Strojniški vestnik - Journal of Mechanical Engineering 68(2022)10, 642-653

DOI:10.5545/sv-jme.2022.298
Short Scientific Paper
Received for review: 2022-07-23
Received revised form: 2022-09-16
Accepted for publication: 2022-09-28

Development of a New Expert System for Diagnosing Marine Diesel Engines Based on Real-Time Diagnostic Parameters

Hla Gharib – György Kovács*
University of Miskolc, Faculty of Mechanical Engineering and Informatics, Institute of Manufacturing Science, Hungary

Implementing adequate diagnostic strategies for marine engines offers a good possibility to focus on the early recognition of potential problems and prevent catastrophic and costly consequences. The successful and increasing application of diagnostic systems and devices for machines depends significantly on the precision of the diagnostic approaches. This research aims to develop an improved diagnosis expert system for determining the real-time technical condition of marine diesel engines. The adequate selection of the diagnostic parameters is crucial in detecting early-stage defects and failures since each parameter responds to the changes in structural parameters of the engine in different modes and degrees. This result provides valuable information on the accurate location of the fault and describes the relationship between operational and structural parameters. Firstly, this article introduces the relevant literature relating to the selection of the diagnostic parameters for marine engines and their subsystems through different statistical methods. The next part contains the description of marine diesel engine subsystems and the selected marine diesel engine's diagnostic parameters. After that, a newly developed expert system for diagnosing marine diesel engines' technical conditions is introduced. Finally, a case study of the operation of the developed diagnostic system is presented. The main contribution of the article is the introduction of the newly developed diagnosis expert system, which can be offered to inexperienced users on ships to effectively manage abnormal situations. Furthermore, this diagnostic tool can be applied to the engines' subsystems to improve the reliability and efficiency of the marine diesel engines' operation and maintenance.
Keywords: marine engines, diagnostic parameters, maintenance, newly developed diagnosis expert system, case study

Highlights

- *The selection of the most effective diagnostic parameters related to the subsystem of the marine diesel engines (fuel, lubrication, cooling, and air and exhaust systems) based on statistical studies and research experiments were studied.*
- *A knowledge-based diagnostic system, based on the selected diagnostic parameters, was developed for the whole engine system to determine the technical condition of the engine.*
- *The newly developed diagnosis expert system can be applied to every four-stroke marine diesel engine to increase their operational efficiency and reliability.*
- *The new diagnostic system can be used to manage abnormal situations on ships effectively and promptly.*
- *A case study for marine diesel engines' technical diagnosis is also introduced to show the operation of the developed expert system.*

0 INTRODUCTION

Marine diesel engines are complex systems; due to the relatively high costs of fuels and lubricating oils, their operational expenses are quite high. This cost may reach 70 % of the ship's machinery operational expenses [1]. The increased operating expenditures are related to the ship engine's technical condition. Application of an adequate maintenance strategy depends on the continuous technical diagnosis with minimal intervention, considering a long process with important multiple steps affecting the system efficiency. The diagnostic system provides a high-quality output (i.e., describes the most possible causes and provides maintenance advice) that helps the decision-making process, which saves time and reduces costly unnecessary maintenance actions.

A proper selection of diagnostic parameters depends on valuable information relating to the current technical condition. Therefore, many relevant articles were reviewed for this paper. Several statistical studies researched the proper diagnostic parameters for each engine's functional subsystem and component, starting with the fuel feeding and injection systems. Witkowski has demonstrated that damage in the injection system can be detected by the heat release characteristic, which enables the use of it in a diagnostic procedure; he focused on the course of heat release reacting to the fuel intensity per cycle [1]. In another paper, Witkowski studied the importance of the selection and minimization of the number of diagnostic parameters. This study aims to simplify the diagnostic process with effective fault recognition; he used the trivalent residue method for injection systems in marine diesel engines. Even though it is a time-consuming and expensive method, it could provide a good diagnostic result [2]. Yu et al. studied the possibility of using a Long Short-Term Memory (LSTM) neural network to study thermal faults. They used seven thermal parameters in their database and

*Corr. Author's Address: University of Miskolc, Faculty of Mechanical Engineering and Informatics, Institute of Manufacturing Science, Hungary altkovac@uni-miskolc.hu

applied these to the Simulink software platform to simulate the thermal failure of marine diesel engines. The study confirmed that LSTM could complete the work with better accuracy than a backpropagation neural network [3].

Radica thermodynamically analyzed a marine engine working cycle using Expert System. The obtained results were compared using the Vibe and Watson-Piley Marzouk correlations. A good match exists between measured and numerically simulated values [4]. Rubio et al. described a failure simulator for marine diesel engines based on a one-dimensional thermodynamic model. This model made it possible to know the symptoms of one failure before it becomes dangerous for the engine and to build a reliable failure database for diagnosis purposes [5].

Monieta planned and performed an experiment on the injection subsystem; he dealt with theoretical research and diagnostic tests to select adequate diagnostic parameters. The results show a good correlation between the selected parameters and the changes in the properties of the injection subsystem [6]. Zadrag and Kniaziewicz studied diagnostic parameters' sensitivity during dynamic processes of fuel supply systems and their normalization for use in diagnostic applications [7]. Lu et al. used stochastic analysis in corporate decision-making models and proved the feasibility of increasing efficiency and reducing costs for managing processes [8]. Dragan addressed a two-stage model for fault detection of an industrial heat exchanger. He applied prior knowledge and collected data; furthermore, he used the least squares method to indicate the presence of initial faults accurately and thus support timely condition maintenance [9]. The same approach led the research for lubrication systems by analysing some sensor parameters in the subsystem; it can quickly and efficiently identify the failure occurrences of complicated marine diesel engine lubricating systems [10] and [11].

For cooling system research, the goals were to identify the diagnostic relationships between coolant parameters (temperature and pressure) and their effect on other structural parameters [12]. Nahim et al. [13] developed a model for the lubrication and cooling systems considering other engines' subsystem interactions. These depend on different fluids' thermal and pressure characteristics.

