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Determining the Set of Elements for Automatic Monitoring and Diagnosing the Relay Interlocking System

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Abstract

The majority of train movement control within a station in Ukraine railways is achieved by the relay interlocking system (RI). There is no self-diagnosing in RI systems. Therefore, the time spent on failure recognition, localization and correction (especially those that occurred in the RI tower) is significant. Most RIs have been operating for more than 30 years, yielding a gradual increase in the failure rate and, consequently, delays. Failure effects can be reduced by automating the process of failure localization in RI applying the appropriate automatic monitoring and diagnosing (AMD) system. A subset of input signals of the latter is composed of signals from the sensors that measure the states of RI's elements. A large number of RI elements and limitations on the resources regarding the AMD system installation stipulate the virtual impossibility to equip all RI elements with corresponding sensors. The purpose of this research is to determine a set of elements in the tower-located part of RI to be equipped with corresponding sensors intended to be used in the AMD system, considering the limitations on the resources regarding the AMD system installation. In this research, we propose to apply fuzzy logic to consider assessing the appropriateness of including particular elements in the tower-located part of RI to the elements-under-monitoring (EM) set obtained from a single individual (Mamdani fuzzy inference system) or a group (rank ordering) of experts in the field of the RI operating. Research results yielded recommendations regarding the process of selecting the elements in the tower-located part of RI to be included in the EM set, considering the limitations on the resources regarding the AMD system installation. The AMD system development is out of the scope of the current research. Further studies are needed to provide an economic justification of the AMD system operation based on the EM set.

KEY WORDS: *relay interlocking system, failure, monitoring, diagnosing, fuzzy logic*

1. Introduction

Railway transport is the important component of Ukraine's economy. This is confirmed by the fact that in 2021 the Joint-stock company “Ukrainian Railway” (national carrier of cargos and passengers in Ukraine) transported 314.3 million tons of cargo [1]. As a rule, effective control of train traffic is achieved through the use of railway automation systems. In Ukraine, the control of train traffic within the railway station is carried out by the system of electric interlocking (EI). Most EI systems that used in the railway network of Ukraine are implemented on a relay element base (relay interlocking – RI). Specialists that maintain the RI systems report a gradual increase in the failure rate of such systems. According to specialists, one of the reasons for this is the excess standard service life of the RI systems (source: own survey at stations equipped with RI).

In RI systems, most failures are detected only after an attempt to use a failed element, instead of the failure occurrence [2]. Thus, in the general case, elimination of the failure requires a delay in the movement of trains (distortion of the train schedule), i.e. leads to increased risk of delays in the transportation of passengers and cargos.

Currently, prompt failure localization in the indoor equipment of the RI system and the determination of the failure causes are implemented through the actions of employees that maintain the RI system. A high level of qualification and extensive experience in the RI system are the mandatory requirement for these employees. Additionally, employees must reside in the RI tower (indoor) at the time of the failure recognition. That is difficult to achieve because the professional responsibilities of the employees also include outdoor operations, e.g. maintenance of the track objects in the railway station.

Alternatively, the failure localisation time may be reduced with automatic monitoring and diagnosing (AMD) of the actual state of RI elements. The AMD is implemented in modern EI systems based on microprocessors [3]. Application of AMD for the RI elements provides the following benefits: requirements for the qualification and experience of employees maintaining RI are simplified; the residence of the employee in the RI tower at the time of the failure recognition is not required; the failure recognition at the time of its occurrence is feasible. These benefits will reduce possible train delays. The development of the AMD system is beyond consideration in this paper.

Among the problems arising in the development of AMD systems for the indoor equipment of RI, there is a selection of the set of elements, which will be equipped with sensors to monitor their state (elements under monitoring – EM). Similar issues are considered in the field of technical diagnostics (see, for example [4]). A comprehensive solution is to assign all elements (relays) of indoor RI equipment to the set of EM. Large railway stations may include more than one thousand relays. Therefore, the cost of AMD equipment is expected to be relatively significant. On the other hand, in the case when the EM set includes relays having a relatively low degree of influence on the failure recognition in the RI indoor equipment, a sufficient level of the AMD system efficiency won't be achieved (a significant number of failures may not be detected).

