

PRZEMYSŁAW PYTLIK*

EXPERT SYSTEM SUPPORTING FAILURE MODE AND EFFECT ANALYSIS (FMEA)

SYSTEM EKSPERTOWY WSPOMAGAJĄCY ANALIZĘ PRZYCZYŃ I SKUTKÓW WAD (FMEA)

Abstract

The goal of this paper is to verify the usefulness of the expert system as a tool supporting the Failure Mode and Effect Analysis (FMEA). For the purpose of this study, a computer program acting as an expert system for FMEA has been implemented. The knowledge base of the expert system contains the medium voltage current transformer data. The Expert system structure, principle of operation and the data acquisition process were discussed. An expert system has been tested during the FMEA analysis of the medium voltage current transformer.

Keywords: expert system, failure mode and effect analysis, optimization, prolog

Streszczenie

Celem niniejszego artykułu jest zweryfikowanie przydatności systemu ekspertowego jako narzędzia wspomagającego przeprowadzanie analizy potencjalnych wad produktu, ich przyczyn oraz skutków (FMEA). W celu przeprowadzenia badań zrealizowano program komputerowy pełniący rolę systemu ekspertowego dla omawianego zagadnienia. Baza wiedzy systemu ekspertowego została uzupełniona danymi dotyczącymi przekładnika prądowego średniego napięcia. Opisana została budowa, sposób działania oraz proces pozyskiwania wiedzy systemu ekspertowego. Użyteczność systemu sprawdzona została podczas testów, wykonując analizę FMEA przekładnika prądowego średniego napięcia.

Słowa kluczowe: system ekspertowy, analiza przyczyn i skutków wad, optymalizacja, prolog

* M.Sc. Przemysław Pytlik, Department of Automatic Control and Information Technology, Faculty of Electrical and Computer Engineering, Cracow University of Technology.

1. Introduction

Expert systems are used as tools supporting decision-making process since the mid-sixties of the twentieth century. Initially, they were used mainly for aeronautics, medicine and geology. Later, they were developed in a business environment. Currently, expert systems occur most often right there. A more extensive description of the history of expert systems can be found in [8].

The main purpose of using the expert system is to solve problems, which are so complex that they require extensive knowledge. Problems are solved using the inference procedures and knowledge contained in the database.

Expert systems have a characteristic construction. These programs are functionally composed of several basic elements [2, 4, 8, 11]. The most important of them are the knowledge base and the inference engine. Usually, programs of this type also have a user interface, dynamic database, knowledge base editor and explanation mechanism. They are important, but not crucial in expert software.

Failure Mode and Effect Analysis (FMEA) is intended to identify potential product defects, their causes and consequences affecting its operation and the environment [6]. This structured method, based on the knowledge of specialists, fully fits in with the assumptions about expert systems.

There are a few types of the FMEA [6, 9]. This article describes the Design FMEA procedure, which is implemented in the early stage of the specified device design. It is intended to optimize the reliability of the construction.

FMEA is used to determine the cause , effect relationships, which can lead to the failure of a particular product. All components of the product are investigated. In the first step, their functions are defined. Then, a team of specialists considers all the possible potential failure modes, which may occur in the component under analysis. After that, they look for causes and effects of each particular failure modes. In the next step, the preventive measures are proposed in order to eliminate the causes of failure, or reduce the likelihood of their occurrence. Recommended adjustments typically involve construction changes, or redundancy of some important functions – usually safety functions.

FMEA is performed by a team of specialists having the knowledge concerning the analyzed product and the moderator, who lead up the discussion. It is usually an employee of the quality management department or the designer of the product under analysis.

This paper is intended to show the implementation of the expert system supporting the FMEA, written in the Prolog language. A current transformer working at a medium voltage level was selected as an exemplary object of the FMEA, which will be supported by the expert system. The impact that the implemented expert system has on the quality of the FMEA will be discussed. The basis for the discussion will be the results of the performed test of the expert system.

The second section of this paper is intended to present an idea of improving the FMEA quality in general. The crucial parts of the paper are sections three, four and five. The third section describes the structure of the expert system supporting the FMEA and its activity diagram. The fourth section contains information about the knowledge acquisition process. The fifth section shows the method and results of the test. At the end, a summary of the work and conclusions are presented in section 6.

2. The need to improve the quality of the FMEA

FMEA is a subjective evaluation of a design, prepared by the team of specialists. They are looking for some potential risks related to design. For this purpose, each expert shares his knowledge. That knowledge can be stored in some database and used during another FMEA analysis. The more data is collected, the better FMEA can be performed.