Relating to the air supply and turbocharger condition diagnosis, some studies assess the relationship between the cause and symptoms of all potential problems that may occur during the operation [14]. Other researchers took experiments on real marine diesel engines and proposed measurements on the sensitivity of signals and the characteristics of exhaust emission parameters [15] to [17]. Zadrag and Bogdanowicz [15] focus on the relationships between output and engine structural parameters, considering output parameters as symptoms of the engine's technical condition. When reliable statistical data is not available or evidence independence cannot be assumed, the certainty factors (CF) theory offers an alternative to Bayesian reasoning (an application of probability theory to inductive reasoning). This theory relies on probability interpretation as expressions of parameter uncertainty, meaning that inductive reasoning is a conception of deductive reasoning, where knowledge of the truth or falsity of a hypothesis corresponds to an extreme probability 1 and 0. The CF represents the degree of confidence in a fact or rule. The CF theory approach has been widely applied in uncertain rule-based inference due to its simplicity and lack of assumptions [18] and [19].

The first aim of this study is to select the most useful diagnostic parameters for each subsystem of marine diesel engines based on other authors' statistical studies and research experiments. The main aim is to develop a knowledge-based diagnostic system (based on the selected diagnostic parameters) for the whole engine system, which can determine the technical condition.

This system is the first specially developed prototype diagnostic expert system. At the same time, this system can be applied to every four-stroke diesel marine engine, which increases operational efficiency and reliability; furthermore, it is a specific diagnostic system for marine engines during operation.

Our newly developed expert system can be added to the ship's planned maintenance system (PMS) (which includes a condition- or preventive-based maintenance strategy) to be able to modify and provide specific maintenance tasks by the maintenance team instead of regularly scheduled activities. The new expert system helps to diagnose and provide supportive advice relating to optimal working conditions. Our system also allows the operator to change and modify the ideal diagnostic parameters' values on one simple screen, depending on the operation conditions, adding the different diagnostic scenarios to the knowledge base. These advantageous options can improve the expert system's efficiency during the operation, as well as the PMS software's efficiency.

This article introduces an overview of marine diesel engine subsystems and their possible failures and effects on the engine operation and condition in

Section 2. Then, in Section 3, parameter correlation analysis methods are introduced to find the direct and indirect relationship between the diagnostic signal and different faults and conditions. After that, a newly developed diagnostic expert system and a case study for the marine diesel engines' technical diagnosis are described in Section 4.

The main added value of the article is the introduction of the newly developed diagnostic expert system, which can be offered to inexperienced users on ships to effectively manage abnormal situations. Furthermore, this diagnostic tool can be applied to the engines' subsystems to improve the reliability and efficiency of the marine diesel engines' operation and maintenance.

1 MATERIALS AND METHODS

1.1 Marine Diesel Engines' Subsystems

Dividing the marine diesel engine into multiple functional subsystems is necessary for diagnosing tasks. Many researchers confirmed the correctness and usefulness of this approach [12] and [17].

1.1.1 Fuel System

The fuel system contains two parts: the fuel injection and the fuel supply system. Fuel supply deals with providing fuel suitable to use in the injection system. The main combustion engines, the fuel feed system, and injection valves in the injection are the most unreliable parts of ship engines [6]. According to statistics, almost 50 % of all possible problems in marine engines are the fault of this system, and it can be classified as shown in Fig. 1.

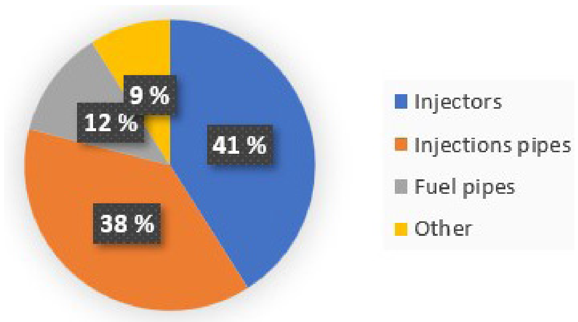

Fig. 1. *Failure statistic in fuel injection components* [1]

Indicator diagrams are the charts used to measure the thermal and cylinder performance of internal combustion engines on ships. Analysing these indicator diagrams' parameters, these parameters have limited value in marine engine technical diagnosis, even though this is a popular technique in actual operations. One of the important problems with injection systems' parameters is that their measurement is complicated due to the limited options for installing sensors [1] and [6].

1.1.2 Lubrication System

The lubrication system of a marine diesel engine distributes oil to engine bearings and as cooling oil to pistons. Oil is pumped from the lubrication oil circulation tank by an oil pump. It is then pumped directly to the main engine's lubrication oil cooler, thermostatic valve, full-flow filter, and eventually to the engine. The lubricating oil is collected in an oil pump before being drained and reused in the lubricating oil-circulating tank [10]. Operation practice shows that the lubrication system is one of the most frequently malfunctioning parts in marine diesel engines [12]. These malfunctions could be divided into four types: abnormal temperature, abnormal pressure, oil failure, and excessive oil consumption. However, the methods used currently to assess lubrication systems can only detect whether the lubrication system is defective or not, and do not provide the specific location, in addition to the major issue in obtaining data on lubrication malfunctions [11].

1.1.3 Cooling System

The cooling system's operation is essential since it is responsible for achieving and maintaining the engine's appropriate operating temperature. A fast increase of the temperature of the engine's critical components occurs when the cooling system is damaged. This change in temperature causes lubrication to degrade (the oil loses its lubricating characteristics and its combustion) and the occurrence of early ignition (self-ignition) of the fuel-air combination. In addition, excessive thermal expansion of the piston in the cylinder may occur, resulting in engine damage [12]. Moreover, low temperature is also inconvenient because the evaporation of the fuel occurs under less suitable conditions, causing the combustion process to be distorted and perhaps resulting in higher emissions of toxic substances. Finally, working at low temperatures can eject oil from the cylinder lining, which is very undesirable for lubrication [12].

