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Selection of computerized maintenance management systems to meet organizations' needs using AHP

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Abstract

Due to the complexity of modern industrial plants introduced by Industry 4.0, it has become increasingly difficult to manage physical assets maintenance without the support of a specialized information system, often referred to as Computerized Maintenance Management System (CMMS). CMMS implementation brings several benefits such as cost reduction, increased productivity and better planning and scheduling. Nevertheless, selecting the most suitable one is not an easy task due to the large amount of CMMS available in the market. This paper presents a multicriteria decision-making method based on Analytical Hierarchy Process (AHP) applied for comparative evaluation of different CMMS alternatives. This method allows the evaluation of CMMS quality level based on a set of functional and non-functional features defined according to ISO/IEC 25010:2011 and distributed into a hierarchical structure of 5 criteria and 16 sub-criteria. This study shows the application of the proposed method in a synthetic foam production company, where it allowed a detailed comparison of three possible CMMS candidates and the selection of the most appropriate according to this organization' specific needs and requirements. It was observed that the differences in the global quality levels of the three CMMS alternatives were practically unnoticeable, requiring a cost-benefit analysis to complete the decision process. The method proposed has shown to be easily applied in an industrial context, leading to a reduction of the probability of failure often faced by organizations at the time of CMMS implementation.

Keywords: Maintenance management; CMMS; AHP

1. Introduction

Modern industry has increased the automation level of industrial processes, where maintenance management is considered a key element to achieve higher levels of productivity, increase safety and reduce costs. To manage efficiently the amount of data and resources related to maintenance, a Computerized Maintenance Management System (CMMS) is needed.

A CMMS is a tool to support maintenance management based on an integrated database set to schedule and follow maintenance activities and monitor maintenance objectives [1,2]. Accordingly, Lopes *et al.* [3] state that a CMMS supports maintenance strategy based on an information system (IS) and a set of functionalities that produces relevant data to decision making by processing performance indicators.

Besides minor differences among authors, the key functionalities of a CMMS include [2-6]:

- Assets management: definition, management and recording all assets information, including technical features, localization, parts list and historical records of maintenance activities;
- Work orders management: allows setting and releasing work orders to maintenance technicians triggered by repairs requests or according to the preventive maintenance plan. It

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includes the monitoring of maintenance activities (e.g., approved, on hold, ongoing, completed);
- Preventive maintenance management: supports planning, scheduling and control of preventive maintenance activities;
- Inventory control: consists of stocks management of materials used in maintenance activities, including spare parts. This involves setting minimum stocks, monitoring current stock levels and managing the inputs and outputs of the inventory;
- Report management and performance indicators: data processing and production of performance indicators and reports.

The ability of a CMMS to manage large amounts of data in real time has allowed the development of new and more flexible approaches to manage physical assets [7]. The benefits of CMMS implementation are evidenced in many studies. Cato and Mobley [2] showed that in US and Canadian industries the productivity of the maintenance sector increased from about 35% to 70 – 80% and inventory costs were reduced by 5 to 12% after CMMS implementation. Another study from O'Donoghue and Prendergast [4] demonstrated that after 7 months of CMMS implementation in a textile company, it was possible to reduce spare parts costs, improve equipment availability, reduce lead times and reduce unscheduled maintenance activities, with a return on investment period of only 0,46 years.

Although the role of a CMMS as a critical tool to support maintenance management, Wienker *et al.* [8] report that the successful implementation rate of these systems is surprisingly low, between 25 to 40% and only 6 to 15% of all users get the most of its full capability. Evans [9] showed that the failure rates of CMMS implementation can be as high as 70% and O'Hanlon [5] reported in 2004 that 57% of recent survey results showed that the CMMS implementation failed to generate the return on investment.

According to Cato and Mobley [2] and Wienker *et al.* [8], there can be several reasons why a CMMS does not meet users' expectations, e.g., the lack of effort and preparation in the CMMS selection process, the failure to sell the benefits to the top management and the lack of training about how to operate the system. Carnero and Novés [1] argue that the unsuccessful implementation of a CMMS can be justified by its incorrect selection and due to the lack of suitable projects to set up and control it.