There are many significant problems, which can occur during FMEA preparation. These problems reduce the quality of the analysis and increase its delivery time:

- omission of important failure modes and their effects due to incomplete knowledge about the product, an incorrectly selected team of specialists, or limited budget (time),
- difficulties in naming and distinguishing failure modes, their causes and effects,
- difficulties in finding archival analysis – lack of a unified database,
- lack of the unified approach to perform FMEA by all team members.

There are several commercial computer programs intended to support the Failure Mode and Effect Analysis. For example, TQM Soft, or Xfmea. The author wants to check the possibility of optimization of the FMEA analysis by using an expert system.

Basically, an execution of the FMEA can be optimized by:

- making a generic list of typical failure modes,
- collecting the data from previous analyses in one place in a clear form,
- highlighting the real failures that occurred in the past,
- providing statistics of failure modes,
- unifying vocabulary of the FMEA analysis,
- improving knowledge sharing – knowledge market,

An expert system, which has those features, will improve the quality of the FMEA. The most significant expected benefits are: more detailed, deeper results of the analyses and shorter delivery time. What is more, important data derived from executed analyses will not be forgotten. Instead, valuable knowledge will be collected and stored in the expert system knowledge base.

3. Expert system supporting the FMEA

The SWI-Prolog environment and “SWI-Prolog editor” have been used during implementation of the expert system supporting Failure Mode and Effect Analysis. Graphical User Interface has been developed using XPCE toolkit.

The results of the expert system work are presented in the table written in HTML file. The structure of the table is in accordance with IEC standard [5].

3.1. Structure of the expert system supporting the FMEA

An expert system supporting the FMEA analysis has a functional structure typical for the expert systems (Fig. 1).

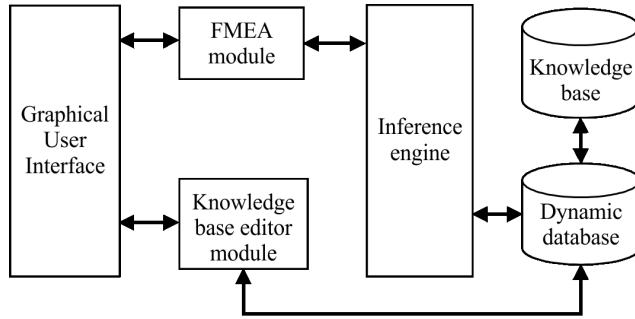


Fig. 1. Functional structure of the expert system supporting FMEA analysis

Knowledge base

The Knowledge base contains specialist knowledge, which is necessary in problem solving process [8]. In the case of the described software, the knowledge base stores all the information important for FMEA: the names of the analyzed components, failure modes, their effects, causes and recommended corrective actions. The knowledge contained in this particular expert system may not be free of mistakes.

The knowledge base is implemented in PROLOG language, in the form of facts. The database is divided into four separate text files, which contain:

- a) components names, functions and failure modes,
- b) failure effects,
- c) failure causes,
- d) recommended corrective actions.

The knowledge has been written using facts in the way presented below:

```

failure(x, y, z).
effect(z, u).
cause(z, w).
recommended(w, t).
  
```

Where: “x” is specific component name; “y” is one of the functions related to component “x”; “z” is one of the failure modes associated with component “x” and its function “y”; “u” is one of the effects of the failure mode “x”; “w” is one of the causes of the failure mode “x”; “t” is one of the recommended corrective action leading to elimination or reduction of the cause “w”.

Listing 1. Example of facts related to primary winding, written in the knowledge base

```

failure(‘Primary winding, Keep specific dimensions’, ‘External dimensions out of limit’).
effect(‘External dimensions out of limit’, ‘Increased partial discharges inside an insulation’).
cause(‘External dimensions out of limit’, ‘Poor assembly quality’).
recommended(‘Poor assembly quality’, ‘Use the tool for verification of external dimensions’).
  
```

The above can be understood as: “External dimensions out of limit” is a potential failure mode of the “Primary winding” component, of which function is to “Keep specific dimensions”. “Increase of the partial discharges” is the effect of the failure mode “External dimensions out of limit”. “Poor assembly quality” is the potential cause of “External dimensions out of limit”. The recommended corrective action eliminating the “Poor assembly quality” is to “Use the tool for verification of external dimensions”.

The knowledge base structure, implemented as above, corresponds to standard FMEA worksheet structure:

Table 1

Example of FMEA worksheet. Part of the FMEA analysis of the medium voltage current transformer

Component	Function	Potential Failure Modes	Potential Effect of Failure	Potential Causes of Failure	Recommended Actions
Primary winding	Keep specific dimensions	External dimensions out of limit	Increased partial discharges inside insulation	Poor assembly quality	Use the tool for verification of external dimensions

According to the FMEA approach: each component can have many functions and many potential failure modes, which have some effects. Each potential failure mode can have many potential causes. Finally, each potential cause of failure can be eliminated by a corrective action. This hierarchical structure of the complete FMEA analysis [5, 6] and relations between particular data, is shown in Fig. 2.

