Expert System design for Fault Diagnosis in Diesel Engines

Ileana. Concho, Mary. Vergara, Francklin. Rivas-Echeverría, Fernando. Chica and Nestor. Rivera

***Abstract*—** In this work it's presented the design and development of a Diagnosis Expert System for Hyundai Diesel Engines CRDi 2.0, that has been created based on the expertise handle by two experts that can give an accurate fault diagnosis for this kind of engine, considering the causes and can give the appropriate actions to be taken. This system is feed with data obtained by Condition Based Maintenance techniques, which allows incorporating a failure isolation and identification procedure based on the data. The Expert System is developed using HTML code, and a Hyundai Diesel Engines CRDi 2.0 database is created including relevant information concerning: engine specifications, operating values, faults, causes and recommended procedures for each situation. Finally, the structure of the developed system is presented, considering that it uses Condition Based Maintenance data and is embedded in a Computerized Maintenance Management System.

***Keywords*—** CMMS, Condition Based Maintenance Diagnosis, Failure, Diesel Engine, Expert System.

I. Introduction

THE demand for diesel engines in the automotive area has caused that companies that perform maintenance to these engines require innovative computational tools to optimize the maintenance management, and to diagnose faults considering the condition of the engines in this area. Considering this, currently have been developed new programs for integrating different technologies, such as Computerized Maintenance Management Systems (CMMS) and techniques of Artificial Intelligence (AI), which focus in a generalized way in engines maintenance without considering diagnostic techniques of the equipment condition. This is why it is very important to generate an integrated program that focuses on the maintenance of diesel engines using a CMMS with a Condition-Based Maintenance system (CBM) and one of the most used AI techniques for diagnosis that are Expert Systems (ES). That allows for both detection and diagnosis of the condition of the engine, orienting the best possible decision-making.

Today it can be found different investigations that deal with the use of ES for diagnosis, in which some consider their application with the CBM and the CMMS. However, most of the research are very general and do not specify the application of CBM and ES within a CMMS for diesel engines, or are proposals that have failed to be implemented. Thus, one of the research that highlight is Ballester et al [1], in which they propose within a CMMS a fault diagnosis of a transportation fleet through an ES with data obtained from the application of predictive techniques such as oil, vibration and thermography analysis. Similarly, Bangemann et al [2] develop the PROTEUS integrated platform for general application, consisting of a CMMS and a Diagnosis ES, which supports the maintenance decision-making taking into account values measured by sensors to diagnose equipment status. In addition, Levrat and Iung [3] develop the TELMA platform of general application, which among its systems has a CMMS and an online expert interface to help decision-making in maintenance. In the same direction, Szanto and Nagy [4] present the BDES program that integrates different ES dedicated to CBM techniques in rotating machines of a refinery, which are ExpertALERT for vibration, ThermoALERT for thermography, LeakageALERT for leak detection, OilALERT for oil analysis and FerroALERT for ferrographic analysis, and which have an interface that connects to a CMMS through a diagnostic module. Also, Simeon et al [5] present the SIMPREBAL program that has an ES for Diagnosis and uses CBM in a hydroelectric plant, which uses equipment evaluation documents, machine failure modes and maintenance expert knowledge. Similarly, Liu et al [6] describe the application of the CBM through an intelligent diagnostic ES for a hydraulic generator unit, using different parameters measured by sensors so that the ES compares the parameters and gives the diagnosis of the condition. In addition, Singh et al [7] propose to integrate a CMMS with Condition Monitoring (CM), where is considered the diagnosis with an ES that analyzes measurements from the CM system and with that diagnose faults in the machine. Likewise, McKee et al [8] performed a review of all the systems used to diagnose and predict failures in centrifugal pumps where they

