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Examination of informativeness of diagnoses expressed with multiple-valued logic

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Abstract. This paper presents the essence of an examination of informativeness in the diagnostic information outputs expressed with multiple-valued logic. The diagnostic test required for the examination was completed on wind turbine equipment. The examination included a constant set of determined diagnostic output values. The DIAG 2 diagnostic system was used for the examination and the diagnostic test. DIAG 2 is a smart diagnostic system capable of any inference k of the set $\{k = 2, 3, 4\}$. The examination results were expressed in an Object State Table, separately for each k-valued logic of inference tested.

Keywords: technical diagnostics, diagnostic inference, multiple-valued logic, artificial intelligence
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1. Background

Technical diagnostics is not only an activity of its own; it is designed to provide owners of engineering facilities with services which favour organisation of effective facility servicing and maintenance systems. Prior solutions applied in these applications of technical diagnostics were based on two-valued logic, where the value 1 denotes an operational state and the value 0 denotes a non-operational state. A strategy of organisation of an operation process based on the operational states determined by two-valued logical diagnostics has poor effectiveness. The two possible states which can be recognised prevent any scheduling of technical servicing. No refurbishment (reconditioning) of serviced facilities is scheduled for the state value 1 (operational). An assumption is valid that a logic valued at ($k > 2$) would be more effective in this regard due to the informativeness of the diagnostic outputs which can support the organisation of engineering facility servicing.

The organisation of facility servicing relies heavily on the ability to identify the states which precede a non-operational state of a facility; hence, the application of two-valued logic for this identification is insufficient [1-14]. Diagnostics based on three-valued logic inference was developed. Hence, any application of two-valued logic in the organisation of a servicing process is insufficient for the objective [1, 2, 3, 6]. Practical applications saw an increasing use of the three-valued logic developed by J. Łukaszewicz. The authors of [2-10] presented their research achievements which significantly increase the value of facility diagnostic solutions as far as three-valued logic inference is concerned. The classification of states applied with three-valued logic defines the operational state "2", the non-operational state "0", and the partially (reduced) operational state "1". The references [1, 2, 5] demonstrate that the application of this third state expands the deliverable scope of diagnostic results. The evaluation of informativeness in the examination of multiple-valued logic-based diagnostic outputs is a problem worthy of interest. Its solution is the objective discussed in this paper.

2. Problematic aspects of multiple-valued logical inference

Engineering facility diagnostics with k-valued logic at ($k > 3$) are currently in development. Three-valued logic applications for technical diagnostics have been extensively researched and developed in recent years, and especially in smart servicing systems. Notable works in the field include [2-10]. Works [2, 5] present a novel organisational concept of a servicing system, including the control of the operating process with three-valued logic. In this concept, reliable diagnostic outputs (information) are determined by a smart diagnostic system developed with the application of an artificial neural network. An innovation introduced by this class of smart diagnostic systems is the diagnosis of states with three-valued logical inference. The experience of this team of authors in the diagnostics of radiolocation systems and the conclusions of the team related to the acquisition of diagnostic information usable in the organisation and design of servicing systems are presented in [4, 6, 8, 9, 14]. These works detail the design of a developed intelligent system, capable of identifying the states of structural members inside facilities and works.

The essence of inference in the multiple-valued logic of diagnostic systems is shown in Fig. 1.

