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MAINTENANCE QUALITY ASSURANCE THROUGH STATISTICAL TECHNIQUES, FMEA AND FTA

Sergio Butkewitsch
Federal University of Uberlândia - Mechanical Engineering Department
Campus Santa Mônica, Bloco M – Uberlândia, MG 38400-089, BRAZIL
Ibrahim Andraus Gassani
Federal University of Uberlândia - Mathematics Department
Campus Santa Mônica, Bloco F – Uberlândia, MG 38400-089, BRAZIL
Mário Jesus Narduchi Filho
Companhia de Cigarros Souza Cruz S/A
Av. José Andraus Gassani, n. 5464, Distrito Industrial, Uberlândia, MG 38405-390, BRAZIL

Abstract. *The present work is intended to demonstrate how Failure Modes and Effects Analysis (FMEA) and "Failure Tree" Analysis (FTA) techniques can add value to total productive maintenance programs. The theoretical foundations of both techniques are addressed, relating FMEA and FTA to general quality management methods, inside and beyond the scope of the maintenance function. In order to establish the parameters needed to evaluate the maintenance process capability, proper statistical indexes are introduced at the stage related to the analysis of control devices. Finally, with the aim of illustrating the concepts employed hereon, some of the proposed tools are deployed to analyse a specific case belonging to a real manufacturing environment.*

Keywords: *FMEA, FTA, Quality in Maintenance*

1. INTRODUCTION

Equipment reliability is a key issue within the industrial agenda, in order to ahieve the goal of running plants with the absolute minimum of planned outages without unplanned shutdowns, producing high quality products at the lowest possible cost. In practical terms, the reliability challenge consists of, given limited resources, eliminate failures instead of striving to limit damage after primary or component failure has occurred. The obvious question to arise from these considerations is: how to eliminate failure?

The answer to this question is twofold. First, equipment design plays a very important role: significant research effort is deployed in the field of machine design in order to elaborate equipment with robust behaviour. Second, reliability is strongly dependent upon a proper maintenance strategy. This paper adresses such a strategy, in which FMEA/FTA fundamentals guide a set of practices belonging to an existent maintenance plan. A statistical evaluation method is chosen to judge the merit of this plan. This way, it is easier to relate maintenence performance to overall process quality.

2. FMEA/FTA FUNDAMENTALS (Helman and Andery, 1995)

The FMEA/FTA approach to quality in maintenance is essentially a managerial set of techniques. This means that the implementation of a comprehensive maintenance plan aimed to impact quality results is a question of corporate policy, dependent on decisions made within the upper management level.

An outline of technical aspects regarding this approach is presented in the sequence:

2.1 FMEA: Failure Modes and Effects Analysis

The Failure Mode and Effect Analysis (FMEA) is an engineering technique used to define, identify and eliminate known and/or potential problems from a system. As suggested by its own name, its operation is based on the study of **modes** and **effects** of failures.

The failure mode is a function of the part as an individual machine component. In general, each component part number in a system is analyzed to determine its possible failure modes (open, short, mechanical failure etc.). Every part has numerous potential failure modes and theoretically, there is no limit as to the depth one could go in investigating them. The initial FMEA should include all of the system components that would be repaired or replaced during a maintenance action, and why (i.e., which failure modes are to be prevented). Additional components and failure modes should be added as failures occur.

For example, consider an automotive engine whose lubricant is to be changed each four months: this need exists because the failure mode related to poor lubrication is known, as well as its precaution procedure. Then, suppose that despite proper lubrication, the engine may suffer from unexpected damage at the piston: the mode associated to this failure has to be indexed in the FMEA database, because it will indicate if the cause of the failure has or not any relationship with insufficient lubrication, the previously known failure cause. If, in this case, the failure mode is an impact between the piston and an overhead valve, the cause may be a belt problem: the different **mode** pointed to a different **cause**.

On the other hand, the effect of a part failure depends upon the function of the part in the system. Two valves may have the same part number but the effect of a failure will depend upon what the valve is controlling. Therefore, it is very important that each system component is assigned to an unique symbol or designator that is completely independent from the part number. The system schematic is the key document used to determine the effect of a failure of a specific part, in a specific failure mode. The FMEA considers each part and determines the effect that each failure mode will have on the overall system.

