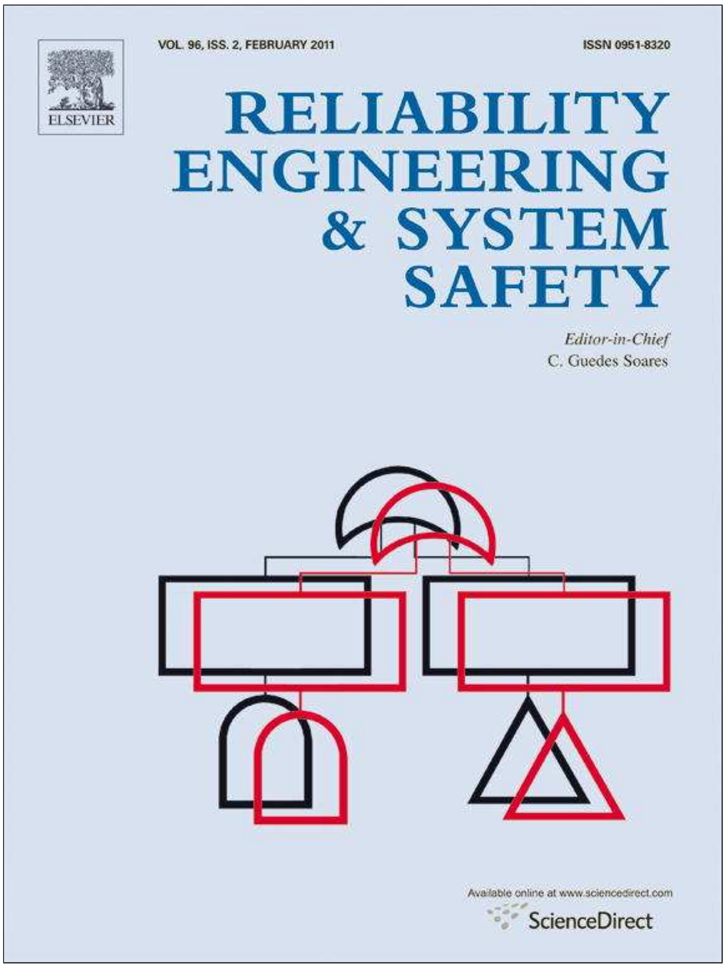

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A practical method for the maintainability assessment in industrial devices using indicators and specific attributes

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ABSTRACT

The objective of this paper is to describe a procedure to obtain maintainability indicators for industrial devices. This analysis can be helpful, among other cases, to compare systems, to achieve a better design regarding maintainability requirements, to improve this maintainability under specific industrial environment and to foresee maintainability problems due to eventual changes in a device operation conditions. This maintainability assessment can be carried out at any stage of the industrial asset life cycle.

With this purpose, this work first introduces the notion of maintainability and the implementation of assessment indicators, including some important requirements to perform that. Then, a brief literature review is presented, including the definition of the main concepts, which are later used in the paper. After studying the maintenance levels and the maintainability attributes, both terms are linked, leading all this analysis to the assessment of the maintainability indicators. It follows a discussion about the information obtained through the maintainability assessment process and its computation into several maintainability indicators. The paper includes a case study, which implements the defined assessment into a practical scenario. Finally, the work concludes summarizing the more significant aspects and suggesting future researches.

1. Introduction

The purpose of this paper is to describe a procedure for obtaining maintainability indicators applied to industrial devices and to discuss how the indicators compiles the technical information in a suitable and useful manner. According to the European Standard EN 13306:2010 [3], the maintainability is defined as "ability of an item under given conditions of use, to be retained in or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources." This definition is completed with the following note: "Maintainability may be quantified using appropriate measures or indicators and is then referred to as maintainability performance". This paper presents a method to accomplish that note, that is to say, to obtain the maintainability performance of an industrial asset, at any time within its life cycle, including the original design ("intrinsic or inherent maintainability", EN 13306:2010 [3]). In order to do so, the first problem is to find a way, a suitable procedure, to measure maintainability in an easy and practical way. Once that procedure is determined, a second problem is to decide precisely what needs to be measured and for which type of maintenance operation (UNE 20654: 1992 [8]). The first purpose of this paper is to deal with these two problems.

In this work, the maintenance operations to accomplish on a certain industrial device are divided into five groups, named maintenance levels (related to the complexity of the maintenance tasks) and two sets of features/attributes to measure maintainability are proposed (only one of these sets will be maintenance level dependent). Finally, six maintainability indicators will be defined and their values calculated by combining the scores assigned to the maintainability attributes.