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emphasize ES, especially one that develops a database with symptoms and possible causes that presents the equipment, so that the user selects the symptoms and the ES determines the cause. Additionally, Sisteplant [9] presents the PRISMA 3 GMAO platform of general application, composed of several modules where it highlights the Knowledge Management, where it has an ES of fault diagnosis with decision rules. Similarly, Invensys Systems [10] develops the Avantis Condition Manager program, which is an intelligent real-time condition management program of general application that collects and analyzes real-time diagnostics from all plan production assets. This program integrates different techniques such as CBM, Multi-Variable ES with rules-based engine, Enterprise Asset Management (EAM)/CMMS, Enterprise Resource Planning (ERP) and Business Intelligence systems. More recently, Villa et al [11] propose a SCADA ES to model failure modes of a ropeway for massive transportation, where sensors are used to measure real-time information that feeds the Fuzzy ES that is combined with CBM techniques to facilitate the operation, maintenance and safety of the cable car. In addition, Akinluli et al [12] developed a Fault Diagnosis ES for excavators, which has a simple structure that can diagnose faults occurring in these machines taking into account their different symptoms, so that this system contributes in repair and maintenance of these excavators. Furthermore, Galar et al [13] propose a hybrid model-based maintenance decision system, which uses a data-driven model to find and confirm the physical damage of an asset, taking into account historical data from CM measurements with Fuzzy ES and work orders taken from a CMMS that manages the maintenance of these assets. The operating conditions in this model are related to the accumulation of degradation in a system with consideration of aspects driven by context.
Considering that faults diagnosis in diesel engines is a critical part in maintaining them and that there are no tools that facilitate the diagnosis, in this work is developed a Diagnosis ES for Hyundai Diesel Engines CRDi 2.0, which in combination with CBM techniques it joins a CMMS for diesel engines in the automotive area.

II. Diagnosis Expert System for Hyundai Diesel Engines CRDi 2.0

There are different tools for fault diagnosis of an equipment, however some of the most widely used are those related to AI systems [14], among which can be found fuzzy logic systems, neural network systems and ES. Of all these AI systems, one of the most successful in terms of fault diagnosis are ES, since they incorporate all the knowledge that can have one or more experts in diagnosis, so that using their expertise the ES can help in the detection and diagnosis of faults. If it is also considered external data such as those obtained with CBM techniques, a detection and diagnosis is obtained that facilitate decision-making in the maintenance of equipment [15].

Within the fields of application of ES, a very important one is the diagnosis of the condition of equipment, among which one of great importance is the diesel engine. So having a tool that facilitates and accelerates the detection and diagnosis of their condition greatly helps in the optimal maintenance and therefore in the proper functioning of the processes in which it is involved. This is why a Diagnosis ES for Hyundai Diesel Engines CRDi 2.0 integrated with CBM techniques is developed.

A. Organization of the information of diagnosis expert system

The Diagnosis ES for Hyundai Diesel Engines CRDi 2.0 is developed with information from two experts in the field and information that is entered from the analysis performed on the engine, which are related to the application of CBM techniques, for the respective diagnosis. This information is internally organized around three main structural components: Knowledge Base, Database of Facts and Inference Engine. Fig. 1 shows the main components and other components that form the internal structure of the ES developed.

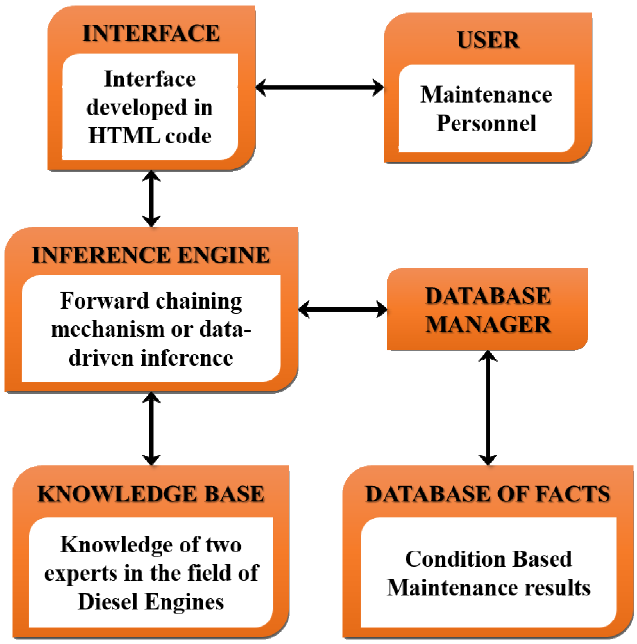

Fig. 1. Structure of the Diagnosis ES for Hyundai Diesel Engines CRDi 2.0.