FMEA (as well as FTA, to be presented in the following section) techniques can produce better results if inserted in a broader, companywide quality process, instead of being applied exclusivelly in the maintenance context. Motivated workforce is an invaluable source of suggestions and observations regarding an enormous quantity of possible failure modes and effects that can arise within the several systems belonging to a complex manufacturing environment. This is the key to avoid outdated, pointless FMEA databases.

In view of this basic concepts, a general implementation flow for FMEA is depicted in figure 1 below. It is worth highlighting that step 7 (Analysis of Control Devices) is of crucial importance to evaluate the program effectiveness. Adequate performance indexes are indispensable tools to identify potential problems and indicate possible corrective actions. This subject will receive a special treatment in this paper, by means of statistical process control tools.

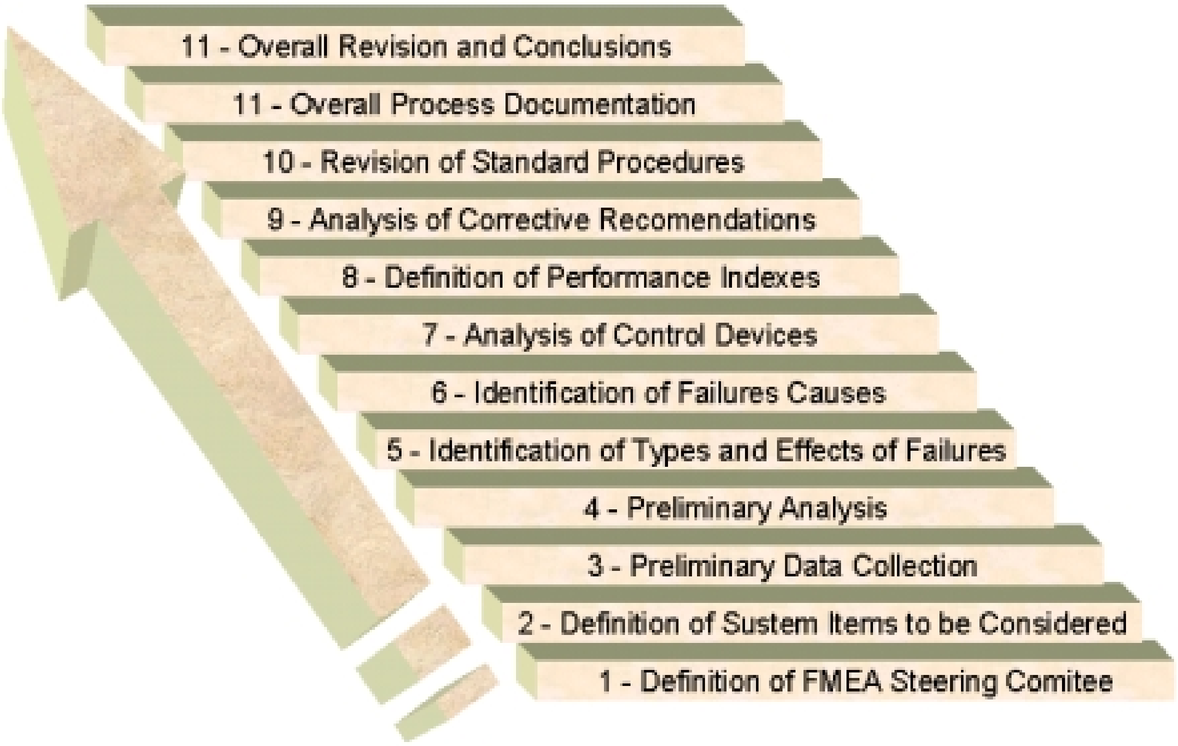

Figure 1 - FMEA Implementation Diagram

2.2 FTA: Failure Tree Analysis

Failure Tree Analysis is the companion technique to the FMEA approcah and is focused in the investigation of failure causes, since they happen and/or are predicted to occur. Applying FTA permits the usage of a standardized method of verifying how failures occur in a given equipment, in order to evaluate the overall reliability status of products and processes.

