Reverse engineering in industrial maintenance component criticality analysis

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***Abstract** - The paper presents an investigation of the criticality analysis applied for the classification of industrial spare parts, in conjunction with the implementation of Reverse Engineering (RE) techniques, for prioritizing the need for re-engineering equipment components for maintenance purposes. In the paper, equipment component criticality is defined through the use of an adapted Failure Mode Effects and Criticality Analysis (FMECA) technique based on the operation and failures history record. A safety stock of the thus defined critical components is of paramount importance and must be readily available. In order to achieve that, especially in case of mechanical equipment that is considered obsolete, remanufacturing through RE techniques must be considered. One of the most critical RE tasks is the assignment of the dimensional and geometrical accuracy specifications of the reverse engineered components that are directly connected with manufacturing cost and time. In the framework of a systematic methodology illustrated in the paper, these parameters are considered, in contrast to the respective component procurement cost and time information, for determining if it is economically reasonable and/or beneficial to manufacture and stock critical industrial spare parts.*

Keywords: Criticality analysis, FMECA, industrial manufacturing, maintenance, reverse engineering

1 Introduction

In most industrial production facilities supplying the maintenance engineers with the correct spares in a timely and economic manner is a rather complex and delicate task. As a rule, the largest percentage of the total risk of the equipment overall mechanical integrity is concentrated in a relatively small percentage of its components. Therefore, emphasis is on those components which are considered critical for sustaining continuous operation of the production equipment. These potential high risk components require greater attention, normally achieved through the application of risk based inspection planning techniques, including NDT, that establish a consistent inspection strategy. However, in the fast-paced industrial environment of today, where technological advancement continuously craves for updating and upgrading, mechanical equipment and/or its constituting components life cycle are constantly becoming shorter and hence their obsolescence time is being accelerated.

Part obsolescence problems occur in all systems with a service life longer than that of one or more of their components. In industrial manufacturing, a frequently met engineering problem is the maintenance of legacy production facilities and/or obsolete mechanical equipment that is still in operation and has a considerable residual service life. Moreover, extension of equipment service life through re-engineering or spare parts remanufacturing on top of the apparent environmental benefits, such as material waste and industrial pollution reduction, offers also substantial economic ones.

In this context, spare parts, especially in cases of unexpected needs, become so rare and hard to find that their procurement availability ends up being economically unaffordable or even impossible. To confront this industrial challenge, most companies worldwide tend to keep a stock on hand of the components believed to be critical and carry an important role in the production line, as a safety precaution measure against a sudden failure occurrence. Nevertheless, without conduction of a proper criticality analysis it is difficult to accurately estimate the spare parts requirements and hence, usually, one of two possible scenarios are occurring depending on the engineers and related maintenance personnel ad-hoc approach. Either an overstock of components and parts is accumulated which in fact poses a high holding/warehouse cost or if an understock strategy is decided there is always the danger of a possible breakdown with substantial equipment downtime consequences. These considerations necessitate the presence of a well grounded and scientifically sound methodology which will establish the criticality of components [1,2]. A well known methodology used to define criticality on the grounds of the severity of consequences induced in a certain production facility/equipment combined with the frequency of that occurring is the FMECA (Failure Modes Effects and Criticality Analysis), [3-5].

In the paper, a step beyond the concept of defining the component criticality is introduced using an adapted FMECA technique and through that identifying the required safety stock to cover failure needs. This includes the utilization of RE techniques in order to assign the technical specifications that are directly related with the manufacturing cost and time of the needed component. In house or outsourced remanufacturing can then be practically considered as an attractive alternative compared to component procurement or, in case of components that are not currently supported by their original manufacturer, be examined as a realistic solution in order to prolong the service life of a production facility. The systematic methodology and the detailed steps that lead to a scientifically sound approach to the engineering problem of manufacturing, procurement and stock critical industrial spare parts are hereby presented.

2 FMECA methodology

The FMECA is a widely established methodology used for identifying and analyzing all potential failure modes of a system. This may be achieved either through the design phase so as to eliminate potential problems before actually being incorporated into the system or during the process phase where every care is taken in the direction of mitigating or eliminating - if possible - current failure consequences [6].

