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APPLICATION OF PROBABILISTIC DIAGNOSTIC MODELS IN DIAGNOSTIC SERVICE DECISIONS-AIDING SYSTEMS FOR SHIP MAIN PROPULSION ENGINE

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Abstract

The paper presents a relational diagnostic model of a ship main propulsion engine used in aiding the service decisions. Ship main engine has been identified as the diagnosed system, diagnostic parameters as well as inter-relations taking place between the main engine states and diagnostic parameters have been specified using appropriate mathematical apparatus.

Keywords: *ME probabilistic diagnostic model, ship main engine, technical condition of ship ME, diagnostic parameters, relational model, rational operation of a ship engine.*

1. Introduction

A high power combustion piston engine used for ship propulsion is a complex technical system designed following the design assumptions, according to which it is to ensure the execution of transport tasks, and to achieve its assumed parameters related to its service, reliability, safety and economy.

Depending on the application, it can be used directly for a direct drive of a screw propeller or in a diesel-electric system or diesel – electric – hydraulic system. Especially in case of a direct drive, the reliability of the main engine (ME) can be of essential importance for ship safety. Therefore it is essential to effect such operational policy that will aim at optimisation of the operational parameters (operation rates) of an engine, as well as at minimising the risk of any serious defect.

For this reason, arriving at reliable diagnosis essential for taking rational operational decisions is best based on the application of the engine diagnostics system.

A reliable diagnosis depends on the quality of the diagnostic process, including: correct identification of the object and its processes and phenomena, accurate selection of tested parameters measured in appropriate measuring points, and optimum use of diagnostic information obtained directly or as a result of information processing.

With regard to the above, in order to obtain a reliable and accurate diagnosis of a diesel engine condition an optimal diagnosis system should be built, consisting of a diagnosed system (object) and a diagnostics system (DS) specially built for a given type of the object.

2. Practical usefulness of currently applied diagnostics systems

Modern diagnostics systems being currently introduced into use are applied for specific types of diagnosed engines. These are systems of specific architectural solutions and their application needs special adaptation of the engines. Spare parts databases, maintenance planning and the procedures of ordering the original spare parts are very useful for an operator and form a very good data set useful for ship operator in his consultations with the technical support services of a shipowner, aiming at reduction of expenditures, but often without taking the required safety level into account.

Also the diagnostic information concerning the assessment of element wear during the execution of maintenance is very useful for the operator. The most troublesome are those diagnostic systems which are designed to aid the operator's decisions during the engine operation. A lot of diagnostic information is calculated by the system, which provides correct results only if correct input data are entered, the verification of which is not always possible in practice. It is visible in the design of such systems which feature data transmission to the manufacturer's server and for the analysis of data by the manufacturer's experts. The knowledge and the experience of a ship engine operator not always allows him to properly interpret the information feedback of diagnostics system presented on its display screens.

There is a lack of data concerning discrete operation of MEs. Manufacturers normally determine the service lives and wear values for parts, subassemblies and systems on the basis of laboratory tests and experience in service. Also maintenance intervals are provided, after which preventative maintenance should be carried out, resulting from the number of hours of operation (apart from other cyclical maintenance provided for by the law). All these maintenance activities aim at renewal of engine's operational potential.

From the economical point of view, service life intervals for particular engine elements (their durability) should be set as multiplies of a common basic time interval, which would facilitate the execution of above-mentioned scheduled maintenance.

From the point of view of reliability and watt-hour efficiency of engine operation this can however cause the accumulation of negative factors often leading to serious disturbances in the engine operation or to its extensive damage and complete failure. Simultaneous progress of element wear in the engine can cause generation of ambiguous diagnostic signals.

With regard to the above, the manufacturers and operators of main engines collect their experiences over the whole time of operation and try to introduce changes aiming at increasing the reliability of main engines through the application of appropriate diagnostics systems for the determination of their technical condition [5,7].

Despite intense research and modernisation of both the diagnostics systems and the supervision procedures of service processes, extensive failures blamed on diagnostics still occur.