All this process requires the observation of five important considerations if we want our set of "standardized" indicators to allow future comparisons:

- Capturing the operating conditions of the item. The description of the device operational conditions/context, previously to the assessment process, is a must. These conditions involve the way that the item operates, its location within the plant layout and relevant environmental aspects.
- Capturing the maintenance level for which the maintainability is assessed. The maintainability definition also includes "…when maintenance is performed under given conditions and using stated procedures and resources".
- Acknowledging the evaluators' skills. In order to obtain objective and comparable measures for maintainability indicators,

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the training of the evaluators will be another key aspect to consider in this procedure.
- Describing the item lifecycle stage where the maintainability assessment is carried out.

Avoiding to take into consideration the existing maintenance organization. When the maintainability indicator assessment is performed during the device operational stage, it is important to take into account that the assessments are on the device capabilities, and not on the maintenance organization.

In the sequel this paper is organized as follows. After introduction, in the second part a brief literature review is presented, including the definition of the main concepts, which are later used in the paper. Afterwards, in Section 3, the maintainability indicators and maintenance levels are presented. Then, Section 4 presents a classification of maintainability attributes from device design perspective, maintenance staff and work conditions perspective and logistics support perspective. Consequently, in Section 5, maintainability attributes and maintenance levels are described and evaluated to discuss and justify the indicators set in Section 6. Moreover, the paper includes a case study, which implements the defined assessment into a practical scenario. Finally, the work concludes summarizing the more significant aspects and suggesting future researches.

2. Brief literature review

It is not the aim of this section to present a comprehensive and exhaustive study of the methods proposed for measuring the maintainability performance, which could be the purpose of a different paper, but to offer a quick overview of the main approaches found in the technical literature dealing with this issue. By doing so, we also contextualize the method that we introduce in this paper.

The most referred contributions that we could find in this area in our literature review were the following:

– Goulden [4] uses MTTR as maintainability indicator (involving, in that MTTR, all the times related with the repair, from the fault location, to the final checking after repair and set up again). This MTTR is calculated throughout statistical inference, using historical data. The MTTR of a complex device can be calculated by combining the MTTR, individually determined for each of its components.
– Houshyar and Ghahramani [5], presents a software tool for the operators of a device to record data from the device in order to later calculate the performance and the maintainability, based on that information.
– Wani and Gandhi [9], in Tribology (for mechanical devices), assesses the tribo-maintainability, that is, the maintainability from the tribology viewpoint. The tribology features are assessed by a table in which qualitative (expert assessment) assessment corresponds to a numerical value. Using those values, the tribo-maintainability is obtained throughout an algorithm
– Guo et al. [2], calculates MTTR from historical data and validate statistically the result. Although MTTR is related with maintainability, the author makes no considerations about that.
– Liu et al. [6], mainly considers the maintainability dependency on the human factors required for maintaining the device, in order to be taken into account in the device designing process. The author groups those factors in four main categories: maintenance operations safety, accessibility, comfort and practicability
– Lu and Sun [7], presents an expert-based assessment procedure. The expert assesses a set of factors, from which, the author considers the maintainability is depending on (such as identification, ergonomics, testability, simplicity, etc. and other experience evaluated factors). The evaluation of each factor is made by verbal scale, which is translated into numbers by fuzzy logic.
– Barabady [1] determines the reparation time by statistical methods (using Relex software) in a case study. He considers also some environmental and operational conditions to compute with the time to repair data in order to better describe the maintainability with such statistical-based indicator.

These contributions can be grouped, regarding the methods being used, into two main basic approaches, according to the source of the input information and the nature of it as follows:

- *Expert based methods* using the experience and insights of maintenance experts combined with historical data and objective assessments.
- *Statistics based methods* applied to historical data recorded from trials.

The method presented in this paper can be classified within the expert-based approach. By its use, a comprehensive assessment and updated maintainability can be achieved, in a very practical, easy to understand and apply way.

With regards to the type of indicators being used, the contributions reviewed above can be classified into three main groups:

- Multiple maintainability factors stimation without the obtention of a maintainability index or global or partial maintainability indicator [6,7].
- Single maintainability performance indicator based on statistical analysis of historical data and mainly on the estimation of MTTR [4,1,5,2].
- Single maintainability global indicator based on an algorithm involving the different scores in defined maintainability factors.

In this paper we present *multiple* maintainability indicators, which are both general (for all maintenance levels) and specific (related to each maintenance level). These indicators are not based on statistical inference but on maintainability attributes/factors evaluation and on the utilization of different algorithms to use these factors' scores and to obtain the final indicators values (general and specific).

3. Maintainability indicators and maintenance levels description

The maintainability indicators are assessed according to two kinds of attributes or characteristics of the device:

- *General attributes:* those affecting any device maintenance level. That is to say, they are maintenance level independent.
- *Specific attributes:* those depending on the maintenance level. That means they are functions of all the maintenance actions to be performed on a specified maintenance indenture level.

The assessment of the maintainability specific attributes for a device requires, therefore, the classification of the maintenance actions within specific maintenance levels. In this paper we propose five maintenance levels. For each level, the device maintainability performance will be assessed, checking whether the maintainability specific attributes have been taken into account for the development of maintenance actions at that level. The attributes ranking is done using a five values scale from 0 to 4 points, trying to reduce subjectivity and to obtain fair values easily to manipulate.