Knowledge Base stores information that is related to the specific and procedural knowledge extracted from the two experts in the field of diesel engines, such as failures, possible causes and actions or recommendations. This information is represented in the ES by production rules A → B (IF-THEN), i.e. the fact A (faults) and rule (CBM condition for the existence of a fault), the fact B is inferred (causes, alerts, actions or recommendations). Figure 2 shows an example of the representation by production rules of the ES, where condition 1 and condition 2 of CBM values are met to obtain the Alert Level 1 with its respective Fault 2. Then, having Fault 2 is obtained the possible causes 1, 2 and 3 with its recommendations, so that the user selects Cause 2 and the ES gives the Recommendation 2.

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IF CONDITION 1  AND  CONDITION 2;
  THEN  ALERT LEVEL = 1;
  IF ALERT LEVEL = 1;
    THEN  FAULT 2;
    IF FAULT 2;
      THEN  CAUSE 1 AND CAUSE 2 AND CAUSE 3;
      IF CAUSE 2;
        THEN  RECOMMENDATION 2;
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Fig. 2. Example of representation of information in the Knowledge Base.

In the case of Database of Facts, data obtained from the CBM analysis applied to the engine are entered, data related to variables of vibration, noise, temperature and oil condition, and which allow the diagnosis of the condition of the engine when compared with values extracted from the experts.

Moreover, the Inference Engine processes the information from the Knowledge Base and Database of Facts to deduce sequentially which is the engine failure, taking into account the rules proposed in the ES. The Inference Engine is forward chaining, since initially data obtained from CBM are used to diagnose the failure and then the maintenance actions, which is the goal of the ES.

In Fig. 1, components of Diagnosis ES that allows to interact with information are also observed, such as Interface, User and Database Manager. The Interface is where the user interacts with the Diagnosis ES, which in this case is a web site programmed in HTML code. On the other hand, the User of Diagnosis ES is the maintenance personnel of diesel engines, such as engineers, technicians, assistants and mechanics. Moreover, the Database Manager is the person who handles the internal databases of ES and is the responsible for making the internal and external necessary changes to the system.

B. Architecture of diagnosis expert system

The Diagnosis ES developed for Hyundai Diesel Engines CRDi 2.0 is a system that combines functional content and structural content. Functional content is composed of information about failures extracted of the two experts on the subject and that is properly the ES. Structural content corresponds to the engine information extracted from its manual but validated by experts, and which composes a Knowledge Based System. This means that the ES is structured with information needed to diagnose the fault, causes and maintenance activities, and with information of the specifications and structures of the engine.

According to the above, the Diagnosis ES has an architecture composed of eight sections as shown in Figure 3, which are Technical Specifications of Diesel Engine, Diesel Engine Structure, Normal Operating Values, Alert Level, Failure Modes, Possible Causes, Recommendations or Corrective Actions, and Recommended CBM Techniques.

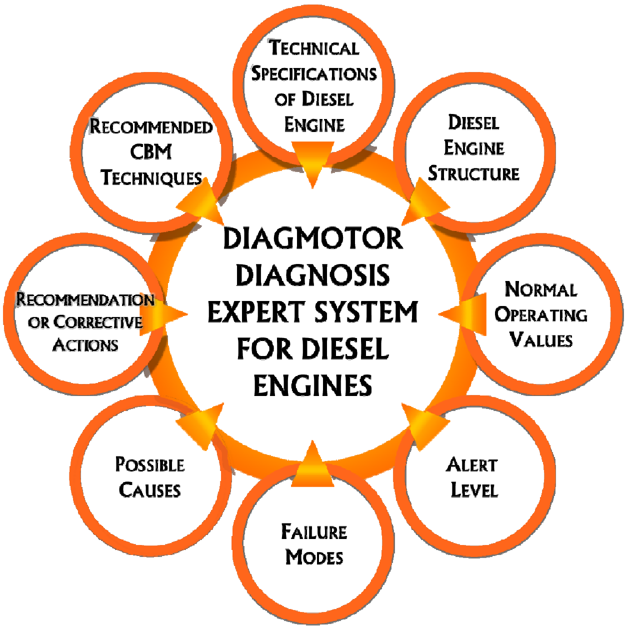

Fig. 3. Content of the Diagnosis ES for Hyundai Diesel Engines CRDi 2.0.