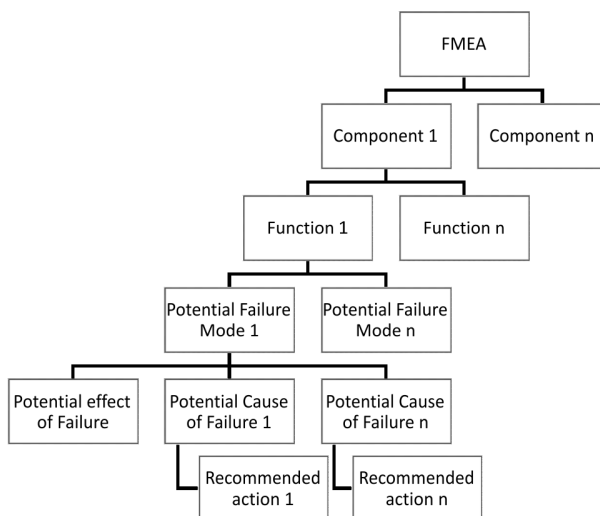


Fig. 2. Structure of the knowledge base of the expert system supporting FMEA analysis. Letter “n” represents next record

The more data is gathered, the better the knowledge base becomes. Theoretically, the knowledge base can be developed unlimitedly. The new data is added in a simple way, using the knowledge base editor module.

Knowledge base editor module

When there is a need to add new data to the knowledge base, appropriate facts have to be written to the knowledge base text files. For that purpose, the knowledge base editor module with graphical user interface has been implemented. The method of its realization and the way the module works were explained below:

Algorithm of knowledge base editor module

1:	IF	there is no record in knowledge base with specific component “x”, function “y” and failure mode “z” in the knowledge base ----- /Searching the record in knowledge base / -----
2:		Add the record with component “x”, function “y” and failure mode “z” to dynamic database at the top of the list. AND
3:		Activate/open appropriate knowledge base text file. AND
4:		List in the activated text file all the facts stored in dynamic data base (old data, and new one) AND
5:		Deactivate/close appropriate knowledge base text file.
	ELSE	do not save.

The procedure described above is the performed for all other facts: failure effect “u”, failure cause “w” and recommended action “t”, which are defined in graphical user interface.

Presented procedure of adding new data to the knowledge base has been implemented according to Listing 2.

Listing 2. Knowledge base editor module implementation

1:	save(X,Y,Z,U,W,T):-
2:	(not(failure(X,Y,Z)),
3:	asserta(failure(X,Y,Z)),
4:	tell('C:\Users\kb_failure.pl'),
5:	listing(failure),nl,
	told;
	%lines from 2 to 6 are repeated for other facts: effect(Z,U), cause(Z,W), recommended(W,T)
)fail>true.

The process of adding new data to knowledge base text files is started by save/6 predicate. Variables X, Y, Z, U, W, T meaning respectively: component name, function,

failure mode, failure effect, failure cause, recommended action; are downloaded directly from the graphical user interface.

Prolog built-in predicate `not/1` was used as a protection against writing the facts that are already in the knowledge base.

Fig. 3. Graphical user interface created to add new facts to knowledge base

Dynamic database

PROLOG provides a built-in dynamic database, which acts as a link between knowledge base text files and other parts of the expert system supporting the FMEA. It is used automatically whenever the user wants to add new facts to knowledge base text files or when an inference process is started to solve the problem. To enable the use of dynamic database, *dynamic/1* functor was used.

Listing 2 shows how the procedure of adding new data to knowledge base text files has been implemented using the *asserta/1* built-in predicate. *Asserta/1* saves new data (entered in specified GUI windows) in dynamic database. Then, the built-in predicate *tell/1* allows to write all data collected in dynamic database (including new-entered data) to knowledge base text files. Built-in predicate *listing/1* prints that data.

When the expert system work is finished, the dynamic data base is automatically cleaned.

FMEA module

The FMEA module was designed to provide the user support during FMEA preparation. Specific data concerning the product under analysis is shown by the FMEA module: component names, functions of the components, potential failure modes of the components, potential effects of the failures, potential causes of the failures and recommended actions eliminating these causes.