The maintenance levels are here established, based on the complexity of the tasks to be performed and the complexity of the human and material resources needed for its performance. The required unavailability time on the device is here also taken into account. In any case, these levels are due to common criteria accepted worldwide and are the following ones:

- Level 1: simple maintenance actions performed in the up state of the device. At this level, the operator performs preventive or corrective activities, which do not require setting the device into a down state. They are, for instance, simple adjustments foreseen by the manufacturer, without assembling or disassembling the device. Another example is the simple replacement of easily accessible components.
- Level 2: maintenance actions with replacement of functional components. These actions set the device into a down state. In this period the operator performs preventive and/or corrective maintenance actions, usually considering functional components of the device for their replacement.
- Level 3: failures identification and diagnosis. In these maintenance actions the operator, after setting the device into a down state, identifies and locates the causes of the failures.
- Level 4: inspections. The inspections refer to an extensive amount of tests and preventive/corrective maintenance actions that may require full or partial disassembly of the device. The purpose of the inspection is to maintain, on a device, the required availability and safety level over the time. Revisions are usually performed at prescribed time intervals or after determined amount of operations.
- Level 5: updating, reconstruction and/or overhaul. These operations are under the maintenance service responsibility of the plant or manufacturer. They are very important operations, which may include modifications and/or improvements. It is therefore possible that these operations increase the lifetime of the original device.

4. Classification of maintainability attributes

The maintainability indicators assessment shall be performed taking into account attributes from the device. These attributes are classified into three groups according to their nature: attributes related to the design, related to work conditions and staff requirements and attributes related to the needs of logistic support. It is important to observe here how these attributes are connected to capabilities of the device under assessment, and not to the actual capabilities of the maintenance organization already existing, where the device is being used.

4.1. Attributes related to the device design

Inside this group, we consider eight attributes as follows:

- *Simplicity*: existing reduction in the amount of elements and unnecessary assemblies.
- *Identification*: clearly location and signs from those components that are going to be mainly maintained, and from those existing points for inspection and test.
- *Modularity*: device design in separated parts, functional assembly units, thus, it is not necessary to disassemble the whole equipment in case of failure, but only the part(s) where the problem is located.
- *Tribology*: right use of materials with appropriated quality in order to increase the use life of fragile elements, and to improve the lubrication of pieces wearing out quickly.
- *Standardization*: spare parts compatibility to other similar materials when it is necessary to replace a device component. This attribute is conditioned by the standards choice during the design of elements like bearings, gaskets, etc. and their dimensional and functional tolerances.
- *Failure watch*: indications in the device about critical parameters and alarms to foresee failures.
- *Accessibility*: schedule for accesses to all those elements to be maintained through gates, sliding doors, etc.
- *Assembly/disassembly*: easiness to remove or replace elements in the different subsystems. This easiness shall be emphasized by gaskets, joints, welding, etc. influencing also the elements size and volume.

4.2. Attributes related to the maintenance staff and work conditions

Inside this group, we consider three attributes:

- *Ergonomics*: space requirements in order to set up the proper working conditions for the development of maintenance activities. This attribute also assesses requirements in locations and spaces where materials to manipulate can be placed when it is necessary to perform interventions on the physical system.
- *Training*: skill required in the maintenance staff for the kind of work to perform.
- *Environment*: requirements on the environmental conditions are referred in order to enable the maintenance under proper conditions and complete safety.

4.3. Attributes related to the necessity of logistics support

Inside this group, we consider five attributes:

- *Relation with the manufacturer*: requirements related to the coordination among the people responsible for the plant maintenance and the manufacturer: common language, same system for machines management, geographical remoteness, same working hours, same jurisdiction, etc.
- *Personnel organization*: amount of people required to carry out the maintenance operation and possibilities of dividing the work into parallel tasks.
- *Spare parts*: requirements in terms of spare parts for their use in the maintenance activity where the acquisition easiness shall be observed.
- *Maintenance tools and equipments*: requirements in terms of tools and instruments for performing the maintenance activity. Functionality, ergonomics as well as the acquisition easiness will be observed.
- *Interdepartmental coordination*: complexity in the task environment: requirements for handling of hazardous parts or elements, for the permit application, for the communication among different departments, etc.
- *Documentation*: indications given by the manufacturer for the device maintenance or prepared for the maintenance service, explaining how to perform the maintenance action.

5. Maintainability attributes and maintenance level

The 17 attributes commented in the paragraph above, are grouped into two sets, according to Section 4. The first group concerns those attributes, which influence the device maintainability at any maintenance levels (General attributes), that is, a type of maintainability, which is independent of the maintenance level. The second group of attributes could influence the device maintainability in a different way and degree, deepening on the level of maintenance, which is being considered (Specific attributes).