Therefore, a good CMMS selection appears to be a crucial task to avoid an implementation where the expected profits are not reached. Hence, it is necessary to truly invest in the CMMS selection process to obtain the intended return on investment. Since the most suitable CMMS depends on the organizational context, each organization should identify the Information Technology (IT) requirements for maintenance management before selecting the most appropriated CMMS according to their needs. After that, a market analysis can be done to search for possible CMMS candidates that match the previously identified requirements. However, there is a large number of CMMS available in the market, which is one of the main reasons why decision making in the field of CMMS selection has become more complex. Some techniques and approaches can help selecting the most suitable CMMS. One of the most promising is Analytic Hierarchy Process (AHP), a multi-criteria decision-making technique that has been applied to the software selection problem in many studies [1,10–14]. This technique was also widely used in other fields of study for selecting the best approach to achieve a certain goal, e.g., the selection of the most efficient maintenance approaches and practices in a specific context [15-17].

Some studies have used AHP for CMMS selection [1,13,14]. Carnero and Novés [1] and Braglia *et al.* [13] have proposed a method in which the hierarchical structure for AHP application includes the cost as a criterion (purchasing cost, set up/implementation cost, maintenance/updating cost). Although the cost influences the CMMS selection process, it is not truly a criterion to evaluate the quality of a software. A CMMS with a greatest performance can justify a higher cost. By considering the cost as a criterion, the results obtained for each CMMS alternative can be skewed because the CMMS with the best set of requirements can be the most expensive one and, in that case, there is a risk of not being selected.

In the present study, the method applied evaluates the CMMS quality based on the functional and non-functional features, according to ISO/IEC 25010:2011 (software quality requirements and evaluation) [18]. Based on the results of the CMMS quality levels obtained by applying AHP, the company can decide if the investment is worth it or not, based on a cost-benefit analysis.

Finally, Durán [14] proposed a fuzzy-AHP methodology for CMMS selection. Besides the advantages of this method to deal with ambiguities in the assessment process, AHP with fuzzy numbers requires many time-consuming calculations, which gets worst as the number of sub-criteria increases, as mentioned by the authors. To be able to apply it, a software was used. For these reasons, this method is not easy to apply.

In addition, none of these studies considered the portability of the CMMS to mobile devices as a sub-criterion. Since the use of information systems from mobile devices is getting increasingly important, this factor should be considered.

This study aims to provide a method to select the most suitable CMMS to meet organizations' needs using AHP. This method is based on a hierarchical structure with few criteria and sub-criteria that cover all the relevant quality characteristics of a CMMS to be considered in the selection process, in order to provide a method that can be easily applied by any organization. To this end, this paper starts with a briefly description of AHP technique. Then, the application of the proposed method in a synthetic foam production company is described, where it has shown its potential for CMMS selection. Finally, a conclusion is included to resume the main results of this study.

2. AHP technique

The AHP technique developed by Saaty [19] is a multi-criteria decision-making technique to deal with complex problems, considering multiple criteria and multiple contributions [14] and that handles both qualitative and quantitative data [13,14]. This technique allows decision-makers to deploy a complex problem by organizing its critical aspects into a hierarchical structure. A complex decision is then reduced to a series of pairwise comparisons and rankings that allow to select the optimal solution [13].

The application of AHP is performed according to the steps described below [13,14,19-21].

2.1. Construction of a hierarchical structure

The first step consists of identifying the main goal, i.e., the problem to be solved. In the context of this study, the main goal is selecting the most suitable CMMS.

Next, the decision criteria for the problem to be solved is defined in a hierarchical structure composed of different levels, from the highest level (i.e., the main goal), to the intermediate levels (i.e., the criteria and sub-criteria) and, finally, to the lowest level (i.e., the alternatives to be compared).

2.2. Weight the criteria, sub-criteria and alternatives

The criteria, sub-criteria and the alternatives must be ranked by their relative importance in relation to the element within the higher level (i.e., rank the criteria in relation to the main goal, rank the sub-criteria in relation to the associated criteria and then rank the alternatives in relation to each sub-criteria).