The reason for that is a continuous technical development and stricter and stricter requirements regarding economics, environment protection and service ease, forcing the increase of the main engine power with simultaneous reduction of their sizes. This leads to introduction of new technologies with simultaneous increase of loads on yet-untested elements and assemblies of main engines. Similar damages to parts and assemblies of main engines discovered in differing diagnostic conditions may be followed by differing results of their occurrence.

Modern diagnostics systems described in the papers [5,7,8] are examples of practically useful expert systems, however the modern methods of accurate, reliable collection of diagnostic information, including technical possibilities and costs of their operation onboard require high qualifications from the operator, the more so that the degree of the diagnostics system complexity increases very quickly, which is followed by a variety of possible irregularities in their functioning. Therefore along with the increase of operational requirements and development of engines as diagnosed systems, it is necessary to carry out works aiming at improvement of their diagnostics systems. Rational service of main engines – and thus, at the same time, also of ships being technical objects of enormous material value, depend on their diagnostics systems. Same applies to the ecological safety of the natural environment and the crew's health and lives.

3. The rationale for building of ME diagnostic models

Analysing the collected material it can be noticed that the building of diesel engine diagnostic models is strongly linked to the development of engines themselves being the diagnosed systems, as well as the development of science fields focusing on the research into phenomena and processes taking place in such engines.

Ship main propulsion engines are complex technical objects of large size and mass, and what follows, of large inertias in parameters characterising their energy transformations. They are also characterised by a variety of energy-related states, depending on their service state [1,2].

As a result of the above the phenomena and the processes taking place in the service of a marine diesel engine have been mathematically modelled in a number of ways, including deterministic, pseudo-deterministic and probabilistic ones.

Various types of models are used simultaneously in modern diagnostic systems.

Deterministic models are most often used for operational control in conditions deemed to be normal.

The transitory or emergency conditions are modelled probabilistically, which better renders the actual conditions at sea. They provide information which facilitates rational decision-making by the operator. [1,2,3,4].

It should also be remembered in the quest for collection and analysis of a largest possible number of parameters that the crew selection process is also of stochastic nature, and that crews represent varying levels of technical training and competence (knowledge and experience).

Because of that, the information presented by a diagnostic system should be as accurate and trustworthy as possible.

Complex structure of a marine diesel engine and the numerous criteria for the evaluation of its service states make a relational model being one of possibilities.

As it has been proved in numerous publications [1,2] that the wear of engine elements and subassemblies often does not depend strictly on their total running hours, so the proposed relational model is based on a hypothesis that:

„it is possible to predict the state of a service process of main propulsion engines in $t + \Delta t$ moment when its state in t moment is only known, due to the fact that the condition in $t + \Delta t$ and its duration only depends on condition in t, and not on an earlier conditions and their duration" [1, 2, 8].

This hypothesis allows for the application in the decision-making process of the controlled semi-Markov process theory or a statistical theory of decision-making.

At the same time, a thesis is adopted that „the application of a probabilistic model for ship main propulsion engine should allow for a more rational decision-making and control of such engines' operation and service process [1, 2, 3, 4, 8].

4. Proposed diagnostic model

As a result of adopted assumptions, the process of building a ME diagnostics model required that the following problems are examined.

Identification of a ship main engine as an energy system, used, operated, diagnosed and controlled.

Identification of a main propulsion engine as a diagnostics system, and a determination of its technical and operational properties discovered its significant characteristics in the process of building a rational diagnostic model, which should consist of a diagnosed system (the engine), already adapted for diagnosing as dictated by identification results in the design phase, and a diagnosing system necessary for identification of its technical condition.

Determination of the influence that the load has on the wear rate and wear condition allows for calculating the probability of reaching parameter limit values which may lead to possible engine damage.