5.1. General attributes and their assessment

They are considered eight general attributes, which are maintenance level independent. The general attributes are simplicity, identification, modularity, tribology, ergonomics, standardization, failure watch and relationship with the manufacturer. For their assessment, the expert will consider each one of them independently. The result of their assessment is an integer number within the range from "0" to "4". Hereafter some examples are presented as follows:

G1. *Simplicity*: the use of a minimal amount of components and assemblies in the devices will be checked, even those components that are redundant.

- 0: Very high number of components with redundant elements, easily visible.
- 4: Optimized, reduced and without redundancy number of components.

G2. *Identification*: the identification of elements to be maintained and the points for testing will be checked, considering whether they are clearly indicated or not. It will be also observed that connectors are identified as well as danger areas, places where technicians have to position themselves for working, etc.

- 0: No identification
- 4: Complete identification, everything can be seen in front of the device

G6. *Standardization*: for those components, which could be replaced at any moment during their life cycle, their compatibility with other ones out of the shelves of the market are checked out. It will result in a minimum storage of components, and minimum amount of adjustments.

- 0: Very bad standardization. High difficulty to find a spare part in the market. High need of spare parts storage.
- 4: Good standardization. High easiness to find spare parts in the market and with competitive prices. There is no need to store spare parts.

5.2. Specific attributes (maintenance level dependents) and their assessment

These attributes will be applied in the place where the device maintenance is performed (which can be different from its usual location), especially in the case of the last two maintenance levels. We consider nine maintainability attributes, such as accessibility, assembly/disassembly, training, personnel organization, environment, spare parts, maintenance tools and equipments, interdepartmental co-ordination and documentation. These attributes should be assessed by an expert, at each maintenance level, by assigning an integer number, ranging from "0" to "4". Hereafter, there are two of those attributes, as examples (see Table 1 with S1: Accessibility and S2: Assembly/Disassembly).

There are similar tables for other seven specific attributes (they are nine in total)

Table 1
Accessibility (S1) and Assembly/disassembly (S2).

Level	Watching this attribute will have as a target	Assessment scale
S1. Accessibility		
1	Checking the proper access for first maintenance level tasks, for instance basic inspections, consumable changes (lubricants), etc.	In the range (0–4) where 0: Very difficult access, it is needed to move things and the technician himself, etc. 4: Very good access
2	Checking the proper access for second maintenance level tasks, easy repairs by replacement of functional elements, etc.	
3	Checking the proper access for third maintenance level tasks, for instance on the diagnosis and finding out of failures causes in the device, or the replacement or repair of minor components.	
4	Checking the proper access for forth maintenance level tasks, which involve important revisions on the device, test performances, etc.	
5	Checking the proper access in order to perform reconstructions, updating or overhauls in the device.	
S2. Assembly/disassembly		
1 2 3 4 5	Checking the easiness for the assembly/disassembly (open, close, connect, disconnect, adjust, etc.) of those subsystems or elements, which are involved in the device first maintenance level tasks.	In the range (0–4) where 0: Many difficulties: many tools are needed. Material weight, volume and size are too important. 4: Very easy to assemble and disassemble.

6. Maintainability indicators assessment

In order to apply this methodology, it is required to calculate six indicators, based on the value of the attributes assessed at general level and at each maintenance level

- One *general maintainability indicator* (GMI), which results from the device general attributes assessment.
- Five *specific maintainability indicators*, one for each maintenance level, named "maintainability indicator of maintenance level *i*" (where "*i*" takes the integer value from 1 to 5) or LMI*i*, as a result of assessing the specific attributes of the device.

6.1. Discussion and justification of the indicators set

The maintainability degree of an industrial asset can be understood by studying the scores obtained for each one of the eight general attributes and for those of the nine specific attributes (per maintenance level, i.e. 45 values considering five possible levels). However it is obvious that such an amount of information is not practical to be managed (especially for comparison purposes). Moreover, the relevance of the different attributes could not be the same, for a device in particular. Additionally, an attribute could be very important for a device in a certain operating conditions while the same attribute could be negligible for the asset in a different operating condition, or for a different asset in the same conditions.

For the first reasons (the big amount of heterogeneous information concerning the maintainability of an asset), it would be convenient to aggregate all this information in a few indicators, leaving the whole attributes information for an in-depth analysis. For the second consideration (the different importance of the attributes, depending on the kind of asset and/or its operating conditions), it is recommended to assess also the relevance of each attribute. That means that we have to consider two figures for each attribute (the score for each attribute and the attribute relative importance within the set of attributes), instead of only one (the score of the attribute), as it has been considered until now. But this consideration drives to a new problem: to assess the relative importance for each attribute. Note that the complexity related to the large amount of information to deal with the maintainability performance results now even increased when considering the relative importance of each attribute.

For all previous reasons, the aggregation of the information becomes an absolute need, and in order to carry out such aggregation, in each case, the maintainability indicators are obtained by the weighted average of the values achieved in the attributes assessment.