Through the FMECA application the mechanisms driving failure appearance as well as the failure effects and consequences of each individual case are examined. This takes place through a structured methodology which results in the assessment and quantification of the Criticality of a certain component.

In general three factors are used for defining criticality:

- *Severity* (S). Defines the consequences of a failure occurrence and its calculation may be based on the consequences severity induced in qualitative terms (e.g. catastrophic, fatal, severe), or quantitatively (e.g. hours of downtime).

- *Occurrence* (O). Defines the frequency and illustrates the possibility - likelihood that a failure will occur. It may be based on a failure rate, λ, measurement or simply on the number of occurrences over a specified time interval (e.g. six months, one year).

- *Detection* (D). Defines the likelihood that symptoms of a potential failure may be detected before having the actual failure occurrence. This factor is not given equal importance and even omitted in some studies of FMECA, especially those aimed most on process-based FMECA.

Criticality for each component is evaluated as the product of these three terms which forms the Risk Priority Number (RPN).

$$RPN = S \times O \times D \qquad (1)$$

The goal is to minimize as possible the RPN through the application of a suitable set of corrective actions. After their implementation, the refined RPN is reassessed and a decision is further carried out on whether to continue with the same corrective actions, change plans or accept the new situation. An example of an FMECA worksheet [7] is shown in Figure 1.

Id.	Comp.	Function	Failure mode	Failure cause	Local effects	Global effects	S	O	D	RPN	Corrective actions

Figure 1: A typical FMECA worksheet

Even though international standards and guidelines do exist, [8, 9] giving an indication of some quantitative approaches on FMECA, it is generally accepted that the levels showing different S, O and D factors are highly subjective and that the best way is to use custom ones for better suitability to specific cases.

3 Adapted FMECA methodology

As it is already pointed out, FMECA may well be considered as a tool for both Reliability and Maintenance and it is strongly dependent on the application type (Design-FMECA or Process-FMECA) whether it aids in the direction of improving the former or the latter.

In the context of the paper, FMECA is utilized as a tool for improving Maintenance and especially for defining the criticality of components in order to provide for a well grounded decision about their optimum safety stock. It is here to be emphasized that the focus of attention in the paper is upon *the unscheduled maintenance occurrences*. These occur in a random pattern and necessitate the presence of a safety stock in addition to that covering scheduled spare replacements and needs in general, to deal with unexpected downtimes hindering productivity rates.

In this case an adapted FMECA approach is utilized using solely the two main criteria of Severity (S) and Occurrence (O) to provide for a criticality RPN index. The values used in each of these two criteria form three categories with a respective Criticality rank ranging from 1 up to 3, Tables 1 and 2. More specifically, Severity (S) is assessed based on the consequences induced on the equipment, measured in downtime hours, due to a certain component failure.

Table 1. Severity assessment

Equipment Downtime (hrs)	**Criticality rank**
1-3	1
4-8	2
>8	3

while the Occurrence factor (O) is established on the grounds of the number of failure appearances over one year of full operation of the system under study.

Table 2. Occurrence frequency assessment

Failure appearances (annually)	**Criticality rank**
1-2	1
3-5	2
>5	3

In this way, the following Risk Priority Number (RPN) matrix is formed:

Table 3. The RPN matrix

Severity	3	3	6	9
	2	2	4	6
	1	1	2	3
		1	2	3
RPN		**Occurrence**		

where the RED region illustrates the *Critical* components, the ORANGE region illustrates the *Essential* components and the YELLOW region illustrates the *Secondary* components.

At the present stage of the methodology development, only two regions - states are used to determine acceptable or unacceptable status hence the definition for Critical components is:

IF RPN is 6 or 9 THEN Component is Critical

IF RPN is 1 or 2 or 3 or 4 THEN Component is Non-Critical

An indicative example illustrates the process of determining the critical components on a system consisting of 10 components. In the following table the failure data for the first 5 components is included.