A flow diagram similar to figure 1 illustrates FTA's philosophy:

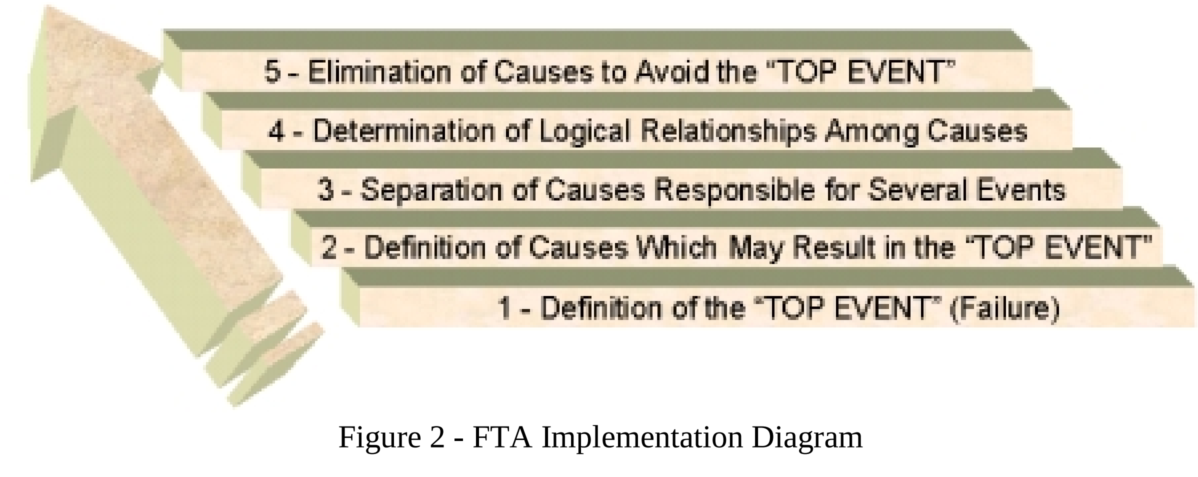

Figure 2 - FTA Implementation Diagram

It is necessary to stress the importance of step 2 in the sequence used to implement the FTA approach. The possible causes and verified and/or predicted failures are arranged in a structure called the Failure Tree. Within this structure, the unwanted "Top Event" (i.e., the failure itself) appears linked to basic events by means of proper logical relationships. An example of such a Failure Tree is depicted below:

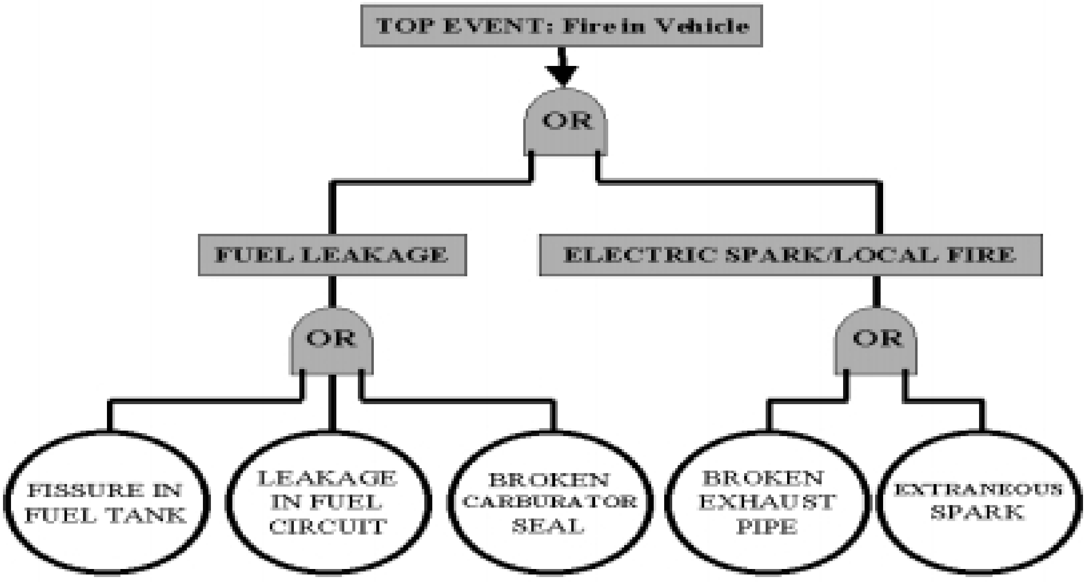

Figure 3 - Failure Tree Example for Fire in a Car

The logic connector "OR" means that if any and only one of the causes arises, the Top Event may happen. Primary causes (base of the Failure Tree) are listed inside ellipses and the secondary ones are contained by the shaded rectangles. Figure 4 below portraits a similar analysis performed with another tool, very familiar to quality control practitioners: the cause-effect (Ishikawa's) diagram:

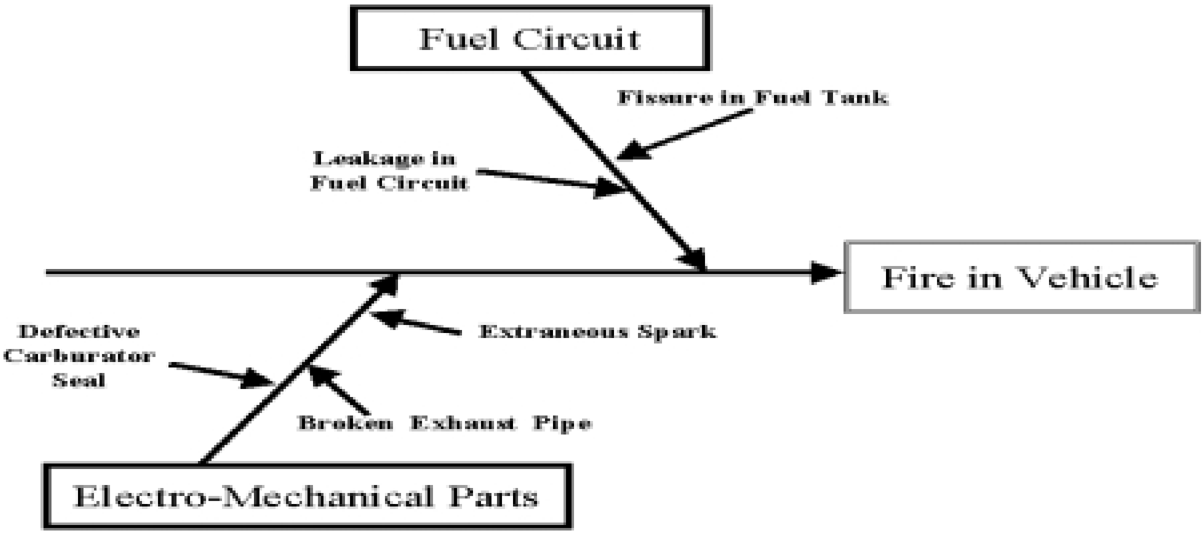

Figure 4 - Partial Ishikawa's Cause-Effect Diagram for the Problem of Fire in a Car

It is important to stress that both techniques (FMEA and FTA) are different, but complementary. However, there is no unique solution to combine them. The specific knowledge about each of many system's characteristics may furnish indications of what is the particular solution best suited to peculiar combinations of activities, processes, products, market and corporate culture, to mention a few important factors. Figure 5 and Table 1 are intended to clarify the general relationship existent between FMEA and FTA:

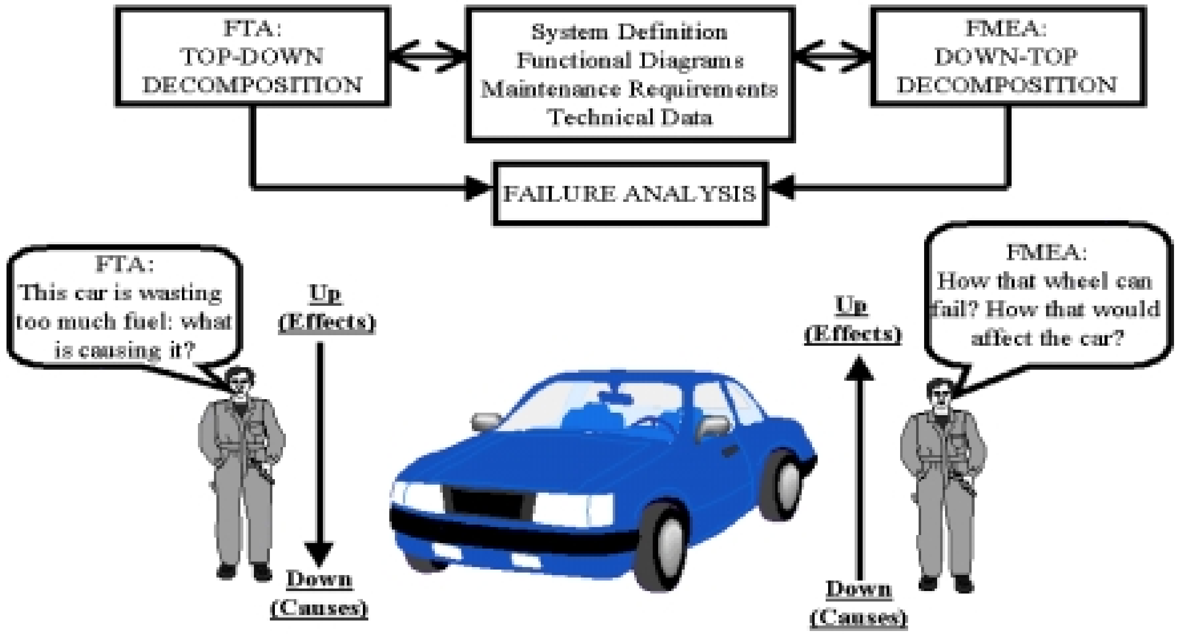

Figure 5 - Relationship and Differences Between FMEA and FTA

Table 1 - FMEA/FTA relationship

	FTA	FMEA
GOALS	➲ Identification of primary failure causes; ➲ Establishment of logical relationships among primary and final failures; ➲ System reliability analysis	➲ Identification of critical failures, their causes and consequences, in a component basis; ➲ Arrange failures according to a hierarchy; ➲ System reliability analysis
PROCEDURES	➲ Failure identification by product user(s); ➲ Relation of end failure with primary ones, by means of logical symbols	➲ Analysis of all potential failures and possible consequences; ➲ Deployement of corrective and preventive actions in view of predicted failures
BASIC FEATURES	➲ Best method for the analyis of an individual failure ("top event"); ➲ Focuses on end failure ("top event")	➲ May be used to approach simultaneous and/or related failures; ➲ All system components may be subject of analysis

3. THE MAUTO PROGRAM: A FMEA/FTA BASED APPROACH FOR QUALITY IN MAINTENANCE

This section is aimed to present the MAUTO program, a quality plan for maintenance implemented at a cigarette production facility installed at Uberlândia, MG, Brazil, as an adaptation of TPM (Total Productive Maintenance) techniques regarding operations based on autonomous manufacturing cells. At its current development stage, MAUTO is essentially a set of FTA procedures, where causes of maintenance problems are more efficiently adressed due to the following key steps:

- Workforce training on important subjects: technical maintenance aspects along with team oriented problem analysis and solving tools;
- Integration between maintenance and manufacturing teams;
- Workforce empowerment by reducing supervising staff and decentralization;

The paragon of the problem analysis/solving methods is the search for failure causes by means of statistical thinking, employing Ishikawa's like failure trees (refer to figure 4).

It is believed that MAUTO's improving potential can reach higher levels as soon as FMEA based procedures are incorporated to the overall program strategy. This is strongly recommended as a practical next step in MAUTO's evolution and the effects obtained by such a change may be discussed by the authors in a future work.

An important aspect to be stressed is the very particular implementation format of the maintenance strategies discussed hereon. This singularity is necessary for every and all operating contexts, since each of them display own unique features regarding procedures, entreprenerial culture and workforce status. The major difficulties in translating FMEA/FTA theory into applications is closely related to this need for very customized solutions.

A relief for such obstacles, however, can be obtained if one chooses to define implementation independent performance indexes to evaluate the program efficiency. Next section shows how this can be achieved through statistical data analysis techniques commonplace within Quality Control strategies. In the context of MAUTO, specifically, this procedure already adresses the implementation of step 7 (see figure 1) in the work of adding the FMEA phylosophy to the program.