To obtain the assumed functionality of the FMEA module, a set of 6 rules was designed:

Rule 1:

IF

“x” is the selected component, under investigation AND

“y” is the function of component “x” AND

“z” is the potential failure mode of component “x” AND
 “u” is the potential effect of the failure mode “z” AND
 “w” is the potential cause of the failure mode “z” AND
 “t” is the recommended action eliminating the cause “w”
 THEN
 “y-z-u-w-t” is the set of FMEA data associated with component “x”.

Prolog implementation:

```
fmea(X,Y,Z,U,W,T):-
    failure(X,Y,Z),
    effect(Z,U),
    cause(Z,W),
    recommended(W,T).
```

Rule 2:

IF
 “x” is the selected component, under investigation AND
 “y” is the function of component “x”
 THEN
 “y” is the set of FMEA data associated with component “x”.
 List all functions related to component “x” in GUI.

Prolog implementation:

```
fmea_function(X,Y):-
    failure(X,Y,_).
```

Rules 3–6 have a structure similar to rule 2. They were used to list: all potential failure modes related to selected component; all potential effects related to selected failure mode; all potential causes related to selected failure modes and all recommended actions related to selected cause of failure.

Rule 1 has been used to create the HTML table with the FMEA analysis of the particular component, selected by user in GUI. Listing 4 shows the way it was done.

Firstly, component name (selected in GUI window) is used as an argument in rule created to draw the FMEA table. Then, the file, where the table will be placed, is activated. /lines 1–5/.

The rule *table_com_fmea/2* draws the FMEA table and fills specified cells with specific FMEA data according to Table 1. Rule *table_com_fmea/2* consists of HTML code and Prolog code. HTML code was used to draw table with a specific form /lines 8–15; 17 and 22–30/. Prolog code was used to impose conditions to be met by the data entered to the table (inference) /lines 28–21/. The data that has met the conditions is entered to particular cells of FMEA table /lines 22–27/.

Graphical user interface (Fig. 4) was implemented to enable dialogue between FMEA module and the user. User selects particular component and gives the command to draw FMEA table (Fig. 5) by clicking the button.

Listing 4. Export the expert system answer to HTML table

```

1: fmea(X):-
2:   get(X,selection,Selected),
3:   open('C:\Users\\Desktop\FMEA of Component.html',write,Stream),
4:   table_com_fmea(Stream,Selected),
5:   close(Stream).
6:
7: table_com_fmea(Stream, X):-
8:   write(Stream, '<html><head><title> FMEA Table </title></head>'),nl,
9:   write(Stream, '<body><table border="1" cellpadding="3" align="center"><tr> ',nl,
10:  write(Stream, '<th style="width: 3mm;">Component</th>'),nl,
11:  write(Stream, '<th style="width: 3mm;">Function</th>'),nl,
12:  write(Stream, '<th style="width: 33mm;">Potential Failure Modes</th>'),nl,
13:  write(Stream, '<th style="width: 40mm;">Potential Effect of Failure</th>'),nl,
14:  write(Stream, '<th style="width: 43mm;">Potential Causes of Failure</th>'),nl,
15:  write(Stream, '<th style="width: 3mm;">Recommended Actions</th></tr>'),nl,
16:
17:  (write(Stream, '<tr>'),nl,
18:  failure(Selected,Y,Z),
19:  effect(Z,U),
20:  cause(Z,W),
21:  recommended(W,T),
22:  write(Stream, '<td>'),write(Stream,Selected),write(Stream, '</td>'),
23:  write(Stream, '<td>'),write(Stream,Y),write(Stream, '</td>'),nl,
24:  write(Stream, '<td>'),write(Stream,Z),write(Stream, '</td>'),
25:  write(Stream, '<td>'),write(Stream,U),write(Stream, '</td>'),nl,
26:  write(Stream, '<td>'),write(Stream,W),write(Stream, '</td>'),
27:  write(Stream, '<td>'),write(Stream,T),write(Stream, '</td>'), nl,
27:  write(Stream, '</tr>'),fail,true),nl,
29:
30:  write(Stream, '</table></body></html>').

```

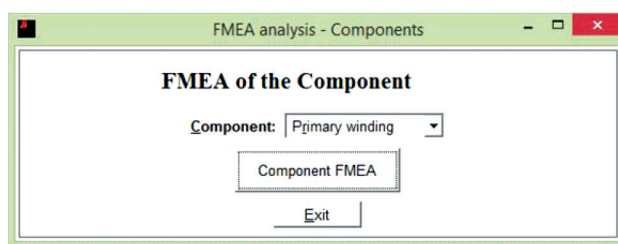


Fig. 4. Graphical user interface created to get the FMEA data of selected component

Rules 2–6 have been used to show particular FMEA data separately in GUI window. The following pieces of information about the apparatus under analysis can be obtained using rules 2–6: list of functions related to selected component; list of potential failure modes related to selected component; list of potential effects related to selected failure mode; list of potential causes related to selected failure mode; list of recommended actions related to selected cause of failure.