1.1.4 Air Supply System

The adequate amount and quality of air needed for efficient combustion processes are determined according to the compressor wheel's efficiency and optimal operating conditions. The main failures of a scavenge air system include air filter blockage, compressor wheel pollution, turbine wheel pollution, cooler tube blockage, and cooler air side blockage [14]. The damage detection issue is critical in this system since the blade wears off 90 % of the time and may occur and lead to catastrophic failure. According to statistics, blades are involved in 65 % of centrifugal compressor unfitness conditions [20].

1.1.5 Exhaust System

The emission of toxic compounds in an engine's exhaust is affected by changes in the engine's structural parameters. This damage includes the charge exchange system, the fuel system, and the engine supercharging system. These changes are substantially greater during dynamic states and time-transient processes [15] and [21]. Generally, it can also be assumed that the increase in exhaust gas temperature decreases the maximum exhaust gas pressure, and the decrease in it causes an increase in the maximum exhaust gas pressure [1].

1.2 Correlation Methods for Diesel Engines' Diagnostic Parameters

One of the primary weaknesses of present marine diesel engine fault diagnostic systems is the inability to perform real-time fault diagnosis of diesel engines [16]. Each diagnostic parameter gives a certain diagnostic signal (depending on its sensitivity) to change and sometimes to the rate of this change. The direct and indirect relationship between the diagnostic signal and different faults determines the value of this parameter as a diagnostic parameter [22] and [23]. Unfortunately, the availability and measuring of the diagnostic parameter might sometimes be a reason for ignoring a good, diagnostically reasonable parameter in the diagnostic system.

One of the statistical analysis methods of data is the so-called correlation, which is a statistical concept explaining the relationship between two or more variables. Given the variety of data types, variables, and even units of measurement in scientific research, correlation coefficients can be calculated using several methods. The purpose of using these coefficients is to evaluate the existence of a relationship between two variables and check whether it is proportional or inversely proportional, strong or weak [24].

Due to the many parameters and sensors on diesel engines, correlation analysis will reduce diagnosis time as much as possible while ensuring the validity and accuracy of the results. In the next sub-sections, we introduce the most common correlation analysis methods used for numerical variables.

1.2.1 Pearson Correlation Coefficient Method

The Pearson correlation coefficient calculates the correlation between the dependent variable (output) Y and the diagnostic variable (input) X [6, 7]. The correlation coefficient values are in the range [−1; 1]; the sign indicates the correlation direction, while the absolute value presents the relation strength [7]. This formula takes the following form:

$$r_{yxk} = \frac{\sum_{i=1}^{N}\left(x_{ik} - \bar{x}_k\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{N}\left(x_{ik} - \bar{x}_k\right)^2 \sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2}}, \qquad (1)$$

where r_{yxk} is the correlation coefficient, x_{ik}, y_i input and output variables, i the i^{th} values of variables, $\bar{x}_k, \bar{y}$ the mean values of variables, and N the number of observations.

1.2.2 Hellwig Method

This method's concern is selecting a set of variables with the largest information capacity and using all potential variables as an information storage unit [7] and [25]. The method requires "Test": an appropriate number of potential combinations of all $L = 2^k - 1$ combinations of k potential independent variables. For each combination, the individual index of information capacity (h_{mxk}) is defined for the variable xk in the m combination of variables:

$$h_{mxk} = \frac{r_{yxk}^2}{1 + \sum_{\substack{k,s \in km \\ k \neq m}} \left| r_{x_k x_s} \right|}, \qquad (2)$$

where r_{yxk} is the correlation coefficient, $r_{x_k x_s}$ the coefficient of correlation between the explanatory variables, m the number of combinations, and k the number of variables for the index of individual capacity information.

The Hellwig analysis continues with the calculation of the H_m information for each combination of the integral capacity indicators:

$$H_m = \sum_{k \in K} h_{mxk} . \quad (3)$$

The criterion for determining the optimum combination of explanatory variables is the highest value of this indicator.

Other types of correlation analysis methods are used according to the type and number of variables or the type of the study. For example, the Spearman correlation coefficient [26] fits many types of relationships but also requires that the data must meet (monotonic relationship or ordinal data). The other variable must tend to increase or decrease, but not necessarily a linear function. This aspect of the Spearman correlation allows the fit of non-linear relationships. However, there must be a tendency to change in a particular direction.

Many studies used the aforementioned methods for the different subsystems' parameters of marine engines, such as fuel oil systems and lubrication systems. In our study, we will focus on the most sensitive diagnostic parameters selected based on the previous studies' statistical results, on other experimental studies on the real marine diesel engine, or on experts' knowledge. After the selection of these diagnostic parameters, we will develop a new diagnostic system for the whole engine subsystems.

We can classify the previous studies' results as shown in Table 1, which shows the diagnostic parameters for diesel engine subsystems and the methods used in the references to select them. The selection methods can be the following: experts' opinions; statistical data analyses (correlation analysis); experimental validation (on real ships and engines); marine diesel engine failure simulator (engines simulation models).

During our research (beside the application of the previous methods) we had long discussions with six marine experts (chief engineers) about the possibility of using their practical experience and knowledge to develop our new technical condition diagnosis expert system. We applied the selected most important diagnostic parameters and built the six marine chief engineers' opinions into the expert system relating to the specific rules for each condition.

2 RESULTS AND DISCUSSION

2.1 Introduction of the Newly Developed Diagnosis Expert System

The primary aim of our research was to develop a new diagnosis expert system to increase the reliability and efficiency of the engines' maintenance and repair strategies. During the research, we utilized previous statistical and experimental results and used the practical experiences of six expert chief engineers. Ship chief engineers are the head of the technical department of the ship; they should have many years of experience in different ranks and positions before they are qualified to become chief engineers. Our experts have at least five years of experience as chief engineers. In our future work, we are planning to add more expertise from other marine engineers with different practical backgrounds to improve our newly developed diagnosis expert system to determine and improve the marine diesel engine's technical condition more precisely.