To do so, AHP uses pairwise comparisons so it focuses only on two factors at a time. The comparisons are done through judgment matrixes according to a numeric scale where each score corresponds to the qualitative decision maker's opinion of the relative importance of one factor (criteria/sub-criteria/alternative) over another. The numeric scale originally proposed by Saaty [19] is shown in Table 1.

Table 1. Saaty's scale used in AHP.

Relative importance	Definition
Equal importance	1
Weakly better	3
Better	5
Strongly better	7
Absolutely better	9

Once the judgment matrixes are defined, it is necessary to determine the priority vectors, which represent the weight of each matrix element. The priority vector is obtained by the normalized eigenvector of the matrix according to algebraic foundations [19].

To evaluate the consistency of the judgments of pairwise comparisons, a consistency ratio (CR) is calculated by diving the consistency index (CI) of an $n \ x \ n$ matrix by the corresponding random consistency index (RI) created by Saaty [19], according to the following equation:

$$CR = \frac{CI}{RI}$$

The CI can be computed as follows, where λ_{max} is the maximum eigenvalue of the matrix:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

The RI created by Saaty [19] can be obtained from Table 2.

Table 2. RI values for each matrix order.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49

The judgments are considered consistent if CR ≤ 0,1 (10%). In cases of inconsistency, the pairwise comparisons for the inconsistent matrix should be repeated until reasonable values are obtained.

2.3. Select the optimal alternative

The last step of AHP consists of selecting the most appropriate alternative. For that purpose, the global priority values should be calculated for each alternative, by the sum of the products of each sub-criterion's weight (i.e., their relative importance) and the respective weight of each alternative in that sub-criterion.

The alternative with the highest global priority value is the one who best responds to the main goal and that should be selected.

3. Selecting a CMMS using AHP

3.1. Hierarchical structure and evaluation criteria

The hierarchical structure proposed for selecting the most suitable CMMS (Fig. 1) was constructed considering functional and non-functional features intended for a CMMS. These features were expressed by the set of criteria and sub-criteria disposed in the hierarchical structure, that were in turn defined according to the guidelines of ISO/IEC 25010:2011 [18] (software quality requirements and evaluation).

The structure has 4 hierarchical levels, with 5 criteria and 16 sub-criteria where the first level corresponds to the main goal, i.e., the selection of the most suitable CMMS, the second level to the criteria, the third level to the sub-criteria and the fourth level to the alternatives of CMMS to be compared.

Performance

This criterion considers the intrinsic characteristics of a CMMS that enable its good performance. Thus, one of the associated sub-criterion is functional fitness, defined as the degree to which the system functions meet implicit and expressed needs when used under specified conditions [18].

The modules' availability sub-criterion aims to determine the number of modules available and their interconnection and completeness by the degree to which the set of functions arrived from their integrated operation can cover all the specified features.

The flexibility for in-house customization (i.e., performed by the company who owns the CMMS) emerges as another sub-criterion. It will be evaluated by the ease of customizing the CMMS to fit the specific needs of the company without requiring manufacturer's intervention and additional costs.

The updates availability sub-criterion seeks to evaluate to which extent the CMMS introduces new updates and provides new software versions aligned with the incoming demands as the state of the art of maintenance management evolves.