Other FMEA module GUI windows have a similar structure to those presented in Fig. 6, but they display different types of information.

Component	Function	Potential Failure Modes	Potential Effect of Failure	Potential Causes of Failure	Recommended Actions
Primary winding	Rounded edges shape	Cable int. wires exposition	PD increase	Low assembly quality	Additional wrapping of soldered connections
Primary winding	Good flatness of ext. Contact surface	Surface porosity of cast	Contact overheating	Technology quality problem @ supplier level	Delivery condition.
Primary winding	high conductivity	Too low conductivity of component	Overheating, Low mechanical endurance and withstand to electrodynamic forces. Source of customer dissatisfaction.	Impurities in raw material	100% of incoming parts control. Delivery condition. Production technology from supplier
Primary winding	high conductivity	Too low conductivity of component	Overheating, Low mechanical endurance and withstand to electrodynamic forces. Source of customer dissatisfaction.	Bubbles inside copper casting (especially for sand mould)	100% of incoming parts control. Delivery condition. Production technology from supplier
Primary winding	Durable coating of ext. Interface (Tin, CrNi))	Break of cover surface	Increase of contact resistance, terminal overheating	Too thin of coating surface	Delivery condition, critical size definition (thickness)
Primary winding	Durable coating of ext. Interface (Tin, CrNi))	Break of cover surface	Increase of contact resistance, terminal overheating	Insufficient protection of shipment	Operator manual note/recommendations
Primary winding	Durable coating of ext. Interface (Tin, CrNi))	Break of cover surface	Increase of contact resistance, terminal overheating	Mechanical break @production	Operator manual note/recommendations

Fig. 5. Fragment of the FMEA analysis of the primary winding of the current transformer, obtained using the expert system

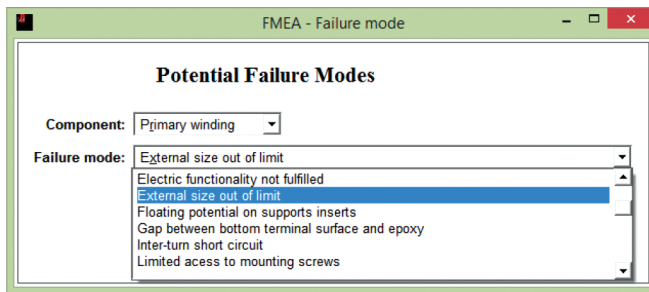


Fig. 6. Graphical user interface created to get the potential failure modes of selected component

Inference engine

Prolog has a built-in inference engine, which has been adopted in the expert system supporting the FMEA. The function of the inference engine is to derive conclusions from the data collected in the knowledge base.

The inference engine is used by the expert system FMEA module in order to get particular FMEA data related to the apparatus being under analysis. For this purpose, the backward chaining method is used.

The inference engine of the expert system supporting FMEA derives the FMEA data about apparatus under analysis from: the facts collected in knowledge base, dialogue with the user and the rules 1–6 listed before in this paper. For example, based on rule 1, an inference engine will find the following facts: components names, functions, potential failure modes, potential effects of failures, potential causes of failures, and recommended actions. However, potential failure modes and potential causes of failure must be common for these facts (according to rule 1).

For example, if the following facts, related to a current transformer, are stored in knowledge base:

failure(Primary winding, Keep specific dimensions, External dimensions out of limit).

failure(Secondary winding, Specific number of turns, Too low number of turns).

effect(External dimensions out of limit, Increased partial discharges inside an insulation).

cause(External dimensions out of limit, Poor assembly quality).

cause(Too low number of turns, Miscalculations).

cause(External dimensions out of limit, Wrong design /too large size/).

recommended(Poor assembly quality, Use the tool for verification of external dimensions).

And if the user requires the FMEA data about *Primary winding* component.

An expert system will give the following answer:

Component name: Primary winding

Function: Keep specific dimensions

Potential failure modes: External dimensions out of limit

Potential effect of failure: Increased partial discharges inside an insulation

Potential cause of failure (1): Poor assembly quality

Recommended action: Use the tool for verification of external dimensions

Potential cause of failure (2): Wrong design /too large size/

What can be written in tabular form according to FMEA standard:

Table 2

Result of inference of the expert system supporting FMEA presented in tabular form

Component	Function	Potential Failure Modes	Potential Effect of Failure	Potential Causes of Failure	Recommended Actions
Primary winding	Keep specific dimensions	External dimensions out of limit	Increased partial discharges inside insulation	Poor assembly quality	Use the tool for verification of external dimensions
Primary winding	Keep specific dimensions	External dimensions out of limit	Increased partial discharges inside an insulation	Wrong design/too large size/	N/A

Graphical user interface (GUI)

The user can perform the dialogue with the expert system and add new data to the knowledge base using the GUI. The expert system supporting FMEA analysis is equipped with a simple and intuitive graphical user interface consisting of several windows. Examples of user interface windows were presented in Fig. 3, 4 and 6.