A basis assumption made during the building of a diagnostic model is not to establish the cause of past defects, but to take action which may lead to such decisions which would in turn enable prevention of engine damage, or at least limit significantly its consequences. Within such an activity, a particular importance is given to decision-based control of combustion engine service process, implemented within the automatic engine control system as presented in publications [1, 2, 3, 4].

Striving for full automation of engine control stems mostly from a need to reduce the influence of these engines' direct user on their operation, and to reduce the number of defects arising as a result of mistakes made in service.

Automatic control of combustion engine running (the engine is both a controlled and a diagnosed system) should be monitored by a diagnostics system integrated with a control system . Such an integration allows for controlling the engine in a way which could take into account the diagnosis generated by its diagnostics system, and then control the energy-related engine states following its changing technical condition and using control signals adapted for this condition. Building such a diagnostics system requires first building the diagnostic model of the engine, which should include the requirements for the identification of both the technical conditions and energy-related states of a given engine, as well as the monitoring of engine control system and its running.

4.1 Identification of engine technical condition.

Technical condition of any engine is a set of technical properties of its structure, which allows it to operate (run) in accordance with its purpose for which it was designed and manufactured.
This condition in any moment t in its service life depends not only on this moment, but also on the technical condition of the engine at initial $t_0<t$ moment, and the flow of engine control during this time period.
Control has a definite influence on the change of engine technical condition, which depends on a number of factors after the conclusion of its manufacturing process, as described in literature [1,2].
What follows is that the process of changes of each engine technical condition is stochastic, but continuous in state flow and time. This means that there is an infinite number of engine technical conditions. Diagnosing all technical conditions of the engine is neither possible nor desirable due to both technical and economic reasons, which leads to a need to have this set divided into a limited number of classes (subsets) of technical conditions. Assuming a dividing criterion to be engine's readiness for service, the following classes of technical conditions can be distinguished, to be called directly the conditions [1,2,8]:

- the condition of full readiness (s_1), which allows the engine to be run in full range of loads, to which it was adapted in the design and manufacturing phase,
- the condition of reduced readiness (s_2), which allows the engine to be run in full range of loads, to which it was adapted in the design and manufacturing phase, but with a meaningfully reduced overall efficiency leading to increased fuel consumption or non-compliance with ecological standards.
- the condition of partial readiness (s_3), which allows for operating the engine in a reduced range of loads, narrower than the one for which the engine was designed in design and manufacturing phase.

the condition of being out of operation (s_4), which prevents the engine from any normal usage (due to e.g. damage, execution of maintenance works, etc.).

One important task is to build a model of engine technical condition changes. In case of any diesel engine the process of its technical condition change is a process where the periods of each of its conditions duration are stochastic variables. Particular implementations of these stochastic variables depend on many factors, including the wear of tribological systems of the engine, media quality and crew competences.

4.2 Identification of engine service conditions

Taking into account the knowledge contained in literature and the results of own empirical research it was assumed that the two-stroke low-speed diesel engine used as a main propulsor drive, may be in a number of service conditions, divided into classes (sets) of elementary states, presented in the work [8].
Diagnostic activity is carried out in each of mentioned state sets, with its scope depending on the capabilities of diagnostics systems used, as well as on time needed for the taking of rational service decision.
It is then necessary to identify impacts of particular elements/ subassemblies/ subsystems on the proper functioning of other elements, as well as the consequence of this impact on the quality of processes taking place in the engine. Due to this reason the physical and chemical properties of engine elements/subsystems having some influence on the quality of engine running and determining its technical condition class have been identified.
A main purpose of ME is to provide the energy for the propulsion of a ship during the execution of a given service task.
The readiness of the engine to enable task execution, its operational effectiveness and reliability in task execution as well as safety of operation depend on the quality of its service process.