4. STATISTICAL EVALUATION OF A FMEA/FTA BASED MAINTENANCE PROGRAM

4.1 Justification for the use of statistics

Reliability is essentially a statistical issue. For a simple illustration, consider the case of a machine that can fail due to a bent shaft. In order to avoid such a failure, the shaft is designed in a way that the yeld limit is beyond the maximum resulting stress by a certain amount, the **safety margin**. In reality, however, both of these important values (the resulting stress and the part strength) cannot be treated as deterministic. Both of them can randomly fluctuate due to several factors, and a good statistical model for this variability is shown below:

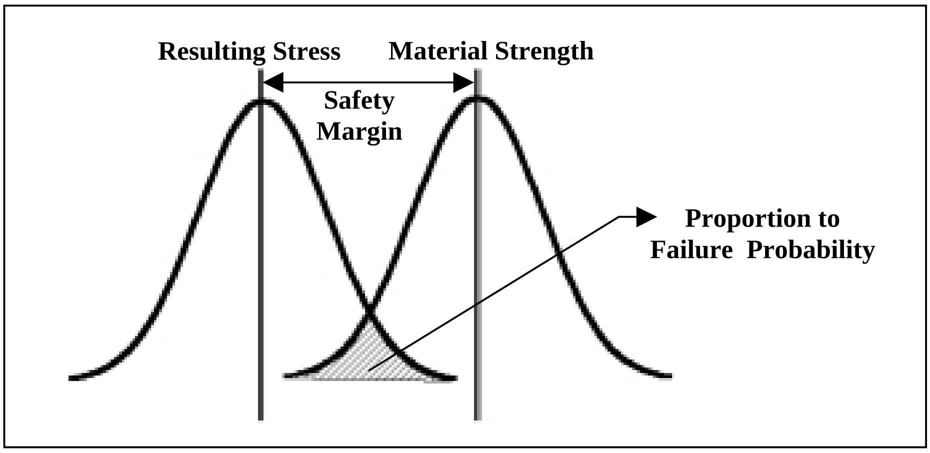

Figure 6 - Illustration of the Probabilistic Nature of Failures

Based upon these fundamentals, sophisticated reliability analysis tools are produced for industrial use as, for example, Weibull (Shigley and Mischke, 1989) analysis software.

For the workforce, however, complex theoretical considerations have to be put apart: it is necessary to create a simple performance index that justifies the assumption that the "Failure Probability" area in figure 6 is getting bigger or smaller.

Since the fifties, japanese are mastering the technique of translating complex statistics into simple control charts (Kume, 1993). The approach of this article is to identify gains or losses in reliability through the state of statistical control of a variable related to maintenance performance. A change in the situatiuon of statistical control, and thus an **assignable variation** of the reliability status, can be easily identified by operators trained in the basic skills of statistical process control.

4.2 Case study: statistical evaluation of efficiency indexes - analysis and discussion of results

Efficiency is defined hereon as the percentage of the net work journey (general stops, setup and planned maintenance times discounted) which is not affected by unplanned equipment shutdown. The following control charts analysis provides an insight of the impact provided by the introduction of MAUTO maintenance plan:

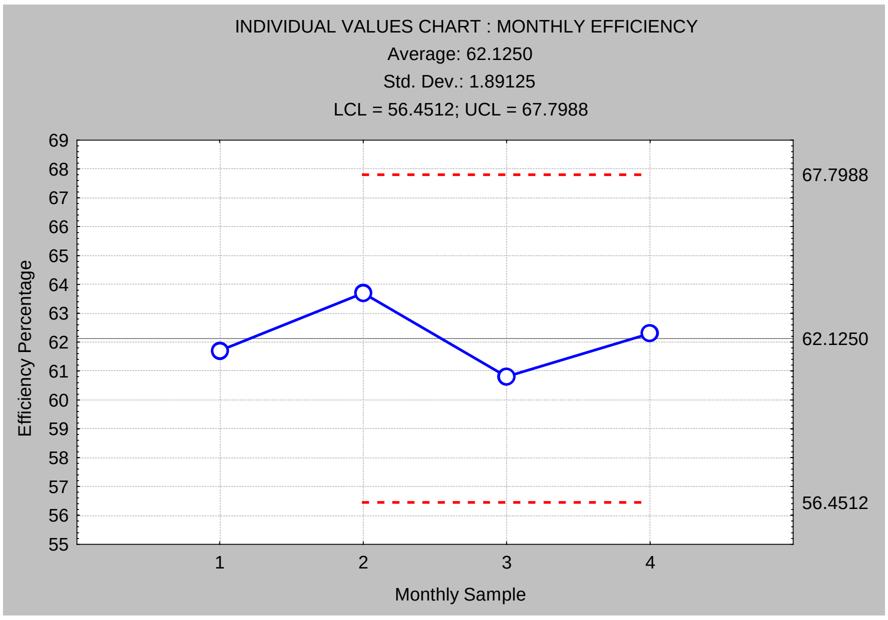

Figure 7 - Efficiency Standard Established Before MAUTO's Introduction

The figure above shows the last four efficiency measurements taken prior to MAUTO's introduction. They obey a state of statistical control established during several precedent months and a statistically reasonable prediction would lead to the conclusion that, in a best scenario configuration, the maximum efficiency to be expected would be of the order of 68% (roughly, the process upper control limit).

Figure 7 below, on its hand, provides strong statistical evidences that MAUTO's effects led to a new efficiency paradigm, as soon as the process reaches a completelly different, superior level of statistical control. The four points in the begining of the time series displayed in this graphic are the same presented in figure 6 and it can be deduced that they belong to another process, featured by lower efficiency (third and fifth points in the sequence, marked **3** and **5** in figure 7, even fall below the lower control limit of the new process). The seven following points belong to a pilot implementation stage in MAUTO's history, and the last of this sequence (marked **12**) shows that the process has started to operate under new statistical control limits:

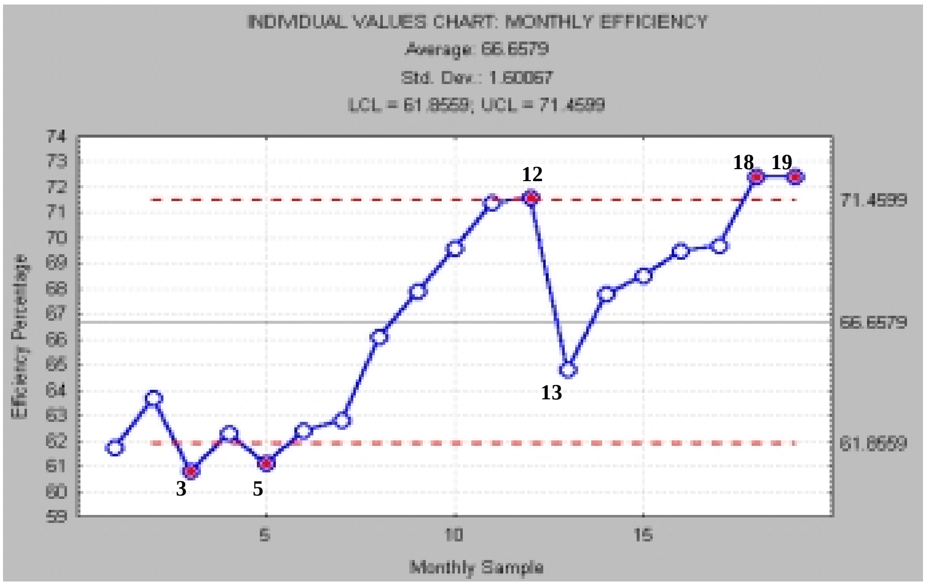

Figure 8 - Control Chart Demonstrating the Effect Obtained at the Begining of MAUTO's Implementation

The next point (labeled **13**), however, displays a serious decrease in efficiency. This happened because this specific month marks the transition between MAUTO's pilot experience to full scale implemmentation: adaptation difficulties are prone to occur and a lower efficiency can naturally happen (it is useful to highlight that this declining point exhibits an efficiency level higher than the average pre-MAUTO figures).

After a consistent raise, points marked as **18** and **19** confirm the trend previously indicated by point **12**: the process has attained a new level of statistical control, and the new average efficiency may be higher than 71.5% (the upper control limit of the chart in figure 7).