There are various methods to determine the set of EM. In paper [5], a method to determine the EM set for the track equipment of the RI system, based on the statistical data, was proposed. This method considers the statistics of the following parameters [6]: the average delay duration of one train, the average delay duration of the train per one failure, the average number of delayed trains per one failure, etc. Paper [7] states that in the case of developing the AMD system for RI indoor equipment, the determination of the EM set is performed by the method of expert evaluations. Unfortunately, the literature review did not reveal an explicit description of the possible implementation of the expert evaluations. Therefore, the topic of this paper, which is devoted to determining the elements of RI indoor equipment that should be included in the EM set of AMD system, is relevant. The purpose of this paper is to define elements of the RI indoor part that must be equipped with appropriate sensors for use in the AMD system, considering the resource constraints regarding the installation of the AMD system.

Since a detailed description of the expert evaluation implementation to determine the EM set of the RI indoor equipment wasn't found in previous papers, the application of fuzzy logic to consider the expert evaluation has been proposed. Fuzzy logic has many applications for solving problems related to railway transport, e.g.: fault detection and identification for point machines [8], bearing fault diagnosis and degradation assessment [9], improving image processing to increase safety at the level crossings [10], tool for supporting decision-making in planning transport development on a strategic level [11]. However, the literature review did not reveal the application of fuzzy logic to determine the EM set of RI indoor part for use in the AMD.

To achieve the aim of investigation in this paper the following tasks have been solved.

1. Seven properties of the element by which the expert evaluated the appropriateness of including the elements of RI system in the set of EM have been determined. Appropriate evaluation scales, based on the method of semantic differentials (SD), have been selected [12].
2. The Mamdani fuzzy inference system (FIS) [13], considering the one expert's opinion (E1P) on the appropriateness of including elements of the RI system in the EM set and based on previously selected seven properties has been designed.
3. To consider the opinions of the expert group (EGP), the membership function (MF) of the “The most significant property” fuzzy set for certain elements of the RI, using the rank ordering procedure, has been defined. Obtained results were used to set to the inputs of Mamdani FIS that developed in the previous step.
4. Comparison of the results obtained from Mamdani FIS in cases of E1P and EGP has been carried out.

2. Methods

2.1. Determining the Properties of RI Elements

We performed the initial steps of the SD method [12] to determine properties and corresponding scales for the expert’s evaluation of the appropriateness of including particular elements in the tower-located part of RI to the EM set for the AMD system. The SD method implies the use of bipolar scales with semantically opposite statements located at their ends. In this paper, we assumed the S scale as the following set

$$S = \{-3 \quad -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3\}. \tag{1}$$

An employee of the JSC “Ukrainian railways” participated in this research as a volunteer expert with a high level of qualification and significant expertise in RI systems. The expert’s survey determined 7 properties designated as $a_1, a_2 \ldots a_7$ and corresponding opposite values in the “Positive value” and “Negative value” columns.

In the Ukrainian railway network, data about the failure rate (the a_3 property) of elements in the tower-located part of RI are collected centrally as an aggregated record (in a single field of a report). Therefore, it's quite problematically to obtain the corresponding value for a particular element in the tower-located part of RI from the official reports (for internal use only). However, data related to faulty elements are stored in the corresponding station logs. This allows to identify the failure rate for each element.

During the estimation of time (property a_5) spent on the failure correction of the element in the tower-located part of RI, the expert should consider the following:

1. The time of failure localization significantly depends on the presence of monitoring of the element's state through the dependencies in the RI system.
2. Failure category: systematic failure or intermittent failure.

Table 1

Properties to evaluate the elements in the RI system

Property ID	Property name	Property description	Positive value	Negative value
a_1	Impact of the element's failure on the rail traffic safety	The influence degree of the failure of the element in the tower-located part of RI	Impact is low	Causes hazardous failure
a_2	Impact of failure on the up state of RI system	The influence degree of the failure of the element on the up state of tower-located part of RI.	Up state is not lost	The system is in the down state
a_3	Failure rate	The failure rate of particular element in the tower-located part of RI	Failures are virtually absent	Failure rate is the highest
a_4	Deviations in the train schedule and delays in train movements within a station	The influence degree of the element in the tower-located part of RI on the train delay in case of this element's failure	Delays in train movements are absent	Delays in train movements are the biggest
a_5	Down time	The time spent on the failure correction of the element in the tower-located part of RI	Is the lowest	Is the highest
a_6	Indirect monitoring	The degree of monitoring of the state of the element in the tower-located part of RI that is provided through other elements.	Is possible	Is impossible
a_7	Maintenance time	The time and periodicity of testing the state of the element in the tower-located part of RI	Is minimal	Is maximal

2.2. Developing the Fuzzy Inference System that Considers the Opinion of a Single Expert

To consider the E1P the Mamdani FIS was developed (see the structure in Fig. 1).