Engine service includes its running and maintenance and these can be simultaneous [1]. The specifics of main engine service in marine conditions require forward planning of the processes outlined in [8]:
- normal ME operation, where efficiency attainable within environment protection limitations is the most important factor,
- emergency ME operation (complex, hazardous, defect or a disaster taking place), where priority is the ability to reach a location guaranteeing safety of ship and its crew,
- planned maintenance, during which there is no danger to crew lives and ship, and the purpose is to restore full readiness of ME,
- unplanned maintenance (necessary in case of defects), often at sea and in unfavourable conditions bringing dangers to crew lives and the ship itself, with the purpose being just to restore partial readiness of ME and to achieve a capability of reaching a safe destination.

During the process of formulating and defining the tasks for ME in its design phase, its service system is formed at the same time [1,2].

The conditions on modern market make the shipowners optimise the ME service system and press ME manufacturers in this direction – and any such action must be based on the appraisal of current ME condition. As a result of the above, it was necessary to determine the ME service states and technical conditions, which allows for a rational service of ME, and facilitates the service-related decision-making also in emergency situations, where there is a reduced chance for making rational decisions due to stress and time pressure, as the emergency situations develop rather quickly.

The service process of any diesel engine is a compound process including the simultaneous changes of its technical condition and its service states, which has been presented in the literature in many forms such as graphs or matrices comprising probability distributions [1,2,8].

4.3 Determination of parameters identifying the technical and service conditions

The diagnosis process is greatly dependent on the information obtained via measurements fed into the diagnostics system.
It is thus necessary to define appropriate sets of diagnostic parameters which are going to provide a reliable representation of ME technical condition and its properties.
These may include the sets of : thermodynamic parameters, parameters related to vibration and acoustics, parameters related to physical and chemical properties of lubricants, and the geometric parameters defining the engine structure.
The parameter sets characterise the changes which are a result of various physical and chemical processes, often inter-related or derivative.
The values of parameters obtained during tests in manufacturer’s laboratory (in known conditions) are adopted as benchmarks.
They are strictly connected with the technical and energy-related condition of the engine, and the properties of engine elements, subassemblies and subsystems are reflected in their values.
Attention should also be brought to the fact that the diagnosing system should not only help collect the information about engine condition, but also to help control it in such a way as to avoid any damage.
In both cases the result is to be a reduction in operating costs, and what follows, also a rise of service efficiency.
Due to the above, a main purpose in the building of diagnostic models is to search for and use such parameters whose changes should most readily indicate a change of engine technical condition, including its subsystems and elements.
Progress of engine structure wear should be signalled according to earlier adopted grading.

4.4 Determination of diagnostic relations between ME technical condition and diagnostic parameters used, taking into account the results of empirical research

Another important problem in diagnostic model building is the determination of mutual relations between factors influencing the correct running and durability of the engine and the diagnostic parameters which reflect its technical condition, while taking into account the operational priorities of particular ME service conditions. The relation sets have been defined following the ME readiness criteria [8]:
- diagnostic relations projecting the full readiness condition set into a set of diagnostic parameters,
- diagnostic relations projecting the reduced readiness condition set into a set of diagnostic parameters,
- diagnostic relations projecting the partial readiness condition set into a set of diagnostic parameters,
- diagnostic relations projecting the out-of-operation condition set into a set of diagnostic parameters.

4.5 Definition of a relation-based diagnostic model of ship ME

ME is a complex object and its model aimed at collection of diagnostic information may be a combination of various types of models, and may be presented in analytical, functional or topological form. Each model representation form has its research and educational value. The utilitarian value of a model of examined object depends on a number of factors, including a form used for the presentation of the results of analysis performed on data collected within the real-life diagnostic system.

Scientists tend to use forms of models different than those which could be easily understandable for ship crews which belong to a wide range of technical cultures and have highly varying levels of technical knowledge and psychological predispositions. In marine environment, the most suitable form of ME model seems to be a topological model containing the bidirectional relations between engine condition and diagnostic parameters. The drawing below presents the selected diagnostic relations projecting the condition of full readiness s_1 into a set diagnostic parameters k.