The graphical user interface created in an XPCE toolkit consists of push buttons, list boxes, static text lines and edit text lines. The XPCE language was chosen for GUI implementation because it is versatile, so it can be used in combination with many programming languages, especially with Prolog.

3.2. Activity diagram of the expert system supporting the FMEA

The expert system supporting the FMEA works in two modes: knowledge base editor mode and FMEA mode as it was presented in Fig. 1.

The activity diagram presented in Fig. 7 illustrates all activities of the expert system supporting FMEA, depending on the options selected by the user.

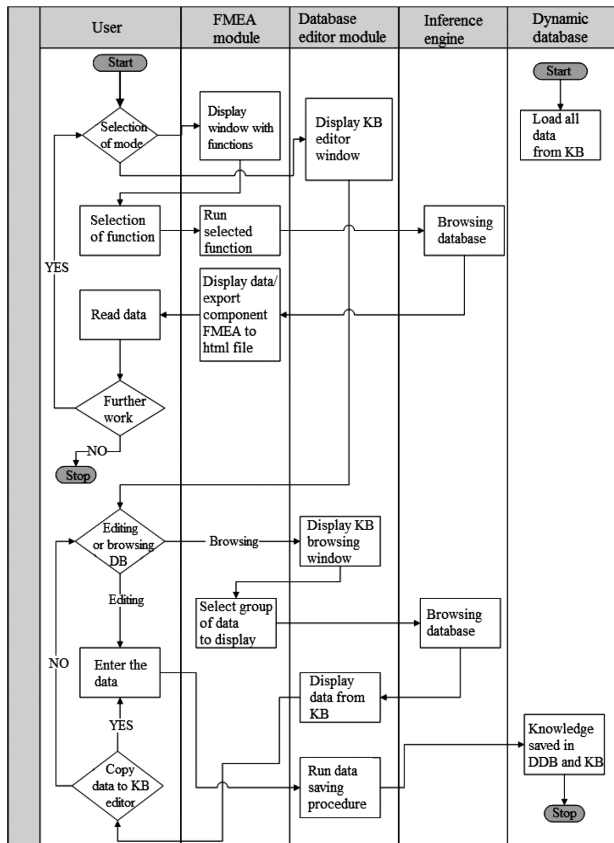


Fig. 7. An activity diagram of the expert system supporting FMEA analysis

4. Knowledge acquisition process

The knowledge acquisition process was one of the most important stages during the creation of the expert system supporting the FMEA. The collected knowledge determines the quality of the FMEA analysis and efficiency of the expert system. Therefore, the expert system supporting FMEA analysis should have as much valuable data in the knowledge base as possible.

From the perspective of the FMEA analysis, it is desirable for the knowledge base to be developed continuously. New data can be added to the knowledge base after each completed and summarized analysis. For that reason, a continuous knowledge acquisition process (Fig. 8) has been proposed for the expert system supporting FMEA.

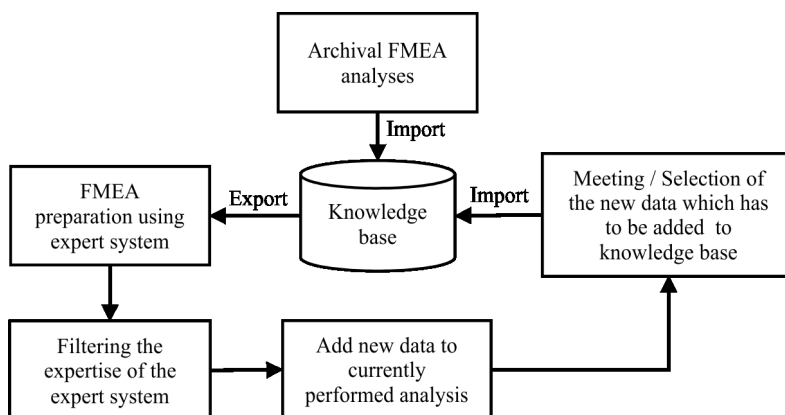


Fig. 8. Model of the knowledge acquisition process of the expert system for FMEA analysis

Initially, the expert system starts with the knowledge base containing the data derived from archival FMEA analyses (according to Fig. 8). The knowledge base was filled with the knowledge concerning potential failure modes of the medium voltage current transformers. The archival FMEA worksheets were provided by specialists, which perform the FMEA analyses of the medium voltage equipment, including: instrument transformers and sensors, switchgears, circuit-breakers, fuses, etc.