Table 1. *Diagnostic parameters and their selection methods*

Subsystem	Parameters	Method	References
Fuel System	Pressure after feeding pump Injection pressure Combustion pressure	Experts' opinion. Statistical data analyses. Experimental validation. Marine diesel engine failure simulator.	[1], [2], [5], [6]
Lubrication System	Oil pump pressure Oil temperature Oil pressure Oil level	Experimental Validation. Marine diesel engine failure simulator.	[5], [8], [12], [10]
Cooling System	Water pressure	Experimental Validation. Marine diesel engine failure simulator.	[5], [11], [12]
Air Supply System	Pressure after turbocharger Temperature after cooler	Experts' opinion. Statistical Data Analyses. Marine diesel engine failure simulator	[2], [5], [13], [17]
Exhaust System	Exhaust gas temperature Exhaust gas colour	Experts' opinion. Statistical data analyses. Thermal failure simulation of diesel engine.	[2], [3], [7], [14], [15], [16]

2.1.1 Conception of the New Expert System for the Diagnosis of Marine Engines

The conception and the evaluation process are demonstrated in Fig. 2. The newly developed software includes 12 diagnostic parameters and 44 most commonly occurring faults and abnormal cases. The operator (the user) inputs the normal ranges relating to the 12 diagnostic parameters (these data are depending on the type of the marine engine) in the main screen (Fig. 3). Then these data will be exported into MATLAB file to import them to CLIPS software. CLIPS is a public domain software tool for implementing expert systems, developed at NASA. CLIPS was written in C programming language. After the diagnosis process is finished, the results will be imported again into a second screen (Fig. 4).

Tables 2 to 6 describe the possible results for each case related to the abnormal conditions of the marine engine's subsystems according to the experts' opinions. The abnormality belongs to the two situations: the value of the diagnostic parameter is 1) higher than the normal ideal range or 2) lower than the ideal normal range.