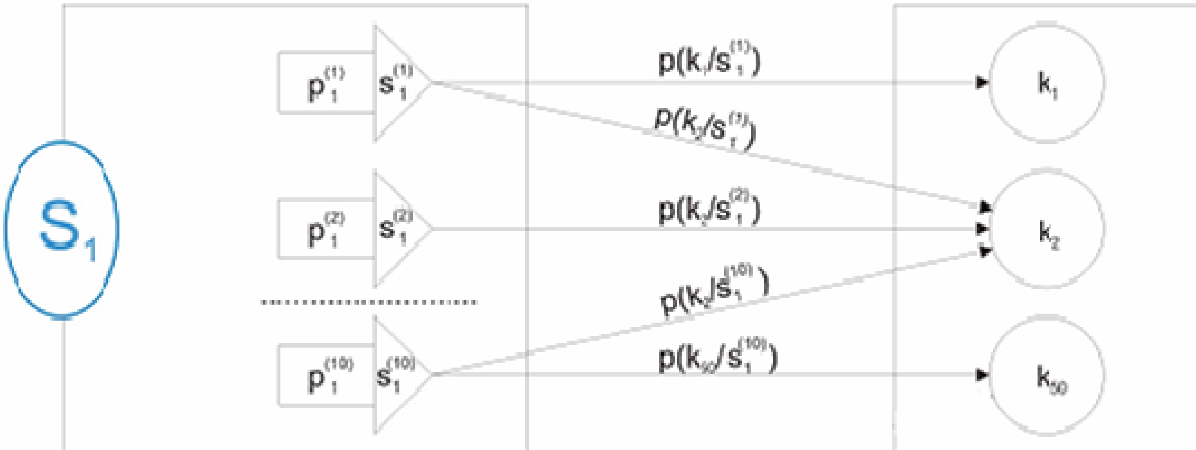

Fig.1 Selected diagnostic relations mapping the full readiness conditions set s1 into a diagnostic parameter set k[8].

Decision-based control of engine service process is the most important and most difficult problem in engine service, which follows from the fact that such a control is carried out in a stochastic situation with regard to decisions.

In such a situation, evaluation of statistical risk connected with making a wrong decision should be taken into account.

Such a wrong decision may be taken as a result of inability to precisely evaluate the unknown parameters of stochastic variable distributions, which are the conditions of engine service process, and also due to a lack of capability to obtain full and reliable diagnosis of engine technical condition.

Rational control of this process requires furthermore that statistical decision-making models are built for the purposes of control.

A theory of decision-based, controlled semi-Markov processes or a statistical theory of decision-making can both be used for the building of such models, being presented in detail in publications [1,2,3,4].

In case it is impossible to use objective probabilistic measure for the specification of diagnosis reliability which is the presented mathematic and logical probabilities, there is a need to frame the idea of diagnosis trueness in terms of subjective probability, also called a psychological one.

This probability refers to the degree the user of a diagnosis is convinced about chances of engine condition prognosis becoming true.

In this case, calling a diagnosis a reliable one is a subjective process, as it depends on the knowledge of a person preparing a diagnosis and his/her conviction about correct functioning of ME diagnostics system.

The above discussion can be based on calculations based on expert method [8].

On the basis of assigning appropriate diagnostic parameters to selected engine service states, which was presented in paper [8], a diagnostic model including relations shown in Fig.2 has been built, with the following concepts included: p_{ij} – probability of s_{ij} condition occurring, s_{ij} – engine service condition from the set S (s_1, s_2, s_3, s_4), $p(k_i/s_{ij})$ – probability of diagnostic parameter k_i occurring simultaneously with condition s_{ij}, k_i – diagnostic parameter, S_1, S_2, S_3, S_4 – classes of ME conditions.

5. Opportunities to implement the engine diagnostic model in service.

Main engine damage in real-life conditions is a random phenomenon. The results of each defect depend on:

- the time the change in ME condition leading to its damage is identified,
- accuracy of ME condition change identification,
- aptness of decisions taken as a result of ME condition change.