Let consider that

$$p_{Ai} = \{0,1\} \text{ with } \sum_{i=1}^{n} p_{Ai} = 1$$

where p_{Ai} is the relative weight of attribute A_i. The treatment is similar for general attributes (G_i), as well as for specific ones (S_i) concerning a maintenance level; i the ordinal number of each attribute, n the number of attributes, which configure the indicator under calculation ($n=8$ for the general maintainability indicator, based on the eight general attributes; $n=9$ for any of the maintainability indicators of any maintenance level, based on the nine specific attributes).

To determine the contribution of each attribute to the maintainability indicator, we propone the following procedure:

- To estimate $P_{Ai}=\{0,4\}$: the importance of each attribute for the maintainability calculation. The expert who is assessing the maintainability should answer how important each attribute (general or specific for a maintenance level) is, concerning the maintenance of the device under evaluation, in its operation conditions (notice that this P_{Ai} is different from $p_{Ai,}$ which is a value between 0 and 1).
- The weight of each attribute (relative importance of each attribute within the set of them) will be

$$p_{Ai} = P_{Ai} \Big/ \sum_{i=1}^{n} P_{Ai} \quad (1)$$

6.2. General maintainability indicator

It is defined as follows:

$$GMI = \sum_{i=1}^{8} G_i p_{Gi} \quad (2)$$

where i is the ordinal number of each of the eight maintainability general attributes; G_i the integer value in the range from 0 to 4, for each of the eight maintainability general attributes; p_{Gi} the decimal value in the range from 0 to 1, weight of each of the eight maintainability general attributes. These weights have been previously calculated (Formula (1)) from the importance of the attributes for the maintainability performance.

6.3. Maintainability indicator of maintenance level j

It is defined as follows:

$$LMI_j = \sum_{i=1}^{9} S_{ij} ps_{ij} \quad \text{with } j = 1\ldots5 \quad (3)$$

where j is the ordinal number of each of the five maintenance levels; i the ordinal number of each of the nine maintainability specific attributes; S_{ij} the integer value in the range from 0 to 4, for each of the nine maintainability specific attributes, for each of the five maintenance levels; p_{Vij} the decimal value within the

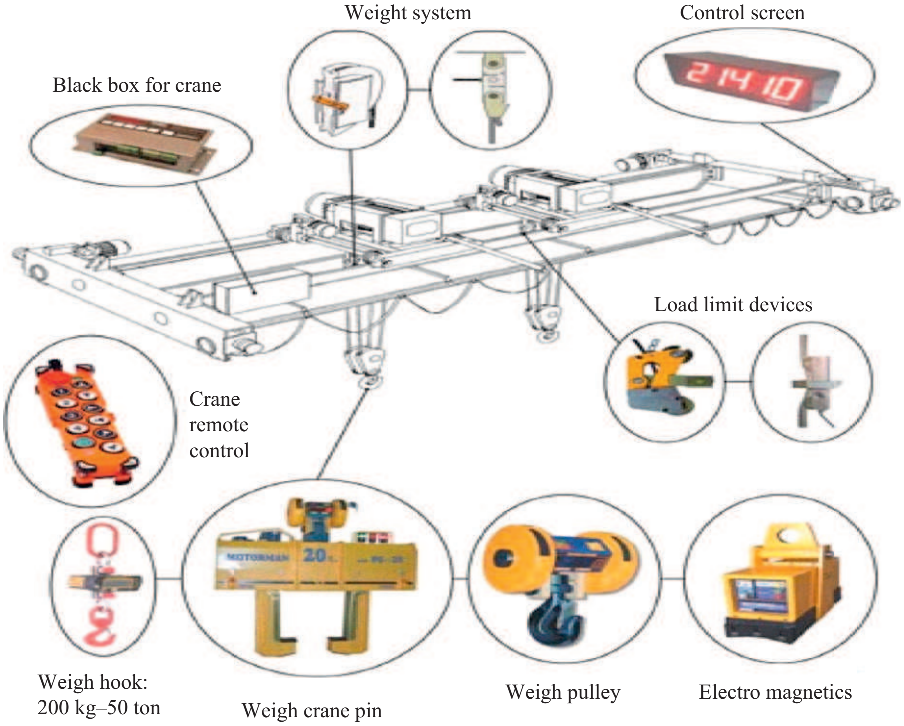

Fig. 1. Bridge crane components.

range from 0 to 1, weight of each of the nine maintainability specific attributes, for each of the five maintenance levels. These weights have been previously calculated (Formula (1)), in a similar way to what we did for the case of GMI.

7. Case study

Here, we present a case of practical application for characterization of maintainability indicators in a bridge crane (see Fig. 1), which is a traveling overhead hoisting machine that spans fixed side rails that are part of a building structure. The hoisting unit also travels laterally between the rails used to handle materials in such a manufacturing plant.