Technical Specifications of the Diesel Engine is part of the Knowledge Based System, since the stored information is extracted from the engine manufacturer's manual and is validated by two experts in the field. It is described all technical information of the engine, such as engine type, displacement, bore, stroke, max torque, max power, cycle, cylinder number, number of valves, cylinder arrangement, firing order, compression ratio, aspiration, alternator, starter motor, timing train, weight dry and dimensions. The Technical Specifications of Hyundai Diesel Engine CRDi 2.0 are shown in Table 1.

In the Diesel Engine Structure section, each of the diesel engine systems and each of its components with their respective specifications are described, which is part of the Knowledge Based System. The systems described in this section are basic engine parts, distribution system, cooling system, lubrication system, intake system, exhaust system, fuel injection system and starting system. This section is additional information in the ES for the user who does not know the complete structure of the engine.

On the other hand, in the Normal Operation Values section are stored all values of normal operation of engine components and systems, which are presented by experts and are related to variables of vibration, noise, temperature and oil. In the case of vibration and noise, the values of normal operating condition and fault condition of the engine are obtained through statistical data that characterizes the signals at different engine speeds (820 rpm, 1660 rpm and 2500 rpm). These statistical data are concerned with mean, variance, standard deviation, median, maximum, minimum, power, energy, kurtosis factor, asymmetry, RMS value, crest factor and power in the frequency range. In the case of temperature, the values of normal operating condition and fault condition of the engine are obtained through thermal signatures plotted on graphs for different engine speeds (820 rpm, 1660 rpm and 2500 rpm). On the other hand, in the case of oil, the values for normal operating condition and fault condition of the engine are obtained taking into account the study of parameters such as viscosity, total base number (TBN), detergency, flash point, water, fuel dilution, carbonaceous matter and parts per million of silicon, chromium, aluminum, copper, iron, nickel, lead and tin. All these are the different kind of data of normal and fault condition that are compared inside the Diagnosis ES to diagnose the current engine condition, and that are summarized in Table 2.

Table 1. Technical Specifications of Hyundai Diesel Engine CRDi 2.0 (D4EA). [16]

Technical Specifications		
Engine type		Diesel Engine
Displacement		1991 cm^3
Bore x Stroke		83 mm x 92 mm
Max Torque		285 N.m/1950 rpm
Max Power		92 Kw/4000 rpm (125 Hp/4000 rpm)
Cycle		4
Cylinder Number		4
Number of Valves		16
Cylinder Arrangement		In line
Firing Order		1-3-4-2
Compression Ratio		17.7:1
Aspiration		VGT
Alternator		12 V - 120 A
Starter Motor		12 V – 2.0 Kw
Timing Train		Belt
Weight Dry		201.4 Kg
Dimensions	**Length**	504 mm
	Width	669 mm
	Height	671 mm

The Alert Level section is similar to the previous one, only in this is stored all the information from the experts regarding the alert levels that can produce the diagnosis of the condition by comparing the tabulated values of ES with measured CBM values of the vibration, noise, oil and temperature. According to the result of comparison between the tabulated values and MBC values, an alert level is generated in the ES. This alert level is between 1 and 4, where 1 means that there is an engine failure and 4 that the engine is operating normally. These alert levels are shown in Table 3.

Table 2. Values of Normal Operating Condition and Fault Condition of Diesel Engine.

Values of Normal Operating Condition and Fault Condition of Diesel Engine		
Vibrations and Noise Data	Speeds: 820 rpm, 1660 rpm, 2500 rpm.	Mean
		Variance
		Standard Deviation
		Median
		Maximum
		Minimum
		Power
		Energy
		Kurtosis Factor
		Asymmetry
		RMS Value
		Crest Factor
		Power in the Frequency Range
Temperature Data	Speeds: 820 rpm, 1660 rpm, 2500 rpm.	Thermal Signatures
Oil Data	Viscosity	
	Total Base Number (TBN)	
	Detergency	
	Flash Point	
	Water	
	Fuel Dilution	
	Carbonaceous Matter	
	Parts per Million of	Silicon
		Chromium
		Aluminum
		Copper
		Iron
		Nickel
		Lead
		Tin

In the case of Failure Modes section, they are stored all faults provided by the two experts that could contain Hyundai Diesel Engines CRDi 2.0 in each of their systems. Each failure that is described in this section is related to the variables CBM mentioned.