In sea conditions, where it should be assumed that the crew can count only on own skills and technical capabilities, possibly quick detection of ME partial readiness condition may contribute to saving the crew and cargo, as it allows the crew to ensure the safety of a ship.

Due to that it is so important to use diagnostic systems adapted for service needs resulting from the necessity that the decisions are made by the crew and the shipowner together. This also applies to diagnostic models which should be adapted for operation in real-life conditions. Many factors capable of interfering in diagnostics system operation need to be taken into account during their building, such as imperfections in ME structure and varying levels of crew competence [1,2,8].

Measurement relations should reflect the conditions of measurement and the accuracy of applied measurement methods, measurement equipment accuracy, physical properties and measured signals and their parameters, and the required accuracy of diagnostic measurement results.

The obtained set of results of a diagnostic examination is always charged with errors, sometimes significant ones, which may be a reason for obtaining a wrong (unreliable) diagnosis.

Due to this the examination results reflect the examined ME condition only to an approximate degree. This means that they do not inform the user of diagnosis about ME condition itself, but only about an approximate picture of this condition.

Therefore, what is important is to what degree the information about ME condition contained in its diagnosis is reliable, because it has to be processed to obtain diagnostic information about ME condition at further stages of deduction which are not immune to their own errors either.

It should be emphasized that the results which shall allow for a verification of a diagnostic model (in real-life service) or the aptness of decisions taken by human operator, are their real-life consequences.

The engineers operating the engine room and main engine propose the concepts of rational service actions to the shipowner. Quite often they are unable to convincingly justify the grounds for a specific preventive maintenance (as the diagnostic parameters do not exceed limit values) and are loathsome to take responsibility for any decision which generates substantial costs. These costs normally exceed the salary of a decision-maker by a dozen or a few dozens times, so their psychological impact is rather strong as none wants to be labelled as a source of such costs, which may lead to less than rational decisions being made.

At the same time the conditions of work in ship engine room, the daily changing of shifts, crew cultural multiplicity, random and varying work conditions (weather, sea states, emergencies, cargo shifts etc.) require constant attention and result in tiredness, loss of sensitivity to stimuli and paradoxically in a highly flux environment, a routine and mindless execution of duties, which also contributes to a loss of rationality in acting.