Table 4. Example of RPN formation

Component No	Failure Mode	Failure Cause	Severity (S)	Occurrence (O)	RPN	Σ(RPN)
1	Blockage	Overheated	1	1	1	**1**
2	Breakage	Overstressed	2	1	2	**2**
3	Blockage	Bad lubrication	3	1	3	**6**
	Fracture	Fatigue	3	1	3	
4	Deformation	Overstressed	2	2	4	**4**
5	Leakage	Seal wear	1	1	1	**2**
	Cracked	Thermal shock	1	1	1	
...	...	...	...	...	...	**...**

With all 10 components ranked and sorted by RPN, the most *Critical* are identified, Table 5.

Table 5. Critical components determination

Component No	RPN
6	9
8	6
3	6
7	4
4	4
2	2
5	2
1	1
9	1
10	1

Critical

The identified critical components - on merit of FMECA defined component criticality – are distinguished into standard and non-standard. The methodology presented in the paper is focused *to non-standard components*. This is due to the fact that in the case of non-standard components it is generally much more difficult to pursue their availability, especially in case that they are out of production and are not currently supported by their original manufacturer. Moreover, lack of technical documentation (blueprints, material properties etc), that is typical for non-standard components met in industrial production equipment, makes them the main candidates for the application of relevant reverse engineering techniques.

In the paper, apart from assigning the component safety stock on the grounds of the component criticality for sustaining operation/production in an industrial environment, a more critical view of the components procuring feasibility and viability is performed. This has to do with an actual comparison between procurement and re-manufacture based, at the moment, on the evaluation of two criteria, cost and delivery time. The contribution of each of the two criteria in the decision making process has to be further sought as for now they are considered equally important.

The proposed methodology is, essentially, divided and undertaken into three steps-processes.

1. The FMECA process
2. The RE process
3. The comparison process

A flowchart of the decision methodology developed is illustrated in the following diagram, Figure 2.