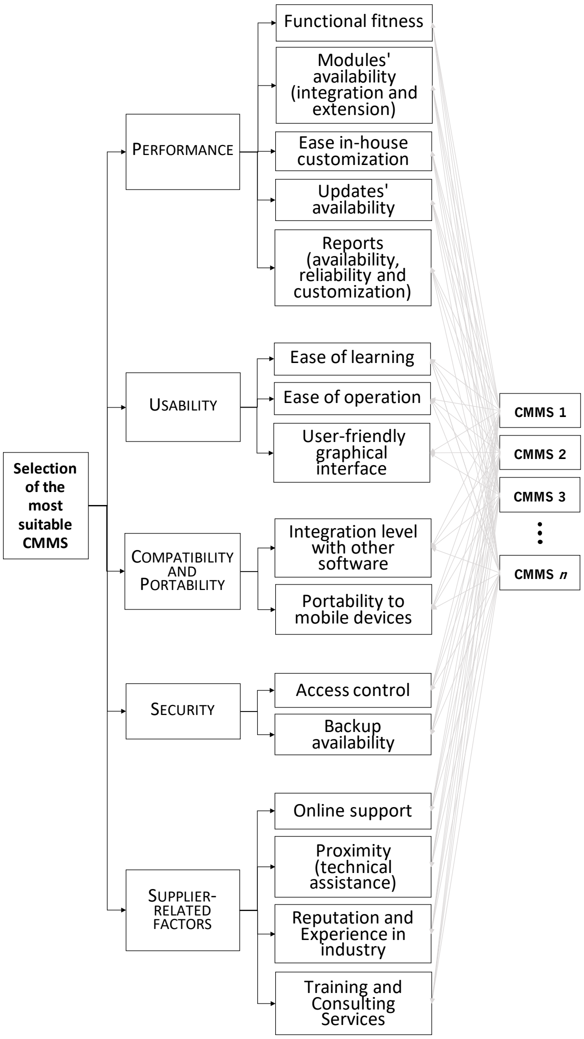

Fig. 1. Hierarchical structure for CMMS selection.

CMMS-generated reports are a way of extracting consolidated information to support decision making, so the quality of the information provided is one of the most important features of any IS, including the CMMS. The reports may include, among others, those related to performance indicators, failures history and material consumption history. Thus, another sub-criterion was introduced to evaluate the reports that can be generated as well as their reliability and flexibility for customization (e.g., ease of adding new performance indicators).

Usability

This criterion intends to analyze the usability of the CMMS, defined as the degree to which the system can be used to achieve specified goals with effectiveness, efficiency and satisfaction under a specified context of use [18]. Usability depends on the ease of learning of how to operate the system (sub-criterion) – learnability – and the ease of operation in a daily routine basis, after the initial learning process (sub-criterion) – operability [18]. Besides that, usability also depends on the system's graphical user interface (sub-criterion), evaluated by the degree to which the interface enables pleasing and satisfying interaction for the user [18].

Compatibility and Portability

This criterion aims to assess, on the one hand, the extent to which the CMMS can be integrated with other information systems (sub-criterion), e.g., the company ERP and the production management IS. It is pretended that the CMMS is able to exchange information with other IS and use the information that has been exchanged (defined as interoperability by ISO/IEC 25010:2011 [18]).

The other sub-criterion was introduced to evaluate how efficiently the system can be transferred to mobile devices and operate on them (e.g., mobile terminals, tablets), defined as the portability to mobile devices. This feature can be relevant for recording maintenance interventions, for stocks management, to monitor intervention status in real time or others, as preferentially this is achieved via mobile devices.

Security

This criterion aims to determine whether the CMMS ensures compliance with the necessary security conditions, regarding the access control (e.g., the extent of the access to different modules may differ between users, as the permission for editing information) as well as the backups' availability that will prevent to lose data in case an interruption or failure affects the CMMS.

Supplier-related factors

The supplier-related factors must also be considered when selecting a CMMS. It is pretended to evaluate if the service provided by the supplier includes remote assistance/online support services (sub-criterion) as well as the quality and extent of these services.

It is also intended to determine the proximity of sites that provide technical assistance (sub-criterion). In case an event cannot be remotely solved, the geographical location of these sites can be a constraint with respect to possible delays and additional charges.

The supplier's reputation and experience in industry is another sub-criterion. These factors increase the confidence in the supplier as they can be possible indicators of the successful CMMS commercialization and associated quality. A supplier with high industrial experience will produce a CMMS better suited to the actual market needs and requirements.

The availability of training and consulting services are relevant to assist the company in CMMS installation and further training in its operation, so that users can get the most of the functionalities available, avoiding the risk of an incipient implementation that does not allow to perceive the expected benefits. These services are also relevant to help users when new upgrades and versions are introduced.

3.2. Selection of the alternatives to be compared

The hierarchical structure previously described was applied in a synthetic foam production company located in Portugal, to help in the selection of the CMMS who better fits this organization's specific needs.