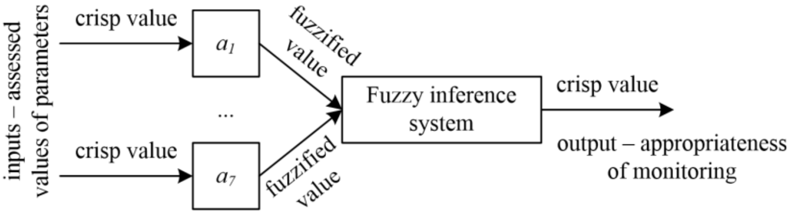


Fig. 1 Structure of Mamdani fuzzy inference system

A number from the S set (see Eq. (1)) was set to inputs of each property (Table 1) in Mamdani FIS (Fig. 1). One expert evaluated numeric values of inputs for the $a_1, a_2 \ldots a_7$ properties of a particular element in the RI system, which should be evaluated for the appropriateness of including in the EM set. At Mamdani FIS's output, the numeric value in a closed interval of real numbers $[0,1]$ was returned, where 0 means the "element is not appropriate to be included in the EM set", 1 - the "element is appropriate to be included in the EM set".

Sets of linguistic values and linguistic variables [13] in the Mamdani FIS (Fig. 1):

1. Inputs were set according to Table 1: $a_i \in \{$"Positive value" "Negative value"$\}$.
2. Output ("Appropriateness of monitoring"): $b \in \{$"Element is not monitored" "Element is monitored"$\}$.

The output value of Mamdani FIS was additionally defined by:

1. MFs of inputs: $\mu_{ai,j}(x)$, where $i \in \{1, 2 \ldots 7\}$ – number of the input (property), $j \in \{1, 2\}$ – index designating the values "Positive value" and "Negative value", correspondingly. The $x \in S$ was assumed.
2. MF of the output: $\mu_{b,1}(y)$ – "Element is not monitored", $\mu_{b,2}(y)$ – "Element is monitored". The $y \in [0,1]$ was assumed.
3. Rules in the "IF-THEN" form, mapping the inputs to the output.

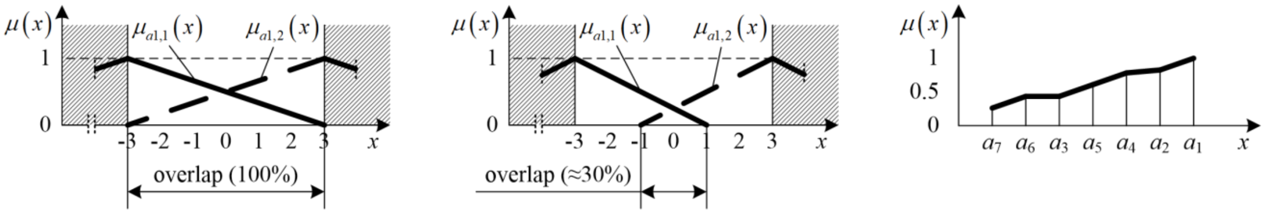
In this study, it was assumed that $\mu_{ai,1}(x)$ and $\mu_{b,1}(y)$ ($\mu_{ai,2}(x)$ and $\mu_{b,2}(y)$) are monotonically decreasing (increasing) and linear over the domain. I.e. the "convex" and "normal" [13].

MFs of inputs and output were implemented in a "triangle" form:

$$f\left(x;a,b,c\right)=\max\left(\min\left(\frac{x-a}{b-a},\frac{c-x}{c-b}\right),0\right), \tag{2}$$

where *a*, *b*, and *c* are numeric parameters, which define the position and shape of a triangle function.

The MFs' shape $\mu_{a1,1}\left(x\right)=f\left(x;-9,-3,3\right)$ and $\mu_{a1,2}\left(x\right)=f\left(x;-3,3,9\right)$ according to Eq. (2) for a_1 is shown in Fig. 2, a. The dashed area on the Fig. 2, a and b plots – values that are out of the domain.



a b c

Fig. 2 Membership functions: a – for the a_1 property in E1P (100 % MF domain overlapping); b – for the a_1 property in E1P (approx. 30 % MF domain overlapping); c – for the “The most significant property” fuzzy set in EGP after being normalized to 1

Expert defined 24 conjunctive rules for the Mamdani FIS. Example of the rule: IF a_1 is “Negative value” AND a_2 is “Positive value” AND a_3 is “Negative value” AND a_4 is “Negative value” AND a_5 is “Positive value” AND a_6 is “Positive value” AND a_7 is “Positive value” THEN *b* is “Element is monitored”.