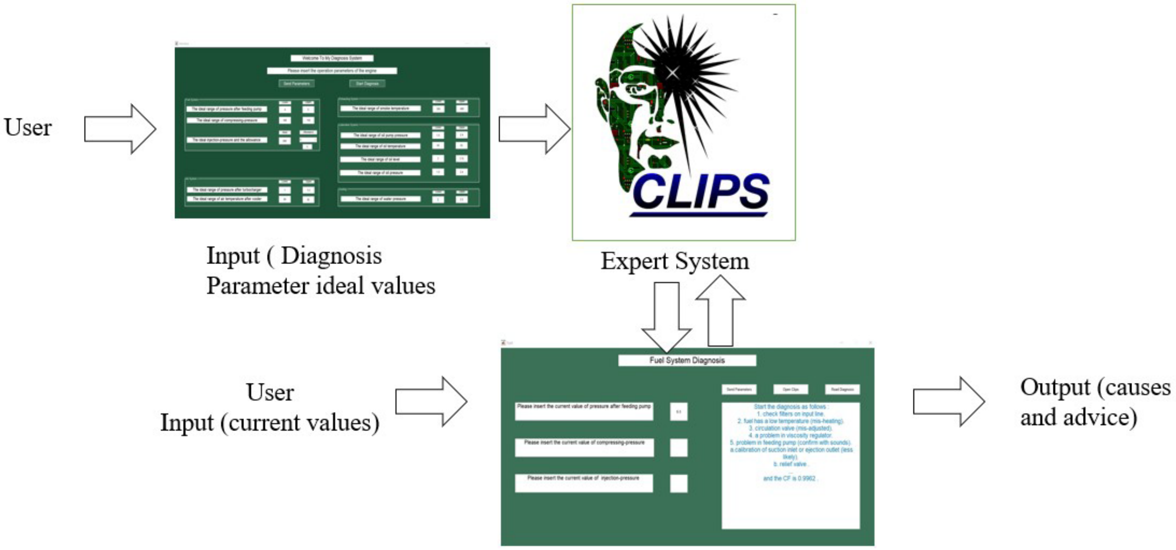

Fig. 2. *Conception of the new diagnosis expert system*

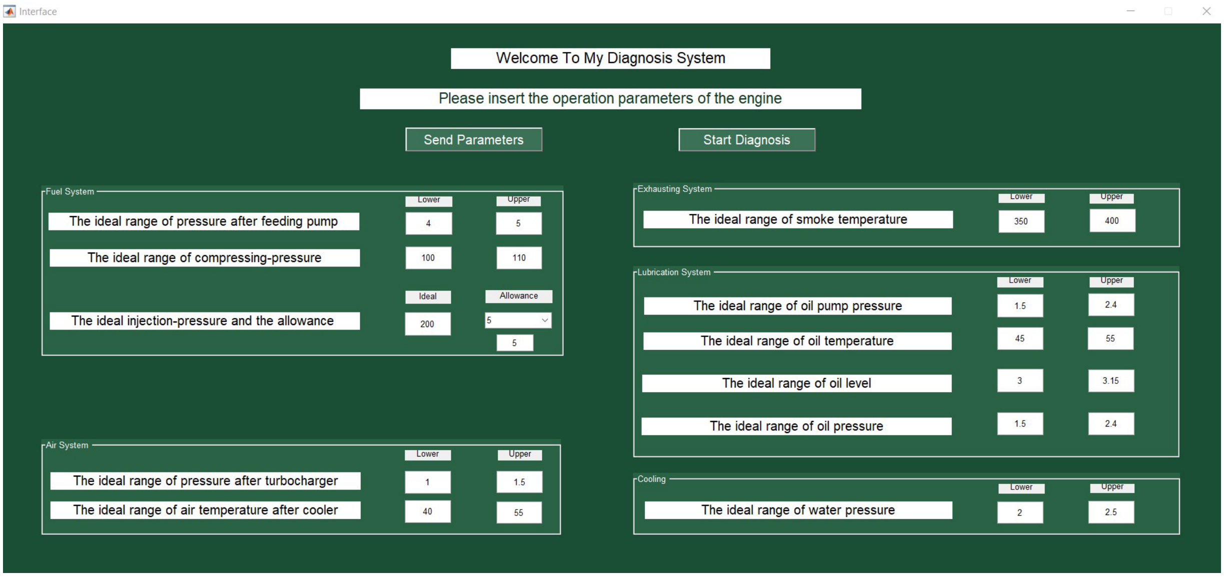

Fig. 3. *The main screen of the newly developed diagnosis expert system*

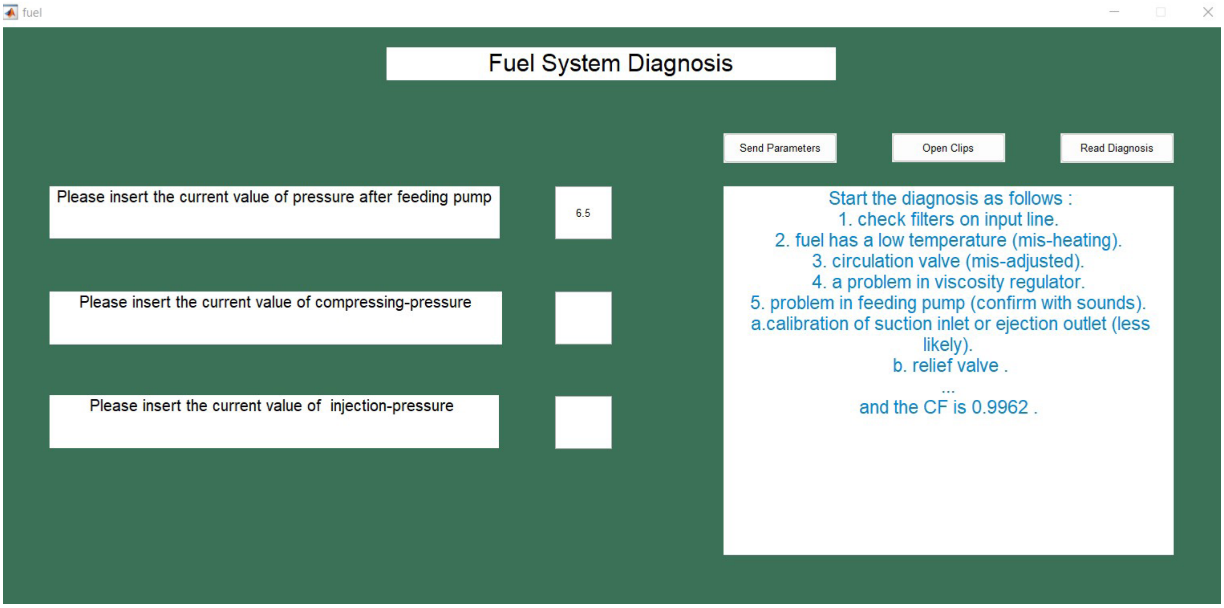

Fig. 4. *Diagnosis results (action plan) relating to the fuel system*

Table 2. *Diagnostic parameters, conditions, and experts' opinions (fuel system)*

Parameter	Condition	Diagnosis, Action
Pressure after feeding pump	Higher than normal range	1. Filters on the input line (check). 2. Fuel has a low temperature (mis-heating). 3. Circulation valve (wrong modification). 4. Problem in viscosity regulator. 5. Problem in feeding pump (confirm with sounds): a. calibration of suction inlet or ejection outlet (less likely); b. relief valve.
	Lower than normal range	1. Fuel has a high temperature. 2. Fuel level at daily service tank. 3. Polluted service tank\Blockage in the inlet pipe. 4. Check filters on the input line. 5. Leak from input line\ pressure sensors. 6. Problem in feeding pump (confirm with sounds). 7. Relief valve. 8. Check circulation line. 9. Measurement error (check with sight).
Injection pressure	Higher than normal value + tolerance	1. First, you must listen to injection sounds on high-pressure pipes (injector failure). 2. Wrong modification (late injecting), it should accompany low compressing pressure and an increase in temperature of exhaust gases.
	Lower than normal value – tolerance	1. Expansion in injection nozzle (chemical ingredients in fuel), check treatment process. 2. Spring elasticity. Both lead to early injection, accompanied by the decrease in the temperature of exhaust gases.
Combustion pressure	Higher than normal range	1. Problem in high-pressure pump (confirm with sounds). 2. Injector (confirm with sounds). 3. Feeding pump (confirm with sounds and pump temperature). 4. Delivery valve (after the high-pressure pump).
	Lower than normal range	1. Delivery valve (after the high-pressure pump). 2. Excessive clearance in the high-pressure pump. 3. Injector (confirm with sounds). 4. Feeding pump (confirm with sounds). 5. Problem in high-pressure pump (confirm with sounds). 6. Air valves (confirm with sounds).

Table 3. *Diagnosis parameters, conditions, and experts' opinions (Lubrication System)*

Parameter	Condition	Diagnosis, Action
Oil pump pressure	Higher than normal range	1. Cold oil (check oil temperature). 2. Pressure regulating valve on the oil pump. 3. Plugged pipes (less likely to happen).
	Lower than normal range	The possible problem is unsealed (or increasing in clearances).
Oil temperature	Higher than normal range	1. Oil cooler. 2. Solid bearing (check heat sensor).
	Lower than normal range	1. Cold engine. 2. Mis-cooling. 3. Polluted oil. 4. Leak from heat regulator. 5. Oil filters problem.
Oil pressure	Higher than normal range	The possible problem is a blockage in oil holes (accompanied by an increase in temperature).
	Lower than normal range	External: leak in the oil lines (diagnosed with sight and excessive heat). Internal leakage: 1. it may appear in exhaust gas colour; 2. oil-consuming detector; 3. it may appear in other systems.
Oil level	Higher than normal range	1. Water leak (confirm from the oil-mist detector). 2. Fuel leak (viscosity test).
	Lower than normal range	The possible problem is oil leakage (check for blue smoke) (in case of an external leak, check with sight).