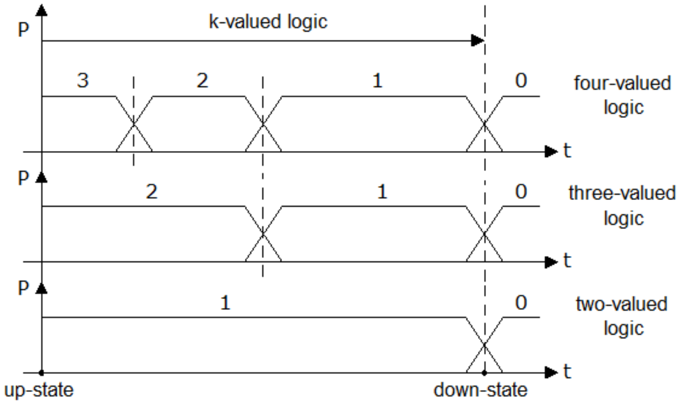

Fig. 1. Essence of inference in the multiple-valued logic of diagnostic systems

The development of three-valued logic ($k = 3$) with the states defined within a set of {2, 1, 0}, was significantly contributed to by the authors of [2, 3, 4]. The application of three-valued logic in the diagnostics of engineering facilities, industrial processes and manufacturing processes, provided significant information effects. A distinctive achievement of application of three-valued logic was the determination of the partially operational state, "1". The ability to determine the partially operational state became a foundation for the development of modern smart systems which support the organisation of servicing systems for engineering facilities [1, 2, 5]. It can be assumed that k-valued logic may provide completely new experiences in the operation of engineering facilities.

The existing references do not include any work concerning applications of k-valued logic with ($k > 3$) in technical diagnostics. If the ***partially operational state, "1"***, is distinctive in three-valued logic ($k = 3$), then four-valued logic ($k = 4$) has the distinctive state ***"1" defined as the critical operational state***. The critical operational state of four-valued logic may include the j structural features of j of a facility, or object, the reliability of which is nearly critical at the given moment. The internal elements in the critical operational state continue to function and are operated directly before their sudden (critical) failure. Hence, the problem of identification of the critical operational state "1" in ($k = 4$) logic becomes extremely important to technical diagnostics.

3. Structure of a smart diagnostic system applied in the monitoring of the technological process state

If a facility is in continuous use (operation) and under continuous diagnosis, it is possible to refurbish (recondition) the facility when a partial operational or non-operational state is identified. If the time to a partial operational or non-operational state is known or can be determined, it is also known when the facility should be refurbished (reconditioned). This approach (the application of refurbishment strategies) solves the basic problem of control systems, the recovery of a control system's asset of functioning, namely a unit of automatic state identification of the facility and its structural elements as shown in Fig. 1. The structure of the smart diagnostic system which monitors the state of a technical and technological process is a complex system of hardware and software devices. A modern diagnostic system (Fig. 2) does not only comprise a test card with a properly selected test circuit; it is all its computer tools above all. Computer programs facilitate proper recording, processing and analysing of diagnostic outputs, and compilation of a test knowledge bases (containing the measured values). A diagnostic system (Fig. 2) was developed for the state identification diagnostic system in a facility. The essential elements of the diagnostic system comprised:

- a test structure of the facility produced by a functional and diagnostic analysis. The deliverable of the functional and diagnostic analysis was a set of facility elements (modules) $\{e_{i,j}\}$ which provided test outputs, and a set of distinctive test outputs (diagnostic outputs) $\{X(e_{i,j})\}$;
- a diagnostic module, which was a unit of test devices of the diagnostic system facilitating the adjustment of the test outputs to the test card via a test interface;
- the test card was a dedicated measurement device which measured the test (diagnostic) output values $\{X(e_{i,j})\}$;
- the test card software was a dedicated computer program which controlled the operation of the test card, by which the test card facilitated the delivery of the test expert knowledge base $\{W(\varepsilon(e_{i,j}))\}$, formatted into a table [2];
- DIAG 2, the dedicated diagnostic software based on an application of artificial neural networks and adapted for multiple-valued logical inference (with selectable two, three and four-valued logic).