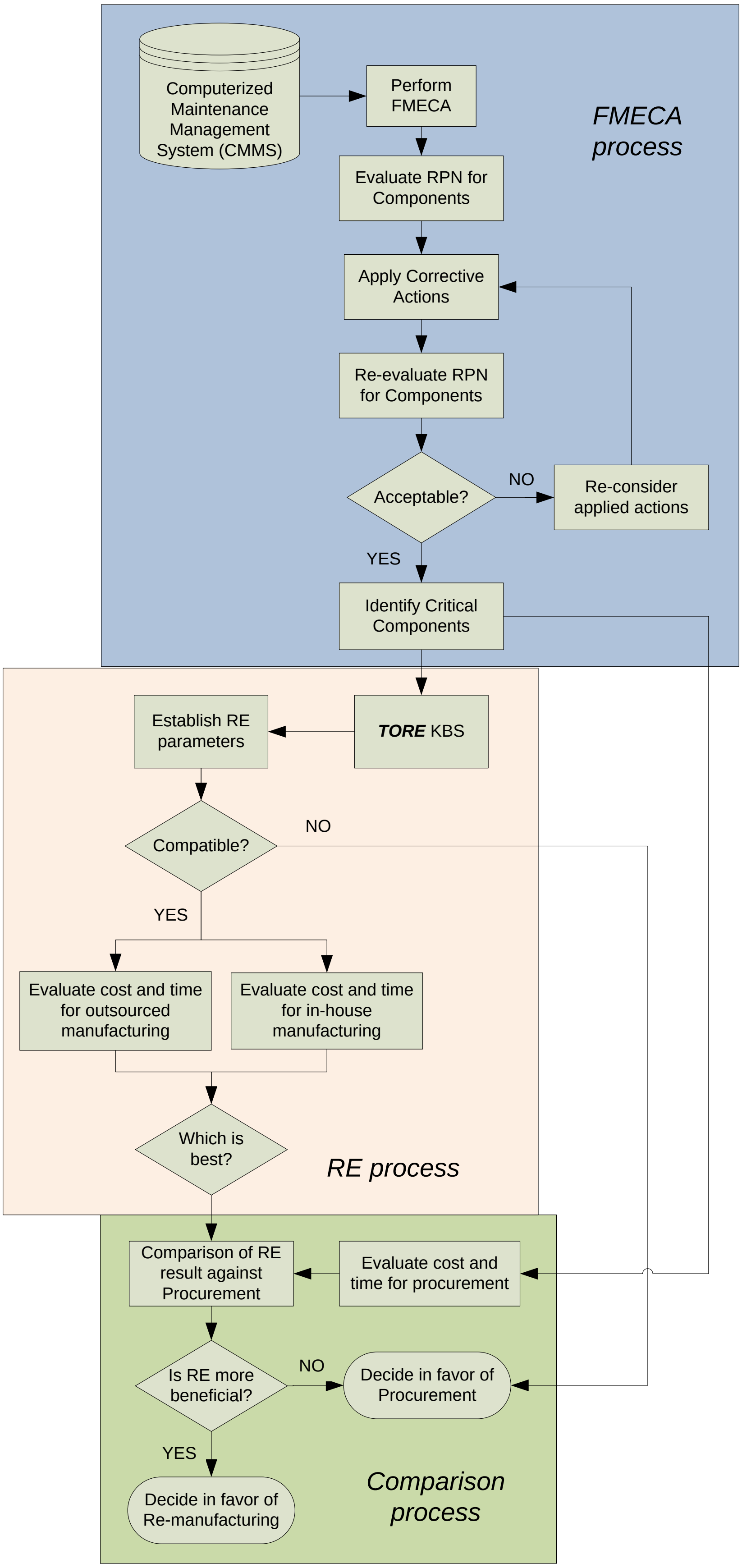
Computerized Maintenance Management System (CMMS)
Perform FMECA
FMECA process
Evaluate RPN for Components
Apply Corrective Actions
Re-evaluate RPN for Components
Acceptable?
NO
Re-consider applied actions
YES
Identify Critical Components
Establish RE parameters
TORE KBS
Compatible?
NO
YES
Evaluate cost and time for outsourced manufacturing
Evaluate cost and time for in-house manufacturing
Which is best?
RE process
Comparison of RE result against Procurement
Evaluate cost and time for procurement
Is RE more beneficial?
NO
Decide in favor of Procurement
YES
Decide in favor of Re-manufacturing
Comparison process

Figure 2: Flowchart of the developed methodology

4. Establishment of RE parameters

In reverse engineering existing mechanical components, for which technical documentation is not available or accessible or do not exist, have to be reconstructed and manufactured through a variety of techniques. The objective of remanufacturing a needed mechanical component which has to fit and well perform in an existing assembly and, moreover, has to observe the originally assigned functional characteristics of the product is rather delicate. In order to achieve that a broad range of technical specifications of the RE component, such as material specifications, heat treatment, surface treatment, surface finish, shape, size etc. and their relevant accuracy requirements, have to be assessed.

Having a significant impact in its manufacturing cost, assemblability and performance, the assignment of the dimensional and geometrical accuracy specifications of the reverse engineered component is one of the most critical RE tasks. The methodology presented in the paper is focused in the designation of geometric and dimensional tolerances that match, as closely as possible, to the original (yet unknown) dimensional and geometrical accuracy specifications. In RE such accuracy specifications for component reconstruction have to be reestablished, one way or the other, practically from scratch. RE tolerancing becomes even more sophisticated in case that coordinate measuring machine (CMM) data and a few or just only one of the original components to be reversibly engineered are within reach. Moreover, if operational use has led to considerable wear/damage, then the complexity of the problem increases considerably. Although RE has an apparently significant role to play in mechanical maintenance and plant equipment availability, RE-accuracy and tolerancing issues do not seem to have been, to this date, adequately addressed. An approach to tackle with this task is presented in [10, 11, 12].