In order to transfer the knowledge contained in FMEA tables to knowledge base files, all the available FMEA documents have been collected in one Microsoft Excel worksheet. Then, the data was converted manually to be suitable for the knowledge base.

Firstly, all the sentences that had a similar meaning, but were written in different way, were unified. Then, all the data (which required this) was generalized. Unnecessary and too detailed information was deleted. It was performed to have universal data, which can be used in many various analyses. Then, all of the sentences were shortened as much as possible – to the form appropriate for the knowledge base and understandable for a typical user of the expert system. Finally, all the data was written to knowledge base text files using Prolog syntax in a way shown in Listing 1.

Afterwards, according to Fig. 8, the knowledge base can be developed continuously with the new data obtained from future FMEA analyses. The user will perform FMEA using the expert system as a support. The FMEA acquired from the expert system has to be filtered by user. Only the data strictly related to apparatus, which is being under investigation, should remain. Then, the user should add some new records to the FMEA worksheet. Records may come from personal experience/knowledge or may be collected during the meetings with other specialists. The most valuable of these new records should be converted in already described way and written to expert system knowledge base.

5. Test of the expert system efficiency

The delivery time of the FMEA has a significant impact on the quality of the FMEA. The longer the time of FMEA preparation, the more potential failure modes are found. The more valuable potential failure modes are found, the better the quality of the FMEA.

Unfortunately, the time of the FMEA preparation is directly connected to financial costs. For that reason, the time of the FMEA should be minimized. The analysis should be released as soon as possible.

The aim of the expert system is to optimize the quality of the FMEA analysis. Thus the quality of the FMEA, obtained using the expert system, can be used as a measure of its efficiency.

The goal of the test is to compare the FMEA results obtained using the expert system as a support with the FMEA results obtained in the traditional way, without the expert system.

The quantity of the rows in FMEA worksheet (the amount of FMEA data) and the time needed to its preparation have been chosen as a measure of the expert system efficiency as a tool supporting FMEA analysis.

The test was carried out by a group of three users, who prepared FMEA analyses independently. The first user was well experienced in the area of current transformers; the second one was moderately experienced; and third one was poorly experienced.

Only one design of apparatus was used for the purpose of the test. It was a single-phase medium voltage current transformer in epoxy insulation. The investigation had 3 stages, the same for each user.

Test scenario

Stage I

User performs the FMEA using the traditional method, based on his experience/knowledge.
Duration: 2 hours.

Stage II

User continues FMEA using the traditional method. *Duration: 6 hours.*

Stage III

User perform the FMEA using the expert system as a support and save FMEA in different file. *Duration: 2 hours*

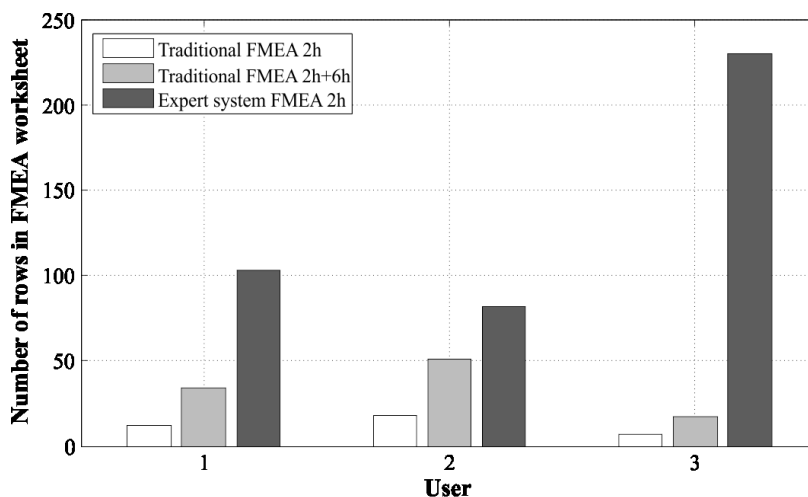


Fig. 9. Efficiency test results of the expert system supporting the FMEA analysis

Based on the test results given in Fig. 9, it was found that all of the 3 users obtained the greatest number of potential failure modes, with the 2 hours support of expert system. Users 1, 2 and 3 wrote respectively: 103, 82 and 230 rows consisting of FMEA data. Comparing the traditional FMEA analysis performed by the same users for 2 hours allowed to gather, respectively: 12, 18 and 7 rows. Even a prolongation of the time to 8 hours gave worse results compared to the expert system – respectively: 34, 51 and 17 rows.