2.3. Using the Fuzzy Inference System that Considers the Opinion of a Group of Experts

To consider the EGP, we developed the MF for the “The most significant property” fuzzy set by the rank ordering method [13]. To achieve this, 15 experts made a pairwise comparison of the properties for each RI element (Table 1). After comparing the a_i and a_j ($i\neq j$), each expert preferred one property to another. Results of comparisons were presented to the “antisymmetric” matrix. That allowed to order ranks for the properties and create the MF $\mu_{r,k}\left(z\right)$, where k – the number of RI element, $z\in\left\{a_1,a_2\ldots a_7\right\}$. The MF value of each element was set to Mamdani FIS inputs (Fig. 1).

3. Results

We considered the following task: develop the AMD for RI system having the structure defined by the station’s neck (Fig. 3). This part of the station includes 14 switches and 22 light signals. To ensure their operation the 678 relays are used. Table 2 contains the results of the expert's evaluation of the properties of 7 elements (relay) in the RI system having the structure shown in Fig. 3.

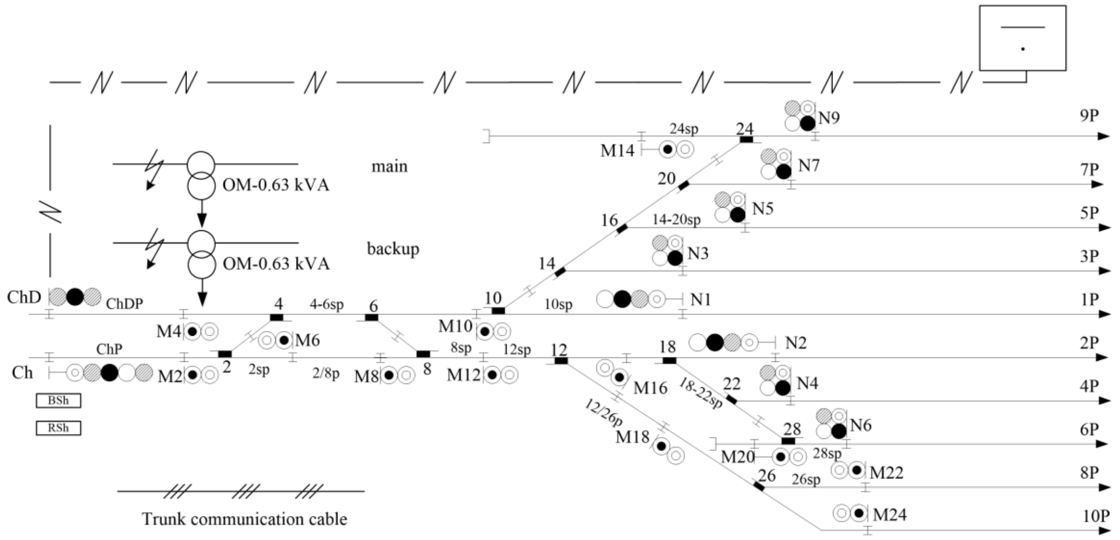


Fig. 3 Schematic representation of the station's neck, as an example of the AMD development

Table 3 shows the evaluation results of the appropriateness of including particular RI elements in the EM set.

Data in the “E1P-1” column correspond to 100% overlap of the MF domain (Fig. 2, a), and data in the “E1P-2” column – to 30% overlap of the MF domain (Fig. 2, b).

Table 4 shows the evaluation results for the “relay KS ChP” RI element provided by the group of 15 qualified experts, who worked with RI at different stations and participated in this research as volunteers. Analogous tables were obtained for the rest of six elements in the RI system. The “Total” column presents the row-wise sums of the experts' preferences. The “Fraction” column is a fraction of the sum in a row relative to the total number of comparisons (the “Total” row of the “Total” column). Considering the values in the “Fraction” column (maximum value ranked as 1, see Table 4) the rank ordering (“Rank order” column) was done and the MF of the “The most significant property” fuzzy set was defined. We normalised values in the “Fraction” column considering the maximum value (see the “Fraction norm.” column visualised in Fig. 2, c) to map the MF domain in the $[0,1]$ interval. Values from the “Fraction norm.” column were mapped in the S set (shifted, scaled and quantized), then presented in the “Fraction norm. mapped to S ” column, and set to the corresponding inputs of the Mamdani FIS (Fig. 1) considering the 100% (EGP-1) overlap of the MF domain. The results were presented in Table 3.