This company had a maintenance management information system that was not efficient as the registration process was too time-consuming and the reliability of data collected to compute performance indicators was questionable.

Since all organizations have different functional requirements for an information system, the first step was to identify the expected requirements that the company wanted for the CMMS to be implemented.

Table 3 shows the functional requirements pretended for the CMMS in comparison to the requirements of the information system that the company had before.

Based on the requirements identified for the future information system (i.e., the CMMS to be implemented), it was conducted a market analysis from which possible candidates of CMMS emerged.

A total of 10 CMMS were analyzed, based on their specification manuals, websites, white papers and by contacting the suppliers via email and phone.

The portability to mobile devices is considered a critical and imperative feature for this company, so it was used as an elimination factor. The systems that did not have this feature were automatically discarded (5 CMMS discarded). Of the remaining 5 CMMS, two were excluded because they could not be integrated with other information systems than those provided by the same supplier. Besides that, the suppliers of these two systems were not very helpful in providing additional information nor responding to requests, which has put them in discredit in relation to customer service.

Thus, the 3 most promising CMMS remained to be compared by AHP technique, in order to select the most suitable one for this company. The 3 alternatives to be compared will be from now referred to as CMMS 1, CMMS 2 and CMMS 3.

3.3. Relative importance of criteria and sub-criteria

The hierarchical structure for CMMS selection (Fig. 1) can be transversely applied to any organization. What will differ between organizations are the weights attributed to each criterion and sub-criterion depending on what matters most for each organization.

Accordingly, to be able to apply the AHP technique in the company under study in this work, it is necessary to weight the criteria and sub-criteria from the perspective of this company. So, the criteria and sub-criteria have been classified by the two maintenance managers of this company with the guidance of a maintenance management specialist to ensure the quality and consistence of the judgments.

The question to ask when classifying two criteria is "Of these two criteria, which one is considered most important by the user in relation to the main goal of selecting the most suitable CMMS?". The relative importance of the criteria and sub-criteria was classified by Saaty's scale (Table 1).

Table 3. Pretended functional requirement for the CMMS.

Current information system	Future information system
PREVENTIVE MAINTENANCE MANAGEMENT	
Planning is done by a list of interventions to be carried out; Scheduling is not integrated (weekly schedule in an Excel sheet)	Planning and scheduling integrated through a Gantt Chart
The intervention status (scheduled, ongoing, completed) cannot be monitored in real time	Real-time monitoring of intervention status by recording them directly in the IS via mobile devices
ASSETS MANAGEMENT	
Equipment record does not include all the necessary information (internal code, manufacturer, year of acquisition, spare parts). This information is available in the equipment technical file (physical format).	Equipment record with all the relevant information by the equipment technical file (or equivalent) predefined by the IS
Historical record of failures does not allow an overview of all the failures that occurred within a specific time frame. It is only possible to visualize each failure event one by one.	Historical record of failures by equipment, by sector, by type of failure or others, expressing its description by a set of symptom, cause, subsystem and component.
There is no integrated methodology or tool for systematic analysis of failure modes (actual ones or potential). The FMEA methodology is applied through a complementary Excel sheet.	Equipment tree structure for the record of failure modes (system, subsystem and component); FMEA methodology integrated in the IS.
WORK ORDERS MANAGEMENT	
It is not able to automatically select the technicians according to the type of intervention or failure (the interventions assignment is done manually by the maintenance responsible in an Excel sheet)	Automatic assignment of the working orders to the technicians, according to their availability and technical skills (e.g., through skill matrix analysis).
The interventions are not directly recorded in the IS by the technicians	Interventions recorded directly in the IS by the technicians (via mobile devices)
INVENTORY CONTROL	
The indicated quantities of materials available in stock are out of date (requests are not directly recorded in the IS due to its practical inconvenience)	Real-time monitoring of current quantities available in stock (requests directly recorded in the IS)
Stocks management based only on professional experience. Materials are not classified according to any criteria.	Stocks management based on materials multi-criteria classification (e.g., historical consumption, criticality for the production process, price)
REPORT MANAGEMENT AND PERFORMANCE INDICATORS	
Performance indicators are not computed by the IS (but instead in a complementary Excel sheet)	Monitoring and reporting of performance indicators (technical, economic and organizational)

Once performed the pairwise comparisons for the set of criteria, the judgment matrix in Table 4 was obtained. To improve results presentation, each criterion was identified with a sequential letter by the order they appear in the hierarchical structure (Fig. 1). Thus, it should be considered the following correspondence: A – Performance; B – Usability; C – Compatibility and Portability; D – Security; E – Supplier-related factors.