The objective of the diagnostic system was to compare the image of a diagnostic output vector to the image of its reference (nominal) output vector. It was

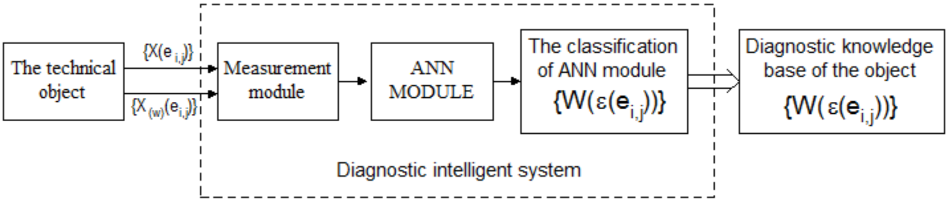

Fig. 2. Structural diagram of the diagnostic system in DIAG 2 software [2], where: $X(e_{i,j})$ — diagnostic signal in j^{th} element of i^{th} set; $X_{(w)}(e_{i,j})$ — model signal for $X(e_{i,j})$ signal; F_C — value (min. and max.) of the function of the use of the object; $W(e(e_{i,j}))$ — value of state assessment logics for j^{th} element within i^{th} module of the object; ANN — diagnostic module with an artificial neural network

convenient to present the images of the compared diagnostic outputs as vectors (Fig. 2). An analytical form of the diagnostic equation which described the process of engineering facility (object) diagnosing (Fig. 2) by comparison of diagnostic outputs to a reference, was shown as the following relation:

$$\underset{e_{i,j}\in\{E_i\}}{\forall}\ \underset{X(e_{i,j})\in X}{\exists}\left(X(e_{i,j})\mapsto X_{(w)}(e_{i,j})\right)\Rightarrow W\left(\varepsilon(e_{i,j})\right), \tag{1}$$

with: $X_{(w)}(e(e_{i,j}))$ — reference diagnostic output of the element *j* in the unit *i*;
$X(e_{i,j})$ — diagnostic output from the element *j* in the unit *i* of the diagnosed facility;
$W(\varepsilon(e_{i,j}))$ — the diagnostic output comparison resultant for the element *j* in the unit *i* of the diagnosed facility;
$\forall$ — general quantifier;
$\exists$ — existential quantifier;
$\mapsto$ — comparative relation;
$\Rightarrow$ — resultative relation.

The relation could be interpreted as follows: the output of each element j in the unit *i* of the facility (the diagnosed object) $e_{i,j}$ has a diagnostic output (signal) $X(e_{i,j})$, compared to its relevant reference diagnostic output. The effect of this diagnostic action is the check result $D_i(\varepsilon(e_{i,j}))$ — the diagnostic output comparison resultant for the element *j* in the unit *i* of the diagnosed facility. If a specific logical value of state was assigned to each of the results in the diagnostic process, the diagnostic check of the facility (the diagnosed object) could be represented with a table of diagnosis (an Object State Table). This diagnostic action process is shown with a flow chart in Fig. 2 [2].

4. Examination of the informativeness in multi-valued logic developed by the smart diagnostic system

The development of technical diagnostics has been seeing a steady improvement, demonstrated by a growing accuracy of identification of the state of engineering facilities (objects). The hierarchical development of technical diagnostics demonstrated applications of two-valued logic for diagnostic inference. These were followed by reference works on the diagnostics of engineering facilities with three-valued logic. The works by [2-5] were significant for the development of three-valued logic diagnostics. The next step in the evolution of technical diagnostics is the application of inference with four-valued logic. The first works in this field are [4-9]. Four-valued logic diagnostics is currently in the first stages of development. The essence of four-valued logic diagnostic applications and its rules are understood. Technical solutions based on practical applications of four-valued logic have been used with a significant effectiveness. A research team headed by professor S. Duer at the Koszalin University of Technology, Faculty of Mechanical Engineering, developed a smart diagnostic system, DIAG 2, which diagnoses engineering facilities with *k*-valued logic of ($k = 2, 3, 4$).