Table 3. Levels of Alert.

Alert Level	Meaning of the Alert Level	Action to Take
1	The values are considered unacceptable, occurrence of engine failure.	Diagnose the failure and apply the recommended actions according to the cause.
2	The values indicate risk of engine failure.	Take preventive actions to avoid occurrence of failure.
3	The values show an incipient fault in the engine.	Inspect for any alteration of normal values.
4	The values are within the normal engine operation.	Do nothing, store data, the equipment works properly.

Then there is the section of Possible Causes, where they have different causes related to each failure that occurs in the engine, which are extracted from the knowledge of experts in the field. For each cause presented, it has a number of maintenance actions recommended by experts in the Recommendations or Corrective Actions section. In addition, for each cause also they have recommendations for CBM techniques that should be used to detect the cause of the failure, which are within the Recommended CBM Techniques section, where it says which of the CBM analysis should be performed for optimal data.

Fig. 4 shows the complete architecture of the Diagnosis ES for Hyundai Diesel Engine CRDi 2.0 described.

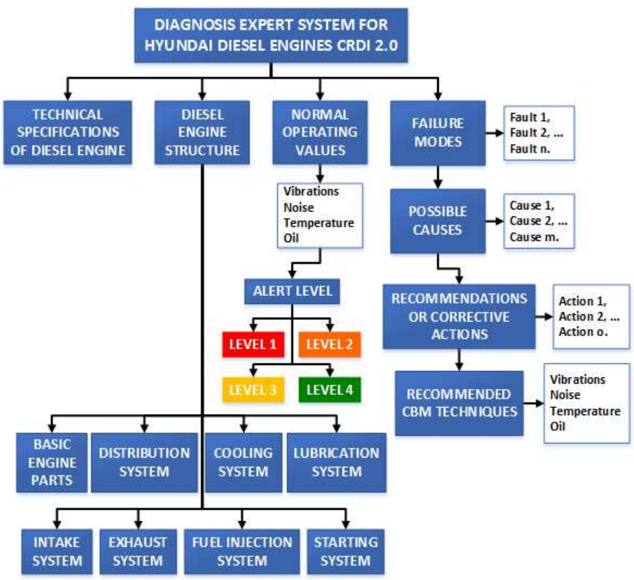

Fig. 4. Architecture of the Diagnosis ES.

C. Information acquisition of the diagnosis expert systeml

The ES presents a compilation of information provided by the experts Fernando Chica and Nestor Rivera, with a wide experience in the field of faults, causes and recommended maintenance actions in Hyundai Diesel Engines Common Rail Direct Injection (CRDi) of 2.0-liter, engines used in Hyundai cars, models Santa Fe, Elantra and Trajet. The information provided by both experts is obtained through interviews and surveys, and is composed of technical specifications, engine normal operation values, failures in each of the systems and components, possible causes of faults, procedures and recommended CBM techniques.

Additionally, the system developed contains the specifications and structure of the diesel engine, information extracted from the manuals of the manufacturer and validated by both experts. Some of this information comes from Diesel Engine D4EA Shop Manual [16], from which the specifications and the most explanatory images of the engine structure are extracted.

D. Interface of the diagnosis expert system

The Interface of Diagnosis ES is developed in HTML 5 code, and is composed of five sections that are Homepage, Diesel Engine, Diesel Engine Structure, Condition Detection, and Troubleshooting. Below are some views of the Diagnosis ES developed, where can be observed each section in the interface of the ES [17].

In Fig. 5, the Homepage section with a brief description of the Diagnosis ES for Hyundai Diesel Engines CRDi 2.0 can be observed. In this section, the user can find an introduction to the program with an explanation of what to find in each part of the Diagnosis ES.