Table 4. Pairwise comparisons of the criteria for CMMS selection.

Criteria	A	B	C	D	E	Priority
A	1	5	3	3	5	0,455
B	1/5	1	1/3	1/3	1	0,072
C	1/3	3	1	1	5	0,217
D	1/3	3	1	1	3	0,190
E	1/5	1	1/5	1/3	1	0,067
				CI = 0,039		CR = 3,44%

From the analysis of Table 4, it is possible to order the criteria by its relative importance in the specific context of this company: A – Performance (most important); C – Compatibility and Portability; D – Security; B – Usability and E – Supplier-related factors (less important). Since CR ≤ 10% the judgments of the matrix are considered consistent.

Then the pairwise comparisons for the sub-criteria were done. For all the judgment matrixes (presented in Appendix A), CR ≤ 10% which proves its consistency. At this point, it was possible to order the 16 sub-criteria by its relative importance (priority) in relation to the main goal, as presented in Table 5. The global priority values were obtained by multiplying the local priority values of each sub-criteria (from the respective matrix) by the priority value of the associated criteria (in Table 4).

Table 5. Sub-criteria ordered by its relative importance.

Code	Sub-criteria	Priority (global)
C.2	Portability to mobile devices	0,180
A.1	Functional fitness	0,176
A.2	Modules' availability (integration and extension)	0,176
D.1	Access control	0,095
D.2	Backup availability	0,095
B.2	Ease of operation	0,051
A.4	Updates' availability	0,042
A.5	Reports (availability, reliability and customization)	0,042
E.1	Online support	0,038
C.1	Integration level with other software	0,036
A.3	Ease in-house customization	0,019
E.4	Training and Consulting Services	0,016
B.1	Ease of learning	0,010
B.3	User-friendly graphical interface	0,010
E.2	Proximity (technical assistance)	0,009
E.3	Reputation and Experience in industry	0,004

3.4. Selection of the most suitable CMMS

The last step of AHP was to compare the alternatives (CMMS 1, CMMS 2, CMMS 3) with respect to each sub-criterion. To do so, 16 judgment matrixes *3 x 3* were constructed since there are 16 sub-criteria and 3 alternatives to be compared. The pairwise comparisons were conducted using Saaty's scale (Table 1).

The comparison between the three alternatives was supported by an extended analysis of their characteristics and technical specifications. This analysis was done through semi-structured interviews with the systems suppliers by phone and in person and by the analysis of the information provided by them via email, including specifications manuals and white-papers. Also, for CMMS 1 it was possible to test a demo version, while for CMMS 2 and CMMS 3 it was only possible to assist to a demonstration provided by the suppliers.

Again, for all the judgment matrixes CR ≤ 10% (proved consistency). The relative importance (priority) values of the three CMMS in each sub-criterion are shown in Table 6.

Table 6. Local priority values for the CMMS alternatives.

Sub-criteria	CMMS 1	CMMS 2	CMMS 3
A.1	0,260	0,633	0,106
A.2	0,455	0,091	0,455
A.3	0,643	0,283	0,074
A.4	0,053	0,474	0,474
A.5	0,633	0,106	0,260
B.1	0,600	0,200	0,200
B.2	0,748	0,180	0,071
B.3	0,283	0,643	0,074
C.1	0,200	0,600	0,200
C.2	0,143	0,143	0,714
D.1	0,260	0,633	0,106
D.2	0,067	0,467	0,467
E.1	0,455	0,091	0,455
E.2	0,071	0,180	0,748
E.3	0,633	0,260	0,106
E.4	0,429	0,143	0,429