For the evaluation of maintainability indicators, we have taken into account the general attributes and the specific attributes. However, in this case study, we have considered the same importance for all the attributes (P_{G1} to $P_{G8}=1$ and P_{S1} to $P_{S9}=1$; consequently the weights are the same for all the general attributes and for all specific ones). The indicators in this case are the corresponding average of the attributes figures (as an example, Table 2 shows the general attributes and Table 3 the maintainability indicator for maintenance levels 1–5). After the tables, a graphical representation illustrates the maintainability indicators (see Figs. 2 and 3).

As a brief discussion of results, we can point out that the general maintainability indicator and those indicators for the three first maintenance levels are over the two third parts of the maximum possible indicator level (71% for the general indicator, and 72.25%, 77.75% and 66.75% for the three first maintenance levels maintainability indicators). Only for those more complex maintenance operations, big complex general maintenance operations and overhauls, the maintainability goes down to 64% and 52.75%. To understand the reasons for those figures, the attributes could be analyzed. As an example, concerning the maintenance levels 4 and 5, those indicators with values lower than 3 (i.e., those ones very badly scored) should be specially followed up. They are summarized in Tables 4 and 5.

8. Conclusions

The objective of this paper has been to define a calculation method for a set of indicators, which assesses the maintainability of industrial devices. The purpose of this assessment can be the comparison of devices according to established criteria,

Table 2
General maintainability indicator.

Code	Attribute	Criteria	Scale (0–4)	Value
General attributes				
G1	Simplicity	The use of a minimal amount of components and assemblies in the devices will be checked, even those components that are redundant.	0: very high number of components with redundant elements, easily visible. 4: Optimized, reduced and without redundancy number of components.	3
G2	Identification	The identification of elements to be maintained and the locations for testing will be checked. It will be also observed that connectors are identified as well as danger areas, places where technicians have to position themselves for working, etc.	0: No identification. 4: Perfect equipment identification.	2
G3	Modularity	It will be checked if there are different functional assembly units in the device, which allow to minimize the parts of the device to be touched in case of maintenance operations.	0: The change of units is complex and requires the movement of other units. 4: Excellent modularization.	3
G4	Tribology	Appropriate choice of device materials that are subjected to friction, lubrication and wear will be checked, with the aim of maximizing their life.	0: 0–10% of properly selected items. 4: 80–100% of properly selected items.	1
G5	Ergonomics	It will be checked how easy it is the development of maintenance tasks, analyzing the weight, size and shape of components to be handled. Those areas allocated for the task completion will be also reviewed, checking their suitability in terms of lighting, volume, etc.	0: Maintenance tasks with complex implementation. Weight, size and shape of the elements to manipulate extremely uncomfortable causing fatigue to the operator. Inadequate working space. 4: Excellent ergonomics of the device, maintenance is very comfortable and agile.	3
G6	Standardization	It will be checked the components compatibility to be replaced with others found in the market. It will result in a minimum storage of components, and minimum amount of adjustments especially in elements to replace at low maintenance levels.	0: Poor standardization. High difficulty to find spare parts on the market. High need for storage of spare parts. 4: Good standardization. Very easy to find spare parts on the market at competitive prices. It is not necessary to store spare parts.	3
G7	Failure watch	The existence of failures indicators on the device will be checked, as well as the possibility of monitoring parameters useful for maintenance.	0: Poor failure watch and diagnosis. There are not indicators of the condition of equipment and is impossible to make any diagnosis on its condition. 4: Good failure watch and diagnosis. There are indicators to know the status of the device and indicators are easily monitored in the device.	4
G8	Relation with the manufacturer	The coordination necessity will be checked for the development of maintenance activities, as well as those requirements on communications and management, which are in common to other parts.	0: Poor coordination. The maintenance worker is far, use different languages, etc. 4: Good coordination. The maintenance worker is near, use the same language, there are no communication problems, use standard communication technologies, etc.	4
			General maintainability indicator	**2.875**

Table 3
Maintainability indicators for maintenance level 1 to 5.