Fig. 5. Homepage of the Diagnosis ES.

Fig. 6 shows the Diesel Engine section interface, where can be found a detailed description and technical specifications of Hyundai Diesel Engines CRDi 2.0. In addition, it can be found a brief description of the engine systems.

Fig. 6. Diesel Engine Section of the Diagnosis ES.

In Fig. 7, the Diesel Engine Structure section with the link of each engine system can be observed. This section contains all the information about the systems of Hyundai Diesel Engine CRDi 2.0, such as technical specifications and diagrams of the components. The user can use this section to learn or remember the structure of the engine that needs to be diagnosed and repaired. Fig. 8 shows an example of one of the systems of Hyundai Diesel Engine CRDi 2.0, where the general information of the system and then the description of each component is presented.

Fig. 7. Diesel Engine Structure Section of the Diagnosis ES.

Fig. 8. Basic Engine Parts of Hyundai Diesel Engines CRDi 2.0 in the Diagnosis ES.

The Condition Detection section of the Diagnosis ES is shown in Fig. 9. In this section, the user can find the place where it can be enter data of the results of each CBM technique, techniques of vibration analysis, noise analysis, temperature analysis and oil analysis. When the user fills in the form in this section and sends it, the ES shows as a response an alert level that describes what is happening to the diesel engine. Also, the alert level shows the next steps that the user must follow to solve the problem. In this section is where the normal operation values are compared with CBM values obtained from the diesel engine.

Fig. 9. Condition Detection Section of the Diagnosis ES.

A representation of a diesel engine failure with their possible causes in the Troubleshooting section is shown in Fig. 10. The user can find a brief description about the failure and a list of links that shows each possible cause of this failure. Fig. 11 presents an example of one of the possible causes of the failure, where the user can find recommendations and corrective actions. As shown in Fig. 11, the Diagnosis ES presents in this section the procedures, personnel and materials needed to perform the maintenance activities. At the end of this part of Troubleshooting section, the ES presents Recommended CBM Techniques for each cause of each failure of the Hyundai Diesel Engine CRDi 2.0.

Fig. 10. Diesel Engine Troubleshooting Section of the Diagnosis ES.

Fig. 11. Example of a Possible Cause in the Troubleshooting section of the Diagnosis ES.

III. Diagnosis Expert System Integrated to a CMMS for Diesel Engines

The Diagnosis ES developed for Hyundai Diesel Engines CRDi 2.0 is integrated within a module of a CMMS for maintenance of diesel engines in the automotive area represented in Fig.12. This ES together with CBM analyzes performed to the engine are recorded in the Detection and Diagnosis Management Module, which interacts with other modules related to the maintenance management of diesel engines, and which is structured as shown in Fig. 13.

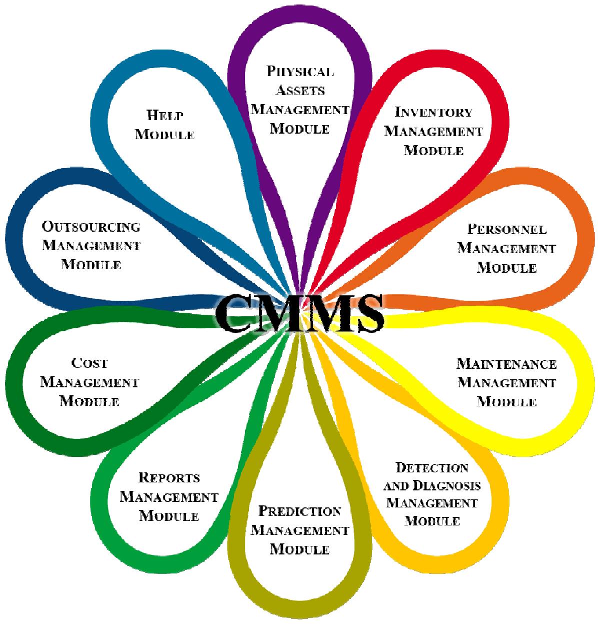

Fig. 12. CMMS for Diesel Engines.