These results allowed to verify which is the best CMMS in each sub-criterion. The higher priority value means the better is the CMMS in respect to that sub-criterion. It was observed that the three alternatives had different distinctive features. CMMS 1 is the best in Ease of operation (B.2), Ease of learning (B.1), Reports (availability, reliability and customization) (A.5), Ease in-house customization (A.3) and Reputation and Experience in industry (E.3). CMMS 2 is the best in Functional fitness (A.1), User-friendly graphical interface (B.3), Integration level with other software (C.1) and Access control (D.1.). Finally, CMMS 3 is the best in Proximity (technical assistance) (E.2) and Portability to mobile devices (C.2).

To be able to find out the most suitable CMMS for this organization, it is necessary to check which of the alternatives best satisfies the overall set of sub-criteria. For that purpose, the global priority values for each alternative were calculated. The global priority values were determined by the weight of the sub-criteria (global priority values from Table 5) and the relative importance of the CMMS in each sub-criterion (local priority from Table 6). The results are shown in Table 7.

As observed according to the previous results, although CMMS 3 is the best in only 2 of the 16 sub-criteria, it is the

CMMS that best satisfies the overall set of sub-criteria because it is the alternative with the highest value of global priority (0,359) – Table 7. However, the results for the three alternatives are very close to each other and none of the CMMS stands out clearly. Thus, it can be stated that the three CMMS have an equivalent global quality level.

Table 7. Global priority values for the CMMS alternatives.

Alternative	Priority (global)
CMMS 1	0,306
CMMS 2	0,335
CMMS 3	0,359

As the differences in the global quality levels are practically unnoticeable, the final decision for selecting the most suitable CMMS was based on a cost-benefit analysis for each CMMS. For that purpose, it was considered the cost of acquisition, customization and integration with the other information systems of the company (ERP and production management IS).

For CMMS 2, the total cost of acquisition and integration with the other company information systems is lower when compared to CMMS 1 and CMMS 3. For CMMS 1 and CMMS 3, the integrations customization (customization of the CMMS so that it can be integrated with other information systems) is seen as an extra service, where the cost is estimated according to the working hours needed and it includes the travel costs to the company. Even though the most advanced version of CMMS 2 is more expensive than the standard versions of CMMS 1 and CMMS 3, the cost of integrations customization service for this CMMS is entirely supported by the supplier if this advanced version is purchased. If the standards versions of CMMS 1 and CMMS 3 are purchased with the extra service of integrations customization with other IS, that will be translated into higher significantly costs. Given that the company intends to integrate the CMMS with their ERP and the production management IS and since it represents a significant effort, the total cost of acquisition and integration with other IS is lower when selecting the most advanced version of CMMS 2 compared to the standard versions of CMMS 1 and CMMS 3.

Besides that, CMMS 2 showed to be the most complete in terms of functionalities given the fact that it has distinctive features that CMMS 1 and CMMS 3 do not have. CMMS 2 is parametrized to include on the asset technical file the safety instructions and precautions, which is an important feature for this company as it is aligned with one of the actions that were predicted to the implemented. Moreover, and most importantly, CMMS 2 is able to read several types of labels (barcode, NFC and RFID). This is a critical feature for this organization as it wants to implement an integrated barcode-based system for recording maintenance interventions and for stocks management and control, which means that this system can be incorporated into this CMMS by taking advantage of this feature. Nevertheless, it is required to proceed to some changes on the CMMS so that it could be integrated.

For these reasons, CMMS 2 has been chosen to be implemented. Even though CMMS 2 is the most complete one in terms of functional requirements, it is important to notice that it still does not meet one of the requirements intended by the company, which is the automatic assignment of the working orders to the technicians (Table 3). To include this feature, it would be necessary to pay for the custom software development service that is not currently supported by this company. This feature is also not available in any of the standard versions of the 10 CMMS initially analyzed, showing that the commercially available CMMS should be upgraded to align properly with the current desired market needs.