By comparing the 3 users to each other, it has been found that user 3 definitely found the biggest amount of FMEA data using the expert system. This happened because user 3 was less experienced than the 2 others in the area of current transformers. Thus, he did not filter the data obtained using the expert system. Therefore, the unnecessary failure modes, which were not related to transformer under analysis, were not rejected. User 2 found the lowest number of FMEA records using the expert system. All the failure modes, which were not related to the apparatus under investigation, were omitted by him – because of his extensive experience. However, the expert system helped him. User 2 found more data using expert the system than based only on his personal experience.

6. Conclusions

In this paper, an idea of improving the quality of the FMEA analysis by support with the expert system was presented. For that purpose, the author implemented an expert system supporting the FMEA with the XPCE graphical user interface. The functional structure of the expert system and the main aspects of its implementation in Prolog programming language were discussed.

The knowledge base was designed, implemented and filled with the necessary data. The data is related to single-phase, medium voltage current transformer in epoxy insulation.

The implemented expert system has been tested to prove its usefulness in improving the quality of FMEA analysis. The test results show that more failure modes can be found using the expert system than using the traditional method for performing FMEA.

It was proven that the time given to perform FMEA analysis using the traditional method has a big impact on the quality of FMEA. The longer the time, the more complete the FMEA. However, the test results showed that the impact of time on the quality of FMEA can be reduced using the expert system as a support during FMEA preparation.

Therefore, in the opinion of the author, it was proven that the expert system can be an efficient and useful tool supporting the FMEA analysis. The expert system both increases the quantity of potential failure modes, which have been found, and decreases the time needed to do that.

It is important that the expert system can be only a support and cannot fully replace a human during FMEA analysis. Data obtained with the expert system is correct according to the FMEA methodology. However, the user must decide which of the data is strictly related to the object under analysis.

The presented expert system can be used successfully in research and development departments – in the area of electrical engineering, mechanical engineering, civil engineering and others. With appropriate knowledge uploaded into the knowledgebase, the expert may help to improve the quality of the products during the design stage.

In most cases, computer programs are continuously developed in order to improve their quality. In the case of the expert system supporting the FMEA analysis, the author plans to implement some additional features, for example: displaying pictures of the objects under investigation, creating flowcharts presenting the types of interfaces between components, redesign of the graphical user interface to improve functionality of the system. Moreover, the author plans to investigate the possibility of improving the knowledge base acquisition process. For this purpose, some interface between C++ and Prolog will be investigated.

References

- [1] Bakarai J., *Automatic Generation of a Diagnostic Expert System from Failure Mode and Effect Analysis (FMEA) Information*, SAE Technical Paper Series, International Congress and Exposition, Detroit, Michigan 1999.
- [2] Clocksin W.F., Mellish C.S., *Prolog: Programowanie*, Helion, Gliwice 2003.
- [3] Covington M.A., *Prolog Programming in Depth*, (online) homepage: <http://www.covingtoninnovations.com/books/PPID.pdf> (access: 27.08.2013).
- [4] *Elementy systemów ekspertowych. Część 1: Sztuczna inteligencja i systemy ekspertowe*, red. M.L. Owoc, wyd. 2 zmien., Wydawnictwo Akademii Ekonomicznej we Wrocławiu, Wrocław 2006.
- [5] IEC 60812:2006, Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA).
- [6] McDermott R.E., Mikulak R.J., *The Basics of FMEA*, ed. 2nd, CRC Press Taylor and Francis Group, New York 2009.

- [7] Merritt D., *Building Expert Systems in Prolog*, (online) homepage: <http://www.inf.fu-berlin.de/lehre/SS08/KI/merritt.pdf> (access: 27.08.2013).
- [8] Niederliński A., *Regulowo-modelowe systemy ekspertowe rmse*, wyd. 2 popr., rozsz., Wydawnictwo Pracowni Komputerowej Jacka Skalmierskiego, Gliwice 2013.
- [9] Stamatis D.H., *Failure Mode and Effect Analysis: FMEA from Theory to Execution*, ASQ Quality Press, Wisconsin 1995.
- [10] *SWI-Prolog's home*, (online) homepage: <http://www.swi-prolog.org> (access: 27.08.2013).
- [11] Todd B.S., *An introduction to expert systems*, Technical Monograph RPF-95, Oxford University Computing Laboratory, Oxford 1992.
- [12] Wielemaker J., Anjewierden A., *Programming in XPCE/Prolog*, (online) homepage: www.swi-prolog.org/download/xpce/doc/userguide/userguide.pdf (access: 27.08.2013).