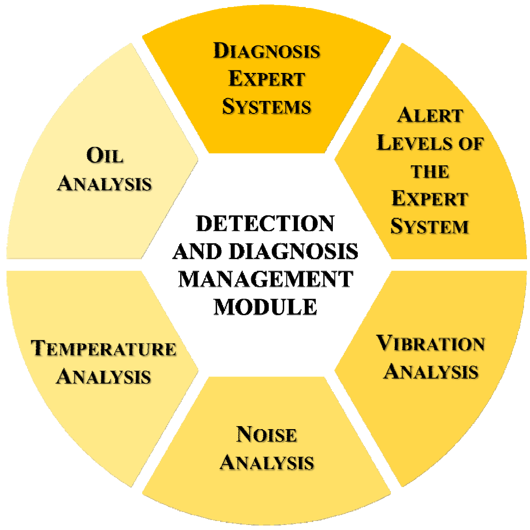

Fig. 13. Scheme of the Detection and Diagnosis Management Module of the CMMS for Diesel Engines.

As shown in Fig. 13, the module comprises six submodules, including the submodule Diagnosis ES that is where are stored all ES related to diesel engines, including the ES described above, so that users can consult whenever required to know the status of an engine. Another submodule is the Alert Levels, which stores each alert level that generates the ES according to the engine condition detected, considering a work order emitted by the CMMS for Predictive Maintenance. There are also four submodules designed to store information about CBM analysis performed to the engine, and that are the results of analysis by Vibrations, Noise, Temperature and Oil. The Diagnosis ES feeds on the information stored in these submodules to diagnose engine condition.

The interaction of Diagnosis ES with CBM and the CMMS is shown in Figure 14, which shows that CMMS generate through a work order a request of performing predictive maintenance activities. According to these activities, data measurements of vibration, noise and temperature through sensors in the diesel engine is performed, and in the case of oil, several samples for analysis are taken. These measurements and samples from the engine are then analyzed by CBM techniques and the results of these analyzes are stored in the respective submodules of Detection and Diagnosis Management Module in the CMMS. Next, the CBM results are entered in Diagnosis ES to be compared with the normal operating values to detect and diagnose the engine condition, so that with the result of the comparison the ES triggers a Level Alert, which in the case that involves a failure, also gives the fault that occurs, the possible causes and recommendations. All responses generated by the ES are converted into actions in the CMMS, actions that generate a work order related to recommended maintenance activities.

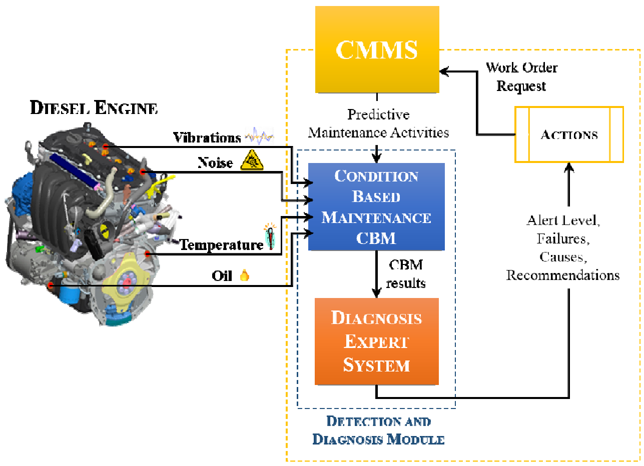

Fig. 14. Interaction diagram of Diagnosis ES with CBM techniques and CMMS for Diesel Engines.

Considering the above, Figure 15 shows a process flow diagram describing the integrated behavior between Diagnosis ES, CBM and CMMS for diesel engines. In this diagram is considered as an initial step the creation of a predictive maintenance work order in the CMMS, whether the maintenance activity has been scheduled or maintenance personnel has requested the activity because the engine has a possible fault or any irregular situation.

