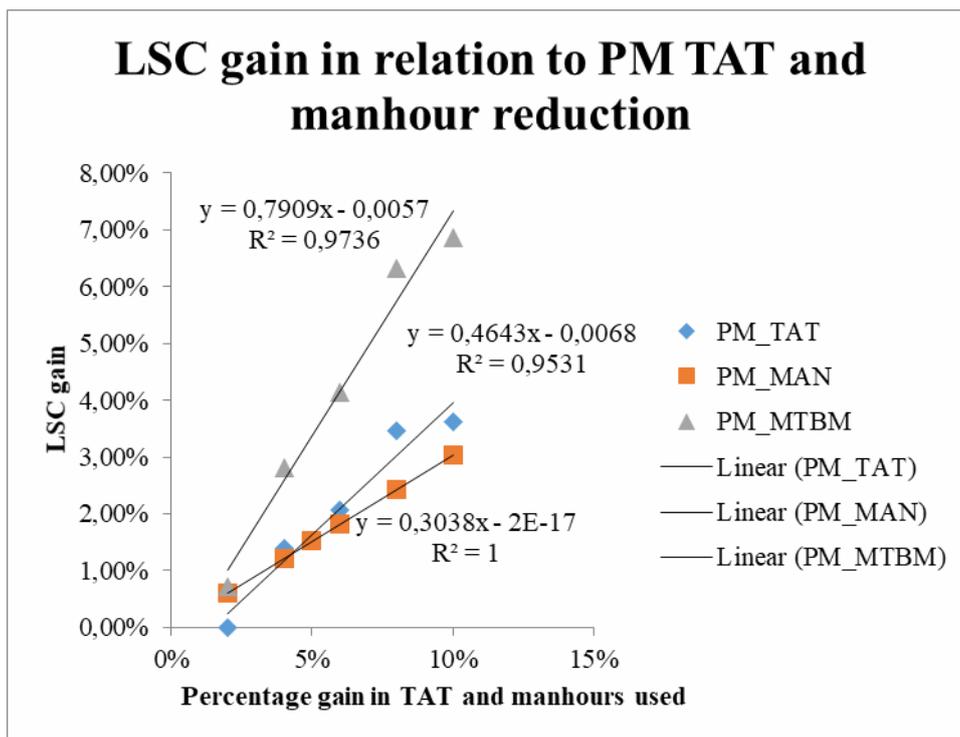


Figure 5. LSC gain

There is, however, a limit to the benefit brought by improving TAT. As is displayed in figure 6, after a certain point (around 12% for this case), the gain in LSC stabilizes around 5%. This likely happens because after a certain threshold, the TAT becomes inexpressive compared to the failure rate of the components. Since the reliability factors in this study are maintained constant, the stock levels do not vary much in function of the TAT.

6. CONCLUSION

This work addressed the design for RAM in a quantitative manner and as the results demonstrated, the impact of these design changes could mean a significant gain in the total support cost of a system. There is also a limit to the gain brought about by the improvement of some of the parameters associated with RAM.

In future studies, a larger model should be incorporated as well as different operating systems. This will give a better understanding of the impact of design for RAM criteria. It is important to see if there are any tendencies in the evolution of LSC gain with respect to other parameters for different systems.

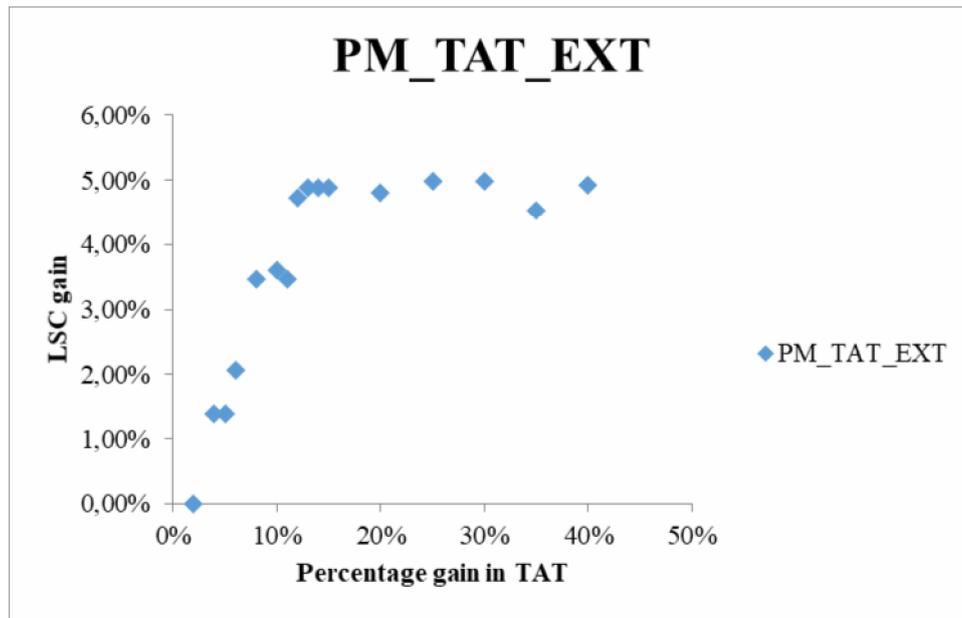


Figure 6. LSC gain x percentage gain in TAT

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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