Table 4. *Diagnosis parameters, conditions, and experts' opinions (Cooling System)*

Parameter	Condition	Diagnosis, Action
Water pressure	Higher than normal range	1. Blockage in water lines (problem in water treatment or calcareous sediments), less likely to happen. 2. Problem in regulator valve (accompanies with temperature change).
	Lower than normal range	Before the engine: 1. If it is not accompanied by an abnormal decrease in water level at the expansion tank, then it is pump problem (confirm with sounds). 2. If it is accompanied by a slow and gradual decrease in water level then it is an increase in wear at pump body (water mistreatment). 3. If it is accompanied by a fast and sudden water level decrease, then it is pump collapses.
		After the engine: the possible problem is accompanied by an abnormal decrease in the expansion tank and may be: 1. Leakage problem: Internal: check exhaust gases' colour and temperature. External: check pipes and joint points. 2. Measurement device error.

In the recent stage of our research, we selected and implemented the most important and most frequently used parameters applied in the practical diagnostic systems and mentioned in the literature. Many further parameters could be suitable for advanced future analysis to cover more abnormal and normal conditions. For example, additional data relating to the noise, the vibration and the engine's total running hours can be implemented in the expert system in the near future. Furthermore, in some specific subsystems like the air supply system, we will study the possibility of adding the air intake and airflow values to achieve more precise monitoring and more reliable decision-supporting output. We can add waterflow and potential of hydrogen (PH) values to the cooling system to check the coolant's acidity. These newly suggested parameters will help to reduce the risk of damaging seals and metal components. Selecting the adequate diagnostic parameters and sub-parameters can help to improve maintenance activities and engines' operation performance.

The main screen of the newly developed diagnosis expert system is shown in Fig. 3. The developed expert system provides the possibility for the end-user to set the ideal operation values of the diagnostic parameters relating to the five subsystems before the system starts running. The software also provides the possibility of changing these operation values after a long operation time because (after a certain amount of time) the ideal range may be changed due to some parts replacements, compulsory changes in the engines' fluids specifications, or increased abrasion.

Table 5. *Diagnosis parameters, conditions, and experts' opinions (Air Supply System)*

Parameter	Condition	Diagnosis, Action
Pressure after turbocharger	Higher than normal range	1. High backpressure. 2. Air valves problem. 3. Partial blockage in air pass (rarely happen). Immediate action: reduce speed, then start diagnosing
	Lower than normal range	Turbocharger surge: 1. Air filter plugging (remove and clean). 2. Polluted turbo (check if the compressor and the turbine had cleaned regularly). 3. Unsteady shaft\Wear damage. 4. Air cooler fouling (accompanied by high temperature). Immediate action: reduce speed to load at which surging stops; If necessary open the air cooler inspection hole to stop surging.
		The turbocharger does not surge: 1. Unsealed joints before engine (check). 2. Turbocharger calibration (check). 3. Excessive clearance (maintenance).
Temperature after cooler	Higher than normal range	1. Blockage in water tubes (sediments). 2. Blockage in air tubes (accompanied by surging in turbocharger).
	Lower than normal range	Overcooling (modify).

Table 6. *Diagnosis parameters, conditions, and experts' opinions (Exhaust System)*

Parameter	Condition	Diagnosis, Action
Exhaust gas temperature	Higher than normal range	One unit: 1. Injector (wrong modification), 75 % probability and accompanied with black smoke. 2. Loose valves. 3. High-pressure pump problem (less likely to happen and accompanied by a change in compressing- pressure).
		All units: 1. Over-loaded turbocharger (check air temperature and indicator card). 2. Fuel problem (check viscosity regulator).
	Lower than normal range	One unit: 1. Unsealed cylinder jacket. 2. Unsealed valves.
		All units: The possible problem is in air temperature.
Exhaust gas colour	Black	1. Small air amount (wrong modification\ leakage). 2. Unsealed cylinder jacket (accompanied by temperature drooping). 3. Fuel components (appear in first use). 4. Fuel parameter (temperature-viscosity); check viscosity regulator. 5. Injectors (wrong modification); check indicator card. 6. Pumps (wrong modification); check indicator card.
	White	1. Economizer (check by reducing load or conversing mechanism). 2. Check the temperature after all units (define the leaking unit) and (confirm from the water expansion tank) most likely: leak from piston cooling tubes (if it is water-cooled). less likely: leak from cylinder jacket. 3. Steam in the air
	Blue	The possible problem is that excess oil burning could be caused by: 1. Oil specifications (if the oil is being used for the first time). 2. Piston oil rings corrosion 3. Collapse in the fire valve lubrication system (wrong modification). 4. Increasing cylinder jacket lubrication (wrong modification). immediate action: Reducing oil amount to minimize leakage
	Yellow	The possible problem is a fuel problem (first use) has increase in sulphur amount.

Initially, the system operator estimates the parameters' ideal operating ranges based on the service instructions book and the engine's total running hours (the engine's operation age), the type of the engine, and its manufacturing year.

However, after unforeseen operational circumstances, like the usage of a not-recommended fuel or replacing of some parts, the ship's chief engineer can make a decision that the ideal intervals of the diagnostic parameters' range have to be smaller. Our expert system provides the possibility for the operator to modify the ideal ranges of the analysed diagnostic parameters. In addition, during the software's development, it is possible to transform the afore-mentioned decision-making of the chief engineer into a fully automated process in our expert system by correlating the values of the ideal diagnostic parameters to the engine's effectiveness. In the next phase of our software development, we will define the engine type specifications in greater detail, and the manufacturing year in the knowledge-base to obtain more precise and reliable diagnostic and maintenance procedures.

2.1.2 Advantages of the Newly Developed Diagnosis Expert System

The newly developed diagnosis expert system provides a high-quality and reliable diagnosis describing the engines' current condition and all the possible reasons and required actions to improve the maintenance and repair procedure, which will save time and eliminate unnecessary actions. Furthermore, this expert system has many advantages compared to other diagnostic systems mentioned in the literature and recently applied in the practice. These advantages are the following:

- The newly developed diagnosis expert system can be applied at the same time for all engine subsystems (fuel, lubrication, cooling, air, and exhaust systems).
- The software absolutely meets companies' demands and is customizable.
- The new expert system can be applied to every 4-stroke marine diesel engine. The user can flexibly set the normal ranges of the selected 12 diagnostic parameters according to the type of marine engine to be diagnosed.
- The application of the expert system does not require any new sensors or measuring devices on the engine; therefore, further investment is not needed.
- The new software is easy to use and very cost-effective.
- The new expert system can be used anytime and anywhere, both in on-line and off-line modes.