Thanks to the informativeness of the diagnoses provided with a specific *k*-value of $\{k = 4, 3, 2\}$, technical diagnostics is a tool which explicitly identifies and describes the performance (reliability) of the diagnosed engineering facility by assigning a correct state [4-9] (Fig. 3). The *k*-value of each of the *k*-valued logic applied to infer the state of the diagnosed engineering facility directly affects the informativeness (entropy of information) in that *k*-valued logic ($k = 4, 3, 2$). Two-valued logic, which was developed and popularized in technical equipment diagnostic engineering, could identify the object states limited to the set of {1, 0}. The diagnostic inference applied in two-valued logic differentiates the operational state "1" and the non-operational state "0". Hence, the informativeness of two-valued logic is very limited. It can only interpret two essential operating states of the diagnosed facility. Fig. 3 shows the flow chart of a diagnostic action based on the permitted potential change of the feature *k* of the diagnostic output.

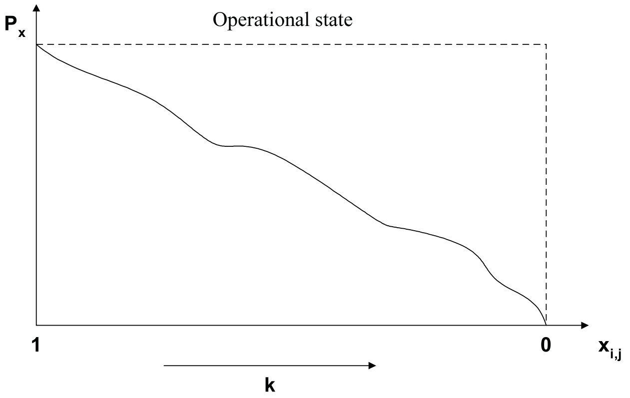

Fig. 3. Flow chart of the principles of diagnosis based the changes of the diagnostic output feature, with: *k* — inference interval size; <1, 0> — interval of the operational state of an engineering facility; P_x — parameter change x of x of the diagnostic output

A successful identification of the actual operational state of a facility which may potentially suffer from different types of faults is more likely when multiple-valued logic is applied. To derive the diagnostic information approximate to the actual information, the set of state classes must be refined by adding more state classes. It is appropriate to introduce a third state class, **partial operational state**, to derive true diagnostic information for engineering facilities in the third period of operation, where ageing, wear, maladjustment, out-of-tune, etc. defects are critical.

Fig. 3 reveals that the values of the feature *k* of *k* of the diagnostic output vector [$X_{i,j}$] shown on the variable axis of the coordinate system can change within an interval of <1, 0>. The interval of potential changes can be divided into more precise values, depending on what *k* the logic is. If diagnostic inference rules are developed in the interval that explicitly identify the intermediate state between the operational state "1" and the non-operational state "0", the **(k = 3) three-valued logic inference** will apply. If diagnostic inference rules are developed in the interval that explicitly identify two intermediate states between the operational state "1" and the non-operational state "0", the **(k = 4) four-valued logic inference** will apply.

The basic form of the derived diagnostic information from DIAG 2 to be analysed was the Object State Table. The finished information can be output into other graphical forms of visualisation, including charts, histograms, and reports. A combination of specific output presentation forms enables a more thorough analysis, or a more efficient comparison of the finished diagnostic information outputs for different *k*-values of the logic applied to evaluate the states (Fig. 4).

Fig. 4 shows a cumulative statement of diagnostic information in the tested *k*-values of the logic of state evaluation in the basic elements *j* of *j* contained in the functional units *i* of *i* of an engineering facility (the diagnosed object). Fig. 4 shows three sections: the top section shows the 4-valued logic-based assessment, the middle section shows the facility (object) testing with 3-valued logic, and the bottom section shows the shows the facility (object) testing with 2-valued logic.

The bottom section of Fig. 4 provides the diagnostic results for the facility (the object) with 2-valued logic inference. Fig. 4 shows that all elements in the set tested with 2-valued logic had the operational state "1". This may happen in practical applications, especially when a factory-new facility has just been commissioned for operation.