COD.	Attribute	Criteria	Scale (0–4)	VALUE at mainten. level 1	2	3	4	5
Specific attributes								
S1	Accessibility	– Hinges – Doors – Removable shelves	0: very difficult access 1: Quite difficult access 2: Difficult access 3: Normal access 4: Very good access	3	3	2	2	1
S2	Assembly/disassembly	– Lock – Welding – Joints – Connections – Edge connectors	0: Many difficulties 1: Quite a lot of difficulties 2: Some difficulties 3: Good manipulation 4: Very good manipulation	4	2	2	2	2
S3	Training	– Presence of people trained according to work type – Operators training	0: Very bad 1: Bad 2: Somewhat bad 3: Regular 4: Good	1	4	4	3	3
S4	Personnel organization	– Amount of people per maintenance operation – Active preventive maintenance time – Logistic cost	0: 5/6 people, no coordination 1: 4/5 people 2: 3/4 people 3: 2/3 people 4: 1 person	3	3	3	3	2
S5	Environment	– Isolation – Leak detection system – Presence of high voltage cables	0: Very dangerous 1: Dangerous 2: Somewhat dangerous 3: Safety 4: Very safety	3	3	3	3	3
S6	Spare parts	Requirements concerning their storing and handling, concerning tasks of maintenance level 1.	0: Many different spare parts in stock and difficult for handling 4: Few number of spare parts in stock and very easy for handling	4	4	4	4	4
S7	Maintenance tools and equipments	– Components and tools with weight and volume that allow an easily use – Standard components and tools	0: Many strange things 1: Many things 2: Quite a lot of things 3: Few things 4: Very few things	3	4	3	2	1
S8	Inter-departmental co-ordination	– Possibility of performing simultaneous maintenance tasks – Permission to perform operations	0: Very complicated 1: Complicated 2: A bit complicated 3: Regular 4: Very well organized	3	3	3	2	1
S9	Documentation	– Appropriate manuals for maintenance and procedures instructions	0: No documentation 1: Incomplete 2: Complete but difficult 3: Regular 4: Very good	2	2	2	2	2
			Maintainability indicators for maintenance levels 1–5	**2.89**	**3.11**	**2.67**	**2.56**	**2.11**

the design improvement regarding maintainability requirements or, simply, the maintenance improvement in a specific item.

In order to describe the maintainability indicators, maintainability attributes have been defined and classified, first of all, according to its general and specific scope (in relation to the maintenance level). Maintenance levels refer to the complexity of the maintenance tasks, which are performed at an indenture level. The attributes ranking is performed with a 0 to 4 scale, in order to reduce subjectivity and to obtain reasonable values, easy to be manipulated. Once defined the maintenance level of the item, each attribute is assessed, making a weighted average for each maintenance level.

The method allows considering different importance factors for each of the attributes, according to the characteristics of the item or its operation. In such cases, the evaluator should also assess that factor in order to estimate the weighted average. Consequently, they are six measures obtained, one for the general indicator and five for each maintenance level maintainability indicator.

Results for each indicator can be presented in a table containing the assigned value for each attribute, the remarks of the

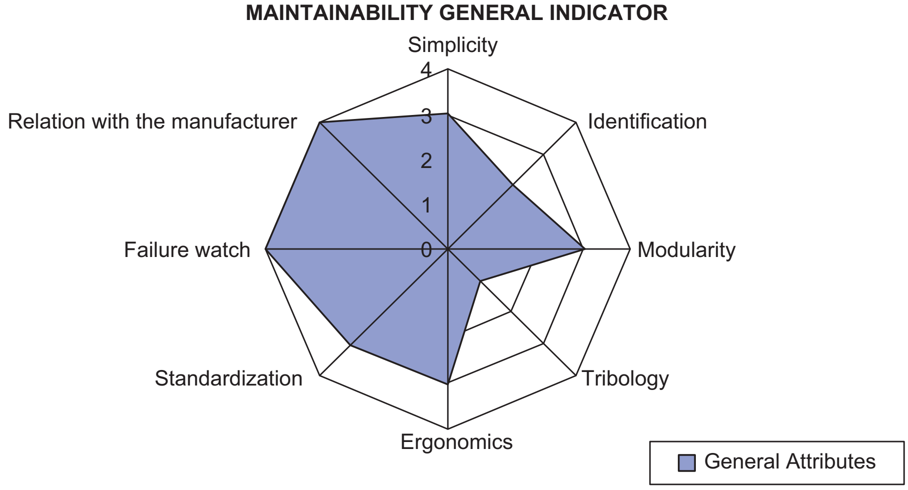

Fig. 2. Graphical representation of general maintainability indicator.