4.1 Tolerance assignment in RE - KBS TORE

Mechanical engineering objects typically possess operational surfaces of simple geometries such as planes, cylinders, tori etc that justify their Feature Based description for RE. Furthermore, in a great range of applications the assessment of size and location tolerances of cylinders and/or bosses constitutes one of the most critical tasks for a successful component reconstruction. TORE (**TO**lerances for **R**everse **E**ngineering) knowledge based system (KBS) is developed in that context. The general concept of the system is shown in Figure 3 [12].

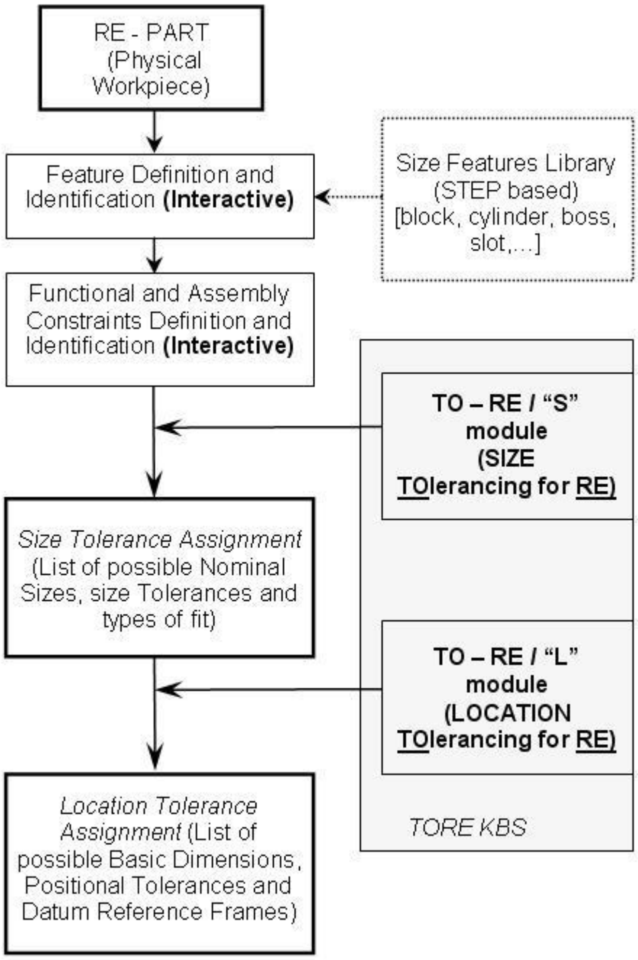

Figure 3 : TORE KBS concept [12]

The nominal size and tolerance assessment of the critical dimensions identified on an RE-component is performed by the TORE–"S" (Size) module of TORE knowledge based system [B]. Through a user-friendly interface, CMM obtained size and form data and, as well as, surface roughness records are introduced into the system. Manufacturing process, the accuracy threshold of the CMM used for the above measurements in accordance with the ISO 10360-2 and, in case of peg and hole assembly, the functional clearances (measured, given or assessed) are also fed into the system. The output of the system is a list of all the possible alternatives for the nominal size and tolerance that concern the particular dimension of the RE-component and satisfy the input data. The system has been originally developed for peg and hole type of assemblies, however, it is also applicable in dimensions that are involved in dimensional chains.

For the location tolerance assignment of critical size features, the TORE-"L" (Location) module, analytically presented in [10, 12, 13], makes use of a search algorithm in order to generate possible alternatives for the basic (theoretical) dimensions, the positional tolerances and the relevant datum reference frames. The effectiveness of TORE KBS has been illustrated in several industrial case studies, [10, 11, 13] providing realistic industry approved results.

5. Conclusions

In the paper a methodology leading into selection of the most critical components based on their historical intensity of failure consequences upon the equipment is described. It is coupled with an appropriate RE methodology which provides an insight into the capability of re-manufacturing selected components and of the possible gain in cost and time over procurement. This continuously enhanced methodology is expected to incorporate a real life example on subsequent stages of development which will test its validity and provide for any adjustments necessary. It is also suggested that further criteria should be included in the consideration later on as there definitely exist additional cost drivers which help shape a more accurate result and decision.

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