It may also happen when the diagnostic test intended to evaluate the state of an engineering facility has a too narrow (acute) permitted value interval <$\Lambda X_{i,j}$> of the features *k* of *k* of the basic elements *j* of *j*, contained in the functional units *i* of *i*. For this examination, a permitted value interval of <$\Lambda X_{i,j}$ = 5%> was adopted for the features *k* of *k* of the basic elements *j* of *j*, contained in the functional units *i* of *i*. The information derived with 2-valued logic on the states of the diagnosed facility (object) was too poor. This confirmed the argument that it is not possible to organise a servicing strategy of engineering facilities (diagnosed objects) with 2-valued logic diagnostics.

The middle section of Fig. 4 shows the information about the states of the basic elements *j* of *j* in the functional units *i* of *i* derived with 3-valued logic. A study of Fig. 4 revealed that the basic elements in the subset {$e_{1,1}$; $e_{1,2}$; $e_{1,3}$; $e_{2,2;}$ $e_{3,2}$; $e_{3,3}$; $e_{3,4}$; $e_{4,2}$; $e_{5,1}$; $e_{5,2}$; $e_{6,2}$} were in the operational state "2". The percentage share of the operational elements *j* of *j* in the tested object's structure was 55%. The basic elements in the subset {$e_{1,4}$; $e_{1,5}$; $e_{2,1;}$ $e_{2,3;}$ $e_{3,1;}$ $e_{4,1}$; $e_{6,1}$; $e_{7,1;}$ $e_{7,2}$} were in the partially

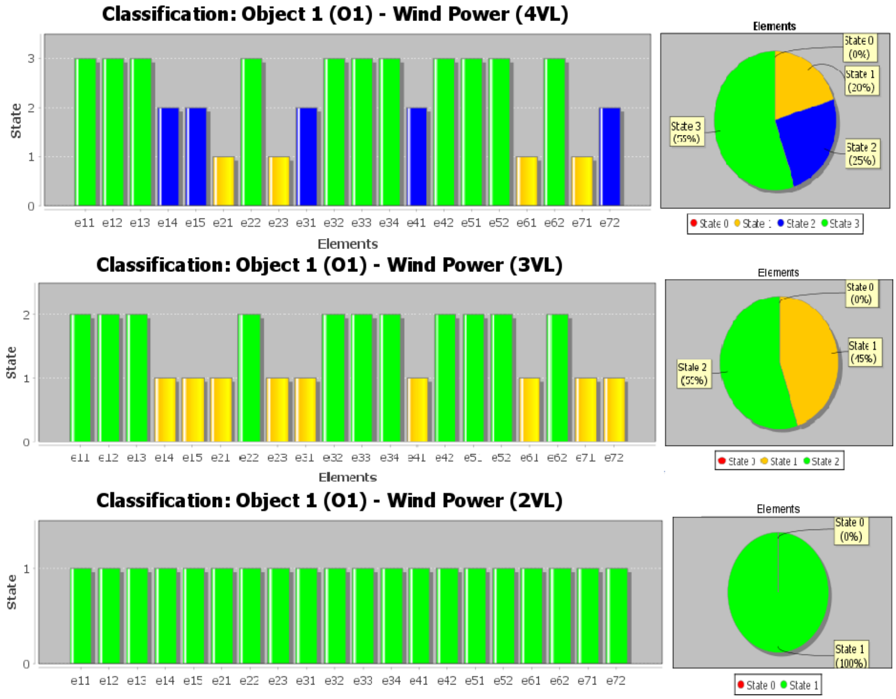

Fig. 4. Diagnostic information summary screen in DIAG 2, where: (4VL) — for concluding in four-valued logic, where: "3" — the usability state of the technical object; "2" — partial usability state; "1" — critical usability state; "0" — means fault state; (3VL) — for concluding in three-valued logic, where: "2" — usability state of the technical object; "1" — incomplete usability (partial usability) state; "0" — means fault state; (2VL) — for concluding in two-valued logic, where: "1" — means the usability state of the technical object; "0" — means the fault state

operational state "1". The percentage share of the partially operational elements *j* of *j* in the tested object's structure was 45%. There were no non-operational state "0" elements in the tested object. A conclusion can be made that the diagnoses made by application of 3-valued logic feature a higher informativeness (a richer information content) than the diagnoses based on 2-valued logic. A confirmation of this statement was the interpreted subset of the object elements with the partial operational state "1". The interpretation (identification) of the partial operational state enables application of an operational-state-based servicing organisation strategy for engineering facilities (objects).