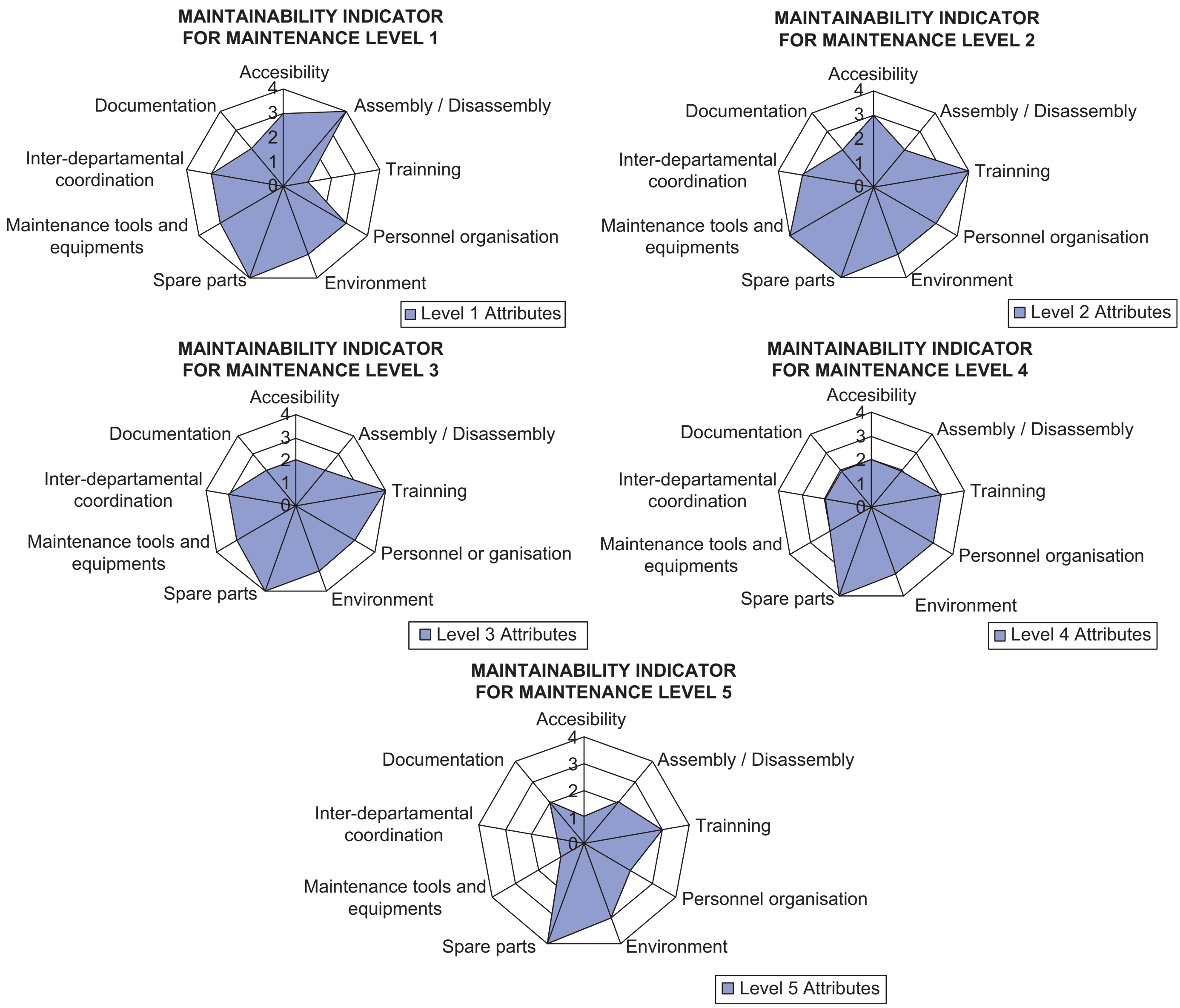

Fig. 3. Graphical representation of maintainability indicators.

Table 4
Poorly scored indicators from Maintenance Level 4.

Code	Attribute	Value	Comments
S1	Accesibility	2	There is a difficult access to the area where the maintenance tasks are carried out.
S2	Assembly/disassembly	2	The manipulation of components and subcomponents presents some difficulties.
S7	Maintenance tools and equipments	2	In order to proceed with the maintenance task, several tools and equipment are needed.
S8	Inter-departmental co-ordination	2	Permission and coordination to perform operations and maintenance tasks are a bit complicated
S9	Documentation	2	Technical manuals are complete but difficult to deal with.

Table 5
Poorly scored indicators from Maintenance Level 5.

Code	Attribute	Value	Comments
S1	Accesibility	1	There is a quite difficult access to the area where the maintenance tasks are carried out.
S2	Assembly/disassembly	2	The manipulation of components and subcomponents presents some difficulties.
S4	Personnel organization	2	The maintenance task requires 3/4 people for its performance.
S7	Maintenance tools and equipments	1	In order to proceed with the maintenance task, quite a lot of tools and equipment are needed.
S8	Inter-departmental co-ordination	1	Permission and coordination to perform operations and maintenance tasks are really complicated.
S9	Documentation	2	Technical manuals are complete but difficult to deal with.

assessment staff and the value for the maintainability indicator. It is also very useful to represent all these results in a graphical way (radar-graphic), with the measurement for each level of maintenance.

This simple process may help us to improve maintainability along the different stages of an item life cycle.

Finally, the application of this method in a case study has shown how important is, for instance, the training of the person who performs the assessment. In fact, the indicator definition is quite simple and applicable to any device. Nevertheless, it requires an adaptation and interpretation of attributes, as well as those maintenance levels in agreement with each item peculiarities.

Further research on this interesting field can be addressed, for instance, to the application of this practical method, not just for industrial devices but also to products already released into the market. In this context, the intervention of the after sales department as well as the experience of the warranty technicians will be crucial for the maintainability assessment. In addition to this, and in a similar way to the concept of maintainability, it is possible to redefine that indicator to a certain specific warranty case study.

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