4. Conclusion

In this paper, an AHP-based method for selecting the most suitable CMMS to meet organizations' needs was proposed. The resulting hierarchical structure can be applied across any organization, since the criteria and sub-criteria reflect the functional and non-functional requirements and features that must be considered when selecting a CMMS. These requirements were defined taking into account the software evaluation quality models of ISO/IEC 25010:2011.

AHP allows decision-makers to guide their opinions through an analytical system that reduces the complex decision of CMMS selection to a series of pairwise comparisons and rankings. This makes the decision-making process more consistent and helps selecting the optimal CMMS.

The proposed method was used to select the most suitable CMMS in a real industrial context, in a synthetic foam production company. The identification of the functional requirements pretended by the company allowed to select the 3 most promising CMMS to meet this organization's specific needs. These 3 CMMS were compared by AHP, encouraging to a reflection process of comparison of these alternatives in relation to a set of sub-criteria, ending with the selection of the optimal one. This structured method for CMMS selection sustained a consistent choice, which made it easier to sell the benefits to the top management of implementing the selected CMMS and hence guarantee his support.

As the global quality levels of the 3 CMMS alternatives considered by the company under study were very close to each other, a cost-benefit analysis was needed to complete the decision process. After that analysis, CMMS 2 was the selected one, even if it was not the alternative with the highest global quality level. This shows the benefit of this method for not considering the cost as a criterion, unlike other studies [1,13,14], since it allows the user to perceive the quality of a CMMS regardless of its cost, deciding only at the end if the investment is worth it or not. Thus, the assessments are made in an impartial way, i.e., the cost is not taking into account in the assessment of the CMMS alternatives, giving emphasis to the selection of the CMMS that better fits the organizations' needs.

This method can be easily applied in different industrial contexts to provide the right choice of the CMMS to be implemented and then avoid an implementation without providing the expected benefits.

The robustness of this method could be enhanced if combined with fuzzy numbers (fuzzy-AHP method) to deal with the uncertainties involved in the assessment of CMMS alternatives, criteria and sub-criteria. However, as a fuzzy-AHP method requires many mathematical and fuzzy operations, it would not be easily applied by most companies, unless they have a dedicated software that automatically proceeds to the operations needed.

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Appendix A. Sub-criteria judgment matrixes

Table 8. Pairwise comparisons for Criteria A (Performance) sub-criteria.

	A.1	A.2	A.3	A.4	A.5	**Priority (local)**	**Priority (global)**
A.1	1	1	7	5	5	0,386	0,176
A.2	1	1	7	5	5	0,386	0,176
A.3	1/7	1/7	1	1/3	1/3	0,043	0,019
A.4	1/5	1/5	3	1	1	0,092	0,042
A.5	1/5	1/5	3	1	1	0,092	0,042
						CI = 0,036	CR = 3,20 %

Table 9. Pairwise comparisons for Criteria B (Usability) sub-criteria.

	B.1	B.2	B.3	**Priority (local)**	**Priority (global)**
B.1	1	1/5	1	0,143	0,010
B.2	5	1	5	0,714	0,051
B.3	1	1/5	1	0,143	0,010
				CI = 0,000	CR = 0,00 %

Table 10. Pairwise comparisons for Criteria C (Compatibility and Portability) sub-criteria.

	C.1	C.2	**Priority (local)**	**Priority (global)**
C.1	1	1/5	0,167	0,036
C.2	5	1	0,833	0,180
			CI = NA	CR = NA

Table 11. Pairwise comparisons for Criteria D (Security) sub-criteria.

	D.1	D.2	**Priority (local)**	**Priority (global)**
D.1	1	1	0,500	0,095
D.2	1	1	0,500	0,095
			CI = NA	CR = NA

Table 12. Pairwise comparisons for Criteria E (Supplier-related factors) sub-criteria.

	E.1	E.2	E.3	E.4	**Priority (local)**	**Priority (global)**
E.1	1	1/3	3	5	0,569	0,038
E.2	3	1	7	9	0,128	0,009
E.3	1/3	1/7	1	3	0,066	0,004
E.4	1/5	1/9	1/3	1	0,237	0,016
					CI = 0,060	CR = 6,62 %