The top section of Fig. 4 shows diagnostic information with 4-valued logic. 4-valued logic expands 3-valued logic with the critical operational state, "1". The identification of the critical operational state enables application of an operational-state-based servicing organisation strategy for engineering facilities (objects) at a very high efficiency.

A study of Fig. 4 revealed that the basic elements in the subset {$e_{1,1}$; $e_{1,2}$; $e_{1,3}$; $e_{2,2}$; $e_{3,2}$; $e_{3,3}$; $e_{3,4}$; $e_{3,2}$; $e_{4,2}$; $e_{5,1}$; $e_{5,2}$; $e_{6,2}$} were in the operational state "3". The percentage share of the basic elements *j* of *j* in the operational state in the functional units *i* of *i* of the objects was 55%. The basic elements in the subset {$e_{1,4}$; $e_{1,5}$; $e_{3,1}$; $e_{4,1}$; $e_{7,2}$} were in the partially operational state "2". The percentage share of the partially operational elements *j* of *j* in the tested object's structure was 25%. The remaining tested subset of basic elements {$e_{2,1}$; $e_{2,3}$; $e_{6,1}$; $e_{7,1}$} were in the critical operational state "1". The percentage share of these critical operational elements *j* of *j* in the tested object's structure was 20%. The tested object featured no non-operational state "0" basic elements.

5. Conclusion

The testing of an engineering facility's operational state by the application of 4-valued logic diagnostics allowed an evaluation of the diagnostic information increment with 4-valued logic. In the diagnostic test, the results of which are shown in Fig. 4, 9 states were determined aside from the operational and non-operational states. Hence, the increment of diagnostic information by the application of *4-valued logic was 45% from 2-valued logic*. A unique achievement of the application of 4-valued logic was the ability of identifying the critical operational state, "1". In the diagnostic test made for this work, the critical operational state "1" was identified for the elements in the subset {$e_{2,1}$; $e_{2,3}$; $e_{6,1}$; $e_{7,1}$}. The percentage share of these critical operational elements *j* of *j* in the tested object's structure was 20%.

The diagnostic test and examination of the results indicated that an aspect which became important to technical diagnostics is the determination of the optimum time of identification of the state of the structural elements of diagnosed facilities which are or will (soon) be in the critical operational state ("1" in 4-valued logic). It is then important to properly identify the (reliability-related) operational states which can occur in an engineering facility prior to its failure. Failure to identify the operational states properly is a risk of failure which will render the engineering facility non-operational.

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Badanie informacyjności diagnoz wyrażanych w logikach wielowartościowych

Streszczenie. W artykule zaprezentowano istotę badania informacyjności diagnoz informacji diagnostycznej wyrażonych w logikach wielowartościowych. Badanie diagnostyczne przeprowadzono dla urządzeń elektrowni wiatrowej. W badaniu wykorzystano stały zbiór wyznaczonych wartości sygnałów diagnostycznych. Podstawą prowadzonych badań był wykorzystany system diagnostyczny (DIAG 2). Inteligentny system diagnostyczny (DIAG 2) posiada możliwość wnioskowania w jednej z dowolnej *k*-tej logiki wnioskowania ze zbioru $\{k = 2, 3, 4\}$. Uzyskane wyniki badania wyrażono w postaci „Tablicy stanów obiektu” oddzielnie dla poszczególnych logik wnioskowania.

Słowa kluczowe: diagnostyka techniczna, wnioskowanie diagnostyczne, logiki wielowartościowe, sztuczna inteligencja

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