Table 2

Evaluation results of the RI system elements

No.	Name of an element (relay)	a_1	a_2	a_3	a_4	a_5	a_6	a_7
1	NKN of the Ch light signal	3	2	1	2	-1	-2	-1
2	NKN of the N9 light signal	-1	-2	0	0	-1	-2	-1
3	S of the M2 light signal	1	1	0	1	-1	-1	-2
4	S of the M10 light signal	1	1	2	2	-1	-1	-2
5	S of the M14 light signal	-2	-2	-2	-2	-2	-2	-2
6	KS ChP	2	2	0	1	1	0	-2
7	KS 28SP	0	-2	-2	-2	1	0	-2

Table 3

Evaluation results of the RI system elements
appropriateness of including in the EM set

No.	Name of an element (relay)	E1P-1	E1P-2	EGP-1
1	NKN of the Ch light signal	0,62	0,75	0,61
2	NKN of the N9 light signal	0,45	0,28	0,59
3	S of the M2 light signal	0,55	0,72	0,61
4	S of the M10 light signal	0,62	0,75	0,61
5	S of the M14 light signal	0,36	0,22	0,59
6	KS ChP	0,59	0,72	0,59
7	KS 28SP	0,41	0,28	0,58

Table 4

Evaluation results for the “relay KS ChP” RI element provided by the group of 15 experts

Properties to be compared with	Number of experts, who preferred these properties							Total	Fraction	Rank order	Fraction norm.	Fraction norm. mapped to S
	a_1	a_2	a_3	a_4	a_5	a_6	a_7					
a_1	–	10	14	8	12	13	15	72	0,23	1	1,00	3
a_2	5	–	11	7	10	12	14	59	0,19	2	0,83	2
a_3	1	4	–	5	6	7	10	33	0,10	5	0,43	0
a_4	7	8	10	–	9	11	13	58	0,18	3	0,78	2
a_5	3	5	9	6	–	9	11	43	0,14	4	0,61	1
a_6	2	3	8	4	6	–	9	32	0,10	6	0,43	0
a_7	0	1	5	2	4	6	–	18	0,06	7	0,26	-1
Total	–							72	1,00	–	–	–

4. Conclusions

In this study, we determined the set of elements in the tower-located part of RI, which is appropriate to equip with sensors that monitor the state of these elements and send corresponding signals to the AMD system inputs (the EM set). To achieve this, the qualified expert determined seven properties that were used in the evaluation of elements in the tower-located part of RI to determine the appropriateness of their including in the EM set. The evaluation scale for each property included the following values: –3, –2, –1, 0, 1, 2, 3. Values at the scale ends were selected semantically opposite (considering the SD method). Additionally, the expert developed 24 rules for the Mamdani FIS and evaluated seven RI elements (Table 2) considering the $a_1, a_2 \ldots a_7$ properties. Thus, the opinion of a single expert was considered – E1P.

Alternatively, the same Mamdani FIS was used to consider the opinion of the group of experts – EGP. To achieve this, we determined the MF for the "The most significant property" fuzzy set by the rank ordering method used for each of the same elements, which were considered to evaluate with E1P. Obtained evaluations of membership of the $a_1, a_2 \ldots a_7$ properties were normalised, mapped in the S set and sent to the corresponding Mamdani FIS inputs.

The results of Mamdani FIS (Table 3) were validated by the expert. In the expert's opinion, the degrees of the monitoring appropriateness among considered RI elements were best represented in the single expert's preference (E1P-2) for the MFs with the 30% (approx.) domain overlap (Fig. 2, b).

The results of evaluations with EGP-1 (Table 3) for elements No. 1, 3, and 4 were equal (the same is true for No. 2, 5, and 6). That was caused by the normalisation of the MF by its maximum value (the "Fraction norm." column in Table 4). Consequently, obtained MF and corresponding evaluations of properties always include at least one property equal to one. This may not correspond to the expert's evaluation of a particular element (e.g. see the second row in Table 2).

Application of the proposed process to select elements for AMD of the tower-located RI considering the single expert's preference (E1P-2), who maintains this system, allows assigning priorities of the appropriateness to monitor mentioned elements. That allows selecting the EM set considering limitations on the resources regarding the AMD system installation for a particular RI system.

Evaluation with E1P-2 was good enough in representing the evaluation of one expert. Further studies are mandatory to provide an economic justification for the AMD system developed with the proposed selection process.

Additionally, further studies may include the identification of the MF's shape impact on the result and an application of the cluster analysis to validate the Mamdani FIS results.

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