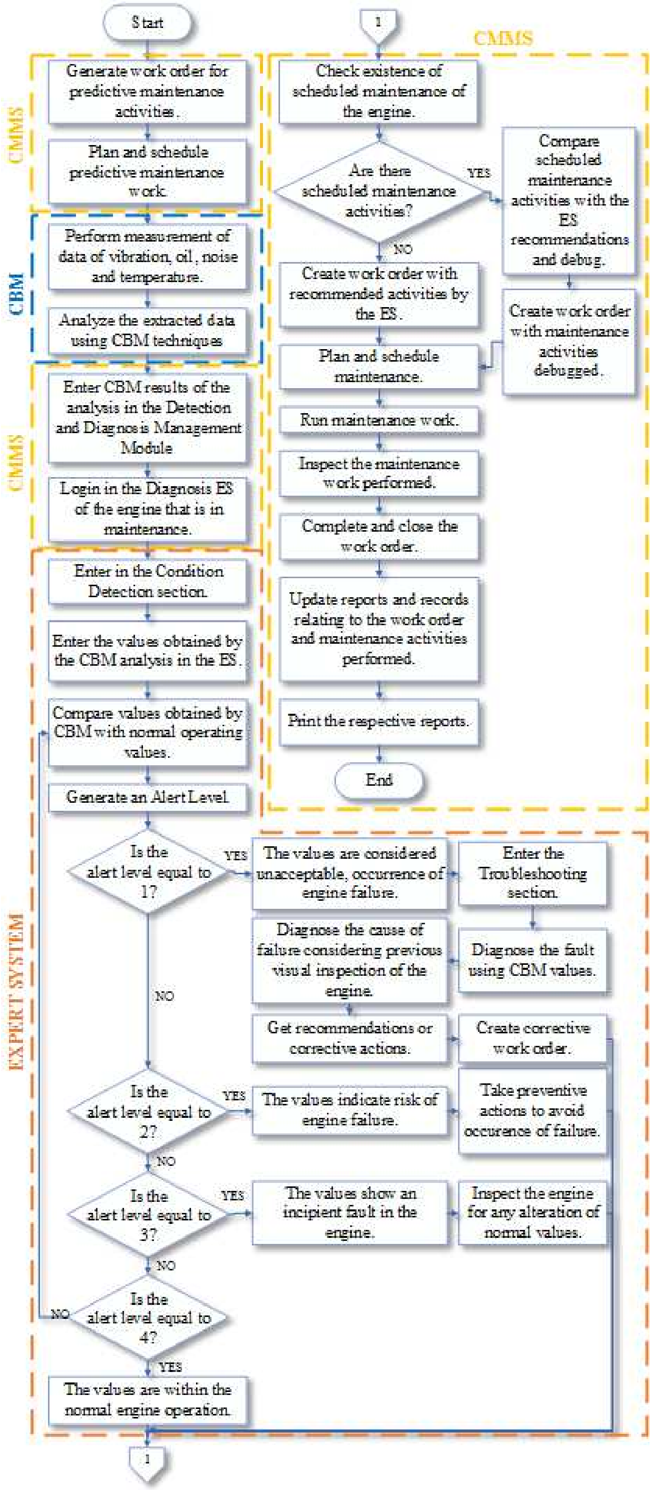

Fig. 15. Diagram of process of interaction between Diagnosis ES, the CBM and CMMS for Diesel Engines.

IV. Analysis

The developed system is simple to use because it provides the user with important information about Hyundai Diesel Engine CRDi 2.0 through a friendly interface, so that at a critical moment of the engine, the system can help solve the problem quickly and effectively.

In addition, this Diagnosis ES has the originality to come structured so that it can be easily integrated into a CMMS for diesel engines that take into account the CBM techniques for the detection and diagnosis of engine failures. This ES through a CMMS helps decision making in terms of maintenance activities for this engine according to the different alert levels that can present considering the behavior of the engine variables measured by CBM techniques with respect to data tabulated in the Diagnosis ES.

V. Conclusion

A Diagnosis ES that uses CBM techniques to guide maintenance optimally and that is embedded within a CMMS for diesel engines has been created.

The ES developed for fault diagnosis facilitates the work of monitoring and diagnosis of Hyundai Diesel Engine CRDi 2.0, and guides the decision-making about their maintenance.

The Diagnosis ES presented, being integrated with CBM techniques and a CMMS for diesel engines, takes maintenance management and in turn to asset management to another level that considers a holistic view of the condition of the diesel engine.

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