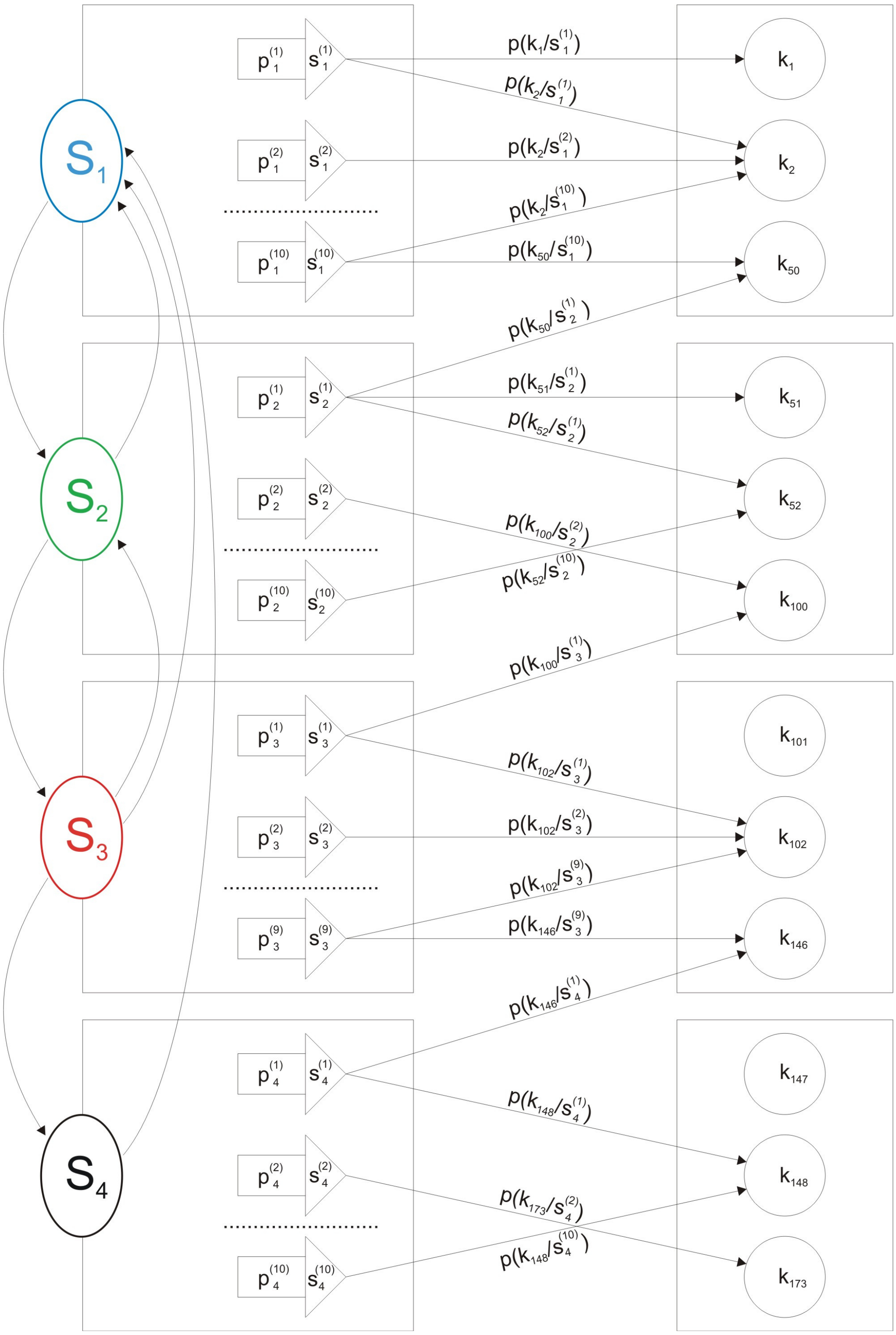

Fig.2 Relations in ME diagnostic model: p_{ij} – probability of s_{ij} condition occurring, s_{ij} – engine service condition from the set $S(s_1,s_2,s_3,s_4)$, $p(k_i/s_{ij})$ – probability of diagnostic parameter k_i occurring simultaneously with condition s_{ij}, k_i – diagnostic parameter, S_1, S_2, S_3, S_4 – classes of ME conditions

6. Summary

In order to make a correct service-related decision, its significance should be estimated first, i.e. its consequences should be predicted. In spite of complexity of this task some mathematical solutions have been proposed [1,2,3,4]. However, in real-life conditions, and particularly in random and variable conditions at sea, it is very difficult to predict the consequences of service decisions, and even more so that in addition to the above there are variable external conditions and the crew operating the ME also changes in a practically random fashion.

A relation-based diagnostic model of ship main engine has educational value and utilitarian value as well. In first case it is because the relations between discrete engine conditions and its signals have been identified, while in the latter it is because the model shall allow for an identification of real-life main engine technical condition and to predict its future conditions as well - through deduction.
Use of this model in practice may facilitate the decisions related to further engine operation or to any preventive maintenance aimed at restoration of its technical condition.

Broad competences of humans are clearly visible in modern diagnostics systems. Most modern decision-support systems on a ship are based on mutual co-operation between the ship engineer (operator), shipowner experts and manufacturer experts. This co-operation may bring about synergistic effect, but it is a ship engineer who has to make a service decision and bear responsibility for it.

Because of that and as a part of expert-evaluated data verification, in further research on the development of diagnostic models and real-life diagnostic systems efforts should be concentrated on the examination of statistical reliability of: engine elements, structural nodes, engine systems, engine as a whole, elements and subsystems of a diagnostics system as well as whole system, the ME – diagnostic system interface, and so the whole diagnosing systems.

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