2.1.3 Case Study for the Validation of the New Diagnosis Expert System

We selected a multi-purpose ship to perform a test on the final diagnostic system with the following specifications:

- Ship name: LAODICEA; Build: in China in 2005;
- Purchase and operation date: 2009; IMO number: 9274343;
- Length of the ship: 138 m; Breadth of the ship: 21 m;
- Dead weight of the ship: 12744 tons;
- Engine type: MaK 6 M 43 C5700HP@500.

The values relating to the diagnostic parameters of the investigated marine engine are shown in Table 7.

Table 7. *Ideal ranges for the parameters to be diagnosed in the case of the examined marine engine*

Feeding pump pressure [bar]	[4; 5]
Combustion pressure [bar]	[100; 110]
Injection pressure [bar]	200 ± 5 %
Air pressure after turbocharger [bar]	[1; 1.5]
Air temperature after cooler [ºC]	[40; 55]
Exhaust gas temperature [ºC]	[350; 400]
Oil pump pressure [bar]	[1.5; 2.4]
Oil temperature [ºC]	[45; 55]
Oil level [m]	[1.5; 2.4]
Oil pressure [bar]	[1.5; 2.4]
Water pressure [bar]	[2; 2.5]

In the case study, we simulated an abnormal situation when the feeding pump pressure increases up to 5.5 [bar], which means that this pressure becomes higher than the normal range [4; 5]. The operator must set this abnormal feeding pump pressure in the main screen of the expert system as can be seen in Fig. 4.

After running the diagnosis expert system, the operator received the action plan as a result of the diagnosis. It can be seen in Fig. 4 that the operator must take the following actions in the given preference order to remove the abnormally high pressure to prevent an accidental catastrophe and costly consequences.

The results of the diagnosis are the following as can be seen in Fig. 4:

1. Check the filters on the input line.
2. Fuel has a low temperature (mis-heating).
3. Circulation valve (wrong modification).
4. Problem with viscosity regulator.
5. Problem with feeding pump (confirm with sounds):

a. calibration of suction inlet or ejection outlet (less likely);
b. relief valve.

It can be also concluded that the result of the simulation has a number equal to 0.9962 (Fig. 4). This CF number represents the degree of agreement of the six marine chief engineer experts according to the rule defined in the expert system. This CF calculates and combines the expert opinions depending on the amount of expertise by years of experience for each expert. The certainty factor has a range between [-1; +1] and (after running the rule) these numbers could be decreased if the diagnose wrong/partially wrong (followed by modification, remove, or add new rules) or increased if it has a correct result. We can summarize that the reliability of the software result is near to the maximal value.

3 CONCLUSIONS

In the case of technically complex marine diesel engines that have multiple diagnostic parameters, it is necessary to minimize the number of the diagnostic parameters. Therefore, the correct selection of the required diagnostic parameters highly determines the efficiency of the developed diagnostic system. The application of an adequate diagnostic system for marine engines offers a good possibility to focus on early recognition of potential problems and prevents catastrophic and costly consequences.

The first aim of our research was to select the most effective diagnostic parameters relating to the subsystem of the marine diesel engines (fuel, lubrication, cooling, air, and exhaust systems) based on statistical studies and research experiments. The main aim of the research was to develop a knowledge-based diagnostic system (based on the selected diagnostic parameters) for the whole engine system to determine the technical condition. The newly developed diagnosis expert system can be applied to every four-stroke marine diesel engine to increase its operational efficiency and reliability.

The article first presented an overview of the marine diesel engine subsystems and their possible failures and effects on the engine operation and condition were introduced. Next, the parameters correlation analysis methods were described to find the direct and indirect relationship between the diagnostic signal and different faults and conditions. Finally, a newly developed diagnosis expert system and a case study for marine diesel engines' technical diagnosis were introduced.

The main added value of the article is the introduction of the newly developed diagnostic expert system, which can be offered to inexperienced users on ships to manage abnormal situations effectively and quickly. Furthermore, this diagnostic tool can be applied to the engines' subsystems to improve the reliability and efficiency of their operation and maintenance.

Our future research plan is to build a bigger knowledge base based on more experts' opinions with different practical experiences and previous diagnoses on similar engine types to improve the recent expert system using artificial intelligence approaches to create a more reliable and accurate diagnostic system.

4 ACKNOWLEDGEMENTS

The research was supported by the Hungarian National Research, Development, and Innovation Office - NKFIH under the project number K 134358.

5 REFERENCES

[1] Witkowski, K. (2019). Research the possibility of obtaining diagnostic information about the ships engine fuel injection system condition based on the analysis of characteristics of heat release. *Journal of KONES Powertrain and Transport*, vol. 26, no. 3, p. 249-256, **DOI:10.2478/kones-2019-0080**.

[2] Witkowski, K. (2017). The correct selection of diagnostic parameters of marine diesel engine and their minimization of as a necessary action in the formation of diagnostic algorithm. *Journal of KONES Powertrain and Transport*, vol. 24, no. 2, p. 287-292, **DOI:10.5604/01.3001.0010.2948**.

[3] Yu, Z., Wang, S., Chen, N. (2022). Thermal fault diagnosis of marine diesel engine based on LSTM neural network algorithm. Vibro*engineering PROCEDIA*, vol. 41, p. 198-203, **DOI:10.21595/vp.2022.22515**.

[4] Radica, G. (2008). Expert system for diagnosis and optimisation of marine diesel engines. *Strojarstvo: Casopis za Teoriju i Praksu u Strojarstvu*, vol. 50, no. 2, p. 105-116.