In fact, as shown in figure 8, the process progresses to operate at an average efficiency of 76.45% and, after the point labeled as **32**, indications arise that an even higher efficiency level is about to be set.

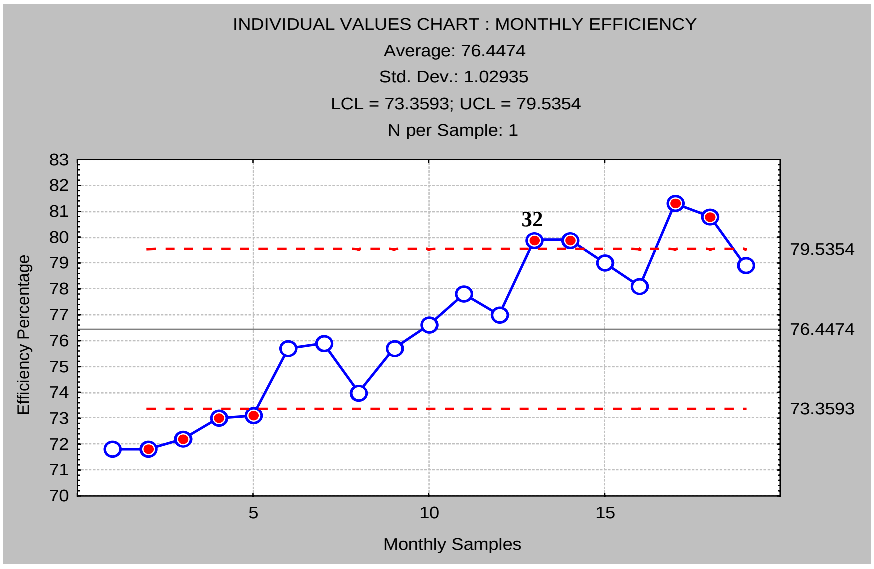

Figure 9 - Upper Level Statistical Control State Set After 32 Months

Thus, after a 32 month implementation experience, the average efficiency rate has raised from a 62.125% level to an expected value of more than 76.450%. Another aspect of the continuous improvement achieved with the new FTA based maintenance strategy is smaller data variability: the difference between upper and lower control limits for percentage efficiency in the pre-MAUTO graph was about 11.35%, while this value is as low as 6.18% up to the stage presented in figure 8. (Remark: The limits are no longer valid since the process has gone out of conrol, but the trend of closer limits can be accounted for due to continuous and systematic observation of the process).

Finally, a most important observation concerns the perception of different states of statistical control (with respect to the efficiency rate variable): the changes which indicate statistically significant improvement (points and/or sequences of points out of control in relation to a less efficient control state) can be readilly noticed within the control chart, given the workforce designated to analyse this data possesses the very basic skills regarding SPC tools.

5. CONCLUSIONS, PERSPECTIVES AND RECOMMENDATIONS

The introduction of a maintenance strategy based upon modern management techniques has the clear goal of establishing superior standards in equipment reliability. An approval or disapproval judgement about the accomplishment of such an expectation must emitted with certainty and agility, so any eventual mistake can be corrected in a timely manner. The statistical criterion suggested in the illustration given at the previous section can be a valuable alternative with respect to these demands: a mathematically sustained conclusion is immediatelly reached since the control charts are available.

It will be very opportune to repeat this same kind of analysis after blending FMEA techniques into MAUTO. Their positive contribution to the FTA based set of procedures already implemented will depend on the correct observation of process particularities, as already stressed in this article: statistical indexes can be used to define if this crucial question will be correctly addressed. If the answer is affirmative, FMEA is supposed to improve current maintenance efficiency in a degree similar to the one MAUTO has already contributed in this issue.

It would be also desirable to consider the amount of planned maintenance stops as a performance index, along with the efficiency rates considered within this article. The reliability effort is to drive this indicator to a minimum and significant reductions in planned outages can be evidenced from trivial variations by means of the statistical analysis illustrated in the precedent section.

Finally, after all possible performance indexes are considered, the search for minimum variance around their target values should be chosen as a goal to be pursuited in order to thrive maintenance process capability: the control charts pointed out in this article remain valid evaluation tools for the level of accomplishment of this task.

6. REFERENCES

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