[5] Rubio, J.A.P., Vera-García, F., Grau, J. (2018). Marine diesel engine failure simulator based on thermodynamic model. *Applied Thermal Engineering*, vol. 144, p. 982-995, **DOI:10.1016/j.applthermaleng.2018.08.096**.

[6] Monieta, J. (2019). Selection of diagnostic symptoms and injection subsystems of marine reciprocating internal combustion engines. *Applied Sciences*, vol. 9, no. 8, art. ID 1540, **DOI:10.3390/app9081540**.

[7] Zadrag, R., Kniaziewicz, T. (2015). Identification of diagnostic parameter sensitivity during dynamic processes of a marine engine. *Combustion Engines*, vol. 162, no. 3, p. 1007-1014.

[8] Lu, J.-B., Liu, Z.-J.,Tulenty, D., Tsvetkova, L., Kot, S. (2021). Implementation of stochastic analysis in corporate decision-making models. *Mathematics*, vol. 9, no. 9, art. ID 1041, **DOI:10.3390/math9091041**.

[9] Dragan, D. (2011). Fault detection of an industrial heat-exchanger: A model-based approach. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 57, no. 6, p. 477-484, **DOI:10.5545/sv-jme.2010.128**.

[10] Zhao, G., Liu, Z., Chen, L. (2019). A fault diagnosis model of marine diesel engine lubrication system based on improved extreme learning machine. *IOP Conference Series: Earth and Environmental Science*, vol. 300, no. 4, p. 1-7, **DOI:10.1088/1755-1315/300/4/042092**.

[11] Ren, D., Zeng, H., Wang, X., Pang, S., Wang, J. (2020). Fault diagnosis of diesel engine lubrication system based on Bayesian network. *6th International Conference on Control, Automation and Robotics Conference Proceedings*, p. 423-429, **DOI:10.1109/ICCAR49639.2020.9108107**.

[12] Krakowski, R. (2014). Diagnosis modern systems in marine diesel engines. *Journal of KONES Powertrain and Transport*, vol. 21, no. 3, p. 191-198, **DOI:10.5604/12314005.1133203**.

[13] Nahim, H.M., Younes, R., Shraim, H., Ouladsine, M. (2016). Modeling with fault integration of the cooling and the lubricating systems in marine diesel engine: *Experimental validation. IFAC-PapersOnLine*, vol. 49, no. 11, p. 570-575, **DOI:10.1016/j.ifacol.2016.08.083**.

[14] Knežević, V., Orović, J., Stazić, L., Čulin, J. (2020). Fault tree analysis and failure diagnosis of marine diesel engine turbocharger system. *Journal of Marine Science and Engineering*, vol. 8, no. 12, p. 1004-1023, **DOI:10.3390/jmse8121004**.

[15] Bogdanowicz, A. Zadrag, R. (2019). Identification of indicators sensitivity of emissions as a diagnostic parameter during the dynamic process of marine diesel engine, *Diagnostyka*, vol. 20, no. 3, p. 79-86, **DOI:10.29354/diag/109886**.

[16] Puzdrowska, P. (2021). Diagnostic information analysis of quickly changing temperature of exhaust gas from marine diesel engine part I single factor analysis. *Polish Maritime Research*, vol. 28, no. 4, p. 97-106, **DOI:10.2478/pomr-2021-0052**.

[17] Qi, Z., Qi, Y., Hu, G. (2020). A practical approach to detect faults of marine diesel engine. *Journal of Computer and Communications*, vol. 8, p. 12-21, **DOI:10.4236/jcc.2020.88002**.

[18] Niederliński, A. (2018). A new approach for modelling uncertainty in expert systems knowledge bases. *Archives of Control Sciences*, vol. 28, no. 1, p. 19-34, **DOI:10.24425/119075**.

[19] Babič, M., Karabegović, I., Martinčič, S.I., Varga, G. (2019). New method of sequences spiral hybrid using machine learning systems and its application to engineering. In Karabegović, I. (ed.) *New Technologies, Development and Application. Lecture Notes in Networks and Systems*, vol. 42, p. 227-237, **DOI:10.1007/978-3-319-90893-9_28**.

[20] Monieta, J. (2018). Fundamental investigations of marine engines turbochargers diagnostic with use acceleration vibration signals. *AIP Conference Proceedings*, vol. 2029, art. ID 020044, **DOI:10.1063/1.5066506**.

[21] Dong, X.T., Nguyen, M.H. (2021). Experimental study of identifying emission sources of acoustic signals on the cylinder body of a two-stroke marine diesel engine. *Polish Academy of Science Archives of Acoustics*, vol. 46, no. 1, p. 105-119, **DOI:10.24425/aoa.2021.136565**.

[22] Cazanas, R., Sobrino, D., Martínez, E., Kostal, P., Mudriková, A. (2018). Integrating production and maintenance planning as an element of success at the tactical level: A fuzzy control theory approach. *Research Papers Faculty of Materials Science and Technology Slovak University of Technology*, vol. 26, no. 42, p. 109-117, **DOI:10.2478/rput-2018-0013**.

[23] Do, V.T., Chong, U.-P. (2011). Signal model-based fault detection and diagnosis for induction motors using features of vibration signal in two-dimension domain. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 57, no. 9, p. 655-666, **DOI:10.5545/sv-jme.2010.162**.

[24] Li, Z., Zhao, H., Zeng, R., Xia, K., Guo, Q., Yuhai, L. (2019). Fault identification method of diesel engine in light of Pearson correlation coefficient diagram and orthogonal vibration signals. *Mathematical Problems in Engineering*, vol. 2019, art. ID 2837580, **DOI:10.1155/2019/2837580**.

[25] Kowalik, P. (2014). On an implementation of the method of capacity of information bearers (the Hellwig method) in spreadsheets. *Probability in Action, Politechnika Lubelska*, p. 31-40.

[26] Rebekić, A., Lončarić, Z., Petrović, S., Marić, S. (2015). Pearson's or Spearman's correlation coefficient-which one to use. *Agriculture*, vol. 21, no. 2, p. 47-54, **DOI:10.18047/poljo.21.2.8**.