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Use of Fuzzy Set Theory in the Inspection of Transmission Lines of Nuclear Installations

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Abstract : The presence of older installations, in particular nuclear facilities, demands extra studies concerning the safety evaluation of those installations. One of the aspects to deal with is the safety of the several transmission lines in a nuclear installation, for instance the safety of control, safety against fire, etc.. . This paper investigates the use of fuzzy set theory in the inspection of transmission lines of nuclear installations at SCK/CEN, Belgium.

1. Problem Description

The safety of a nuclear power plant (NPP) and of research reactors has to be dealed with the greatest attention. During the construction phase of the NPP, several safety related solutions can be studied and ideally implemented. A typical problem is the fire-safety of the installation. Probabilistic fire risk analysis [1, 2] can help to find a proper answer to several questions such as "Is compartimentation of rooms needed?" , "Are cable trays or cabinets safe to fire-hazards?", "Is there more redundancy needed against fire-hazards?" and so on.

During the conceptual phase of a new NPP, one can use lots of classical ways to fulfill a Probabilistic Risk Assessment (PRA). Those PRA's are made up of physical models of the risk itself. If one is interested in the risk of fire-hazards due to either external or internal causes, the physical modelling becomes very uncertain. Indeed, an event of a fire is a chaotic phenomenon, which is very difficult to modelise. The current methodology employs PRA's which have the potential to provide valuable insight into several aspects of plant fire vulnerability but not to be a real basis for licensing decisions. This last step, which makes that a methodology is commonly accepted as a reference-tool, is due to a few significant problems, i.e., the poor quality of the data base related to the comprehensiveness in fire accident reports, the lack of sufficient knowledge of fire accident sequences and operator recovery actions and the validity of fire modelling techniques. This is why classical methodologies are fraught with uncertainties, which results in the use of lots of approximations and the necessary engineering judgement.

The PRA's use essentially a hybrid of models. Firstly one needs physical models to describe the causes and propagation mechanisms, then point probabilistic models give the frequency of causes and finally the probabilistic models result in a comprehension of the probability of fire-propagation.
All these models introduce uncertainties due to intrinsic randomness of the event of fire itself. Mostly a greater source of uncertainties is the mathematical/physical model itself and the use of stochastic models. In general, this results in the conclusion that PRA's need to be modified in order to reduce all those uncertainties.

The use of these classical methodologies can be justified for new NPP's. The cost involved can, at that moment of the conceptual phase, be balanced against the indicative results obtained. Those results give a general indication of which way to go.

However, due to the amount of uncertainties involved, those techniques only give in some manner useable results given the best-known input-parameters for new installations. Once there are uncertainties involved in the input-parameters themself, the results of the classical methodologies become very unreliable. Therefore the use of these methodologies is hard to be justified in existing installations, the inputs are less well known because of aging mechanisms. The amount of work and the cost involved need then to be lowered anyhow to perform a safety analysis.

An additional point to be remarked is the objects one should consider in a new installation. One can modelise the equipment as perfectly performing objects, while in older installations this equipment can become a major cause of fire-accidents.

This is probably the reason this paper tried to develop a new approach, using the strengths of fuzzy set theory. The uncertainty involved in the inspection and the modelisation itself makes it not worthwile to use the costly classical methods. The fuzzy approach can give an easier, better suited method for this study-case of the paper.

In the Belgian nuclear research center one has to deal with existing installations and the fire risk analysis of electrical power cable trays especially. In this particular case we are dealing with several problems, such as "In what extent can those cabinets propagate fire?", "In what extent can those cables be the fire-source due to their state up to now?", and "What are the deterioristic states observed?".

It's clear that a strict answer to those questions can not be obtained. The study of this problem needs a lot of engineering judgement and the practical inspection of those cable trays introduces a lot of subjective input.

If one demands a survey of all transmission lines against several hazards, and that in the nuclear installation, one recognizes directly the enormeous task involved. One may hereby consider a few seperate steps to be taken :

Practical
Each transmission line needs to be checked by an inspector, and there has to be noted which observations are made. Above all, there has also to be accordance between several inspectors themself.

Database
These observations form a database of all lines inspected including the remarks done for each line, in which the database forms the start of the real safety evaluation.

Installation safety
Finally a decision on the safety of each line and moreover of the global installation safety need to be made.

The subjectivity as noted, and the different questions involved, justify the use of fuzzy set theory.

One more remark concerns the question of an economical cost evaluation. The classical methods in general can not give, in a straight direct manner, the lines which need to be replaced or remodeled to increase the overall safety, as well as the cost involved with these actions. The fuzzy approach however can indicate an answer in a more straight manner.

All these questions can be dealed with and can be given a proper solution during this project and even construction phase. Fire hazards have not only direct implementations but also indirect ones, such as fire-initiated accident sequences due to direct degradation of safety equipment, the effects of smoke on the operation staff and of toxic gases on electronic components have undoubtedly safety-implications, the effects of flooding from fire-fighting activities.

All these points make it clear that a fire-risk analysis becomes a more important, difficult and costly task to deal with.

It becomes a real difficult task if one has to analyse the fire risk in existing or research installations. Lots of additional influences and problems arise, i.e. : lack of data on the probability of specific location of fire; a great deal of uncertainty exists about cable routings; the failure models used to identify probability of spurious actuation are heavily influenced by analyst's judgement; large uncertainties exist in the data employed in physical-fire-growth models and their mathematical representations; fire suppression is based upon industry-wide data and is not necesserally directly representative of actual characteristics of the fire areas of concern; errors of commission by control-room operators as instigated by failures in the instrumentation circuit are usually not analyzed explicitly.

Other assumptions and limitations are usually noted throughout fire risk analysis.

The enormeous task involved and the subjectivity in the observations themself can not justify the use of the costly classical methods. When the classical analysis is made, it's quite time-consuming and costly to make the inverse analysis, i.e. to make the economical analysis which cables need changes to fulfill more safety-requirements.

2. Fuzzy approach

This paper proposes a methodology for the safety evaluation of transmission lines, based on fuzzy set theory. Its original application was in the field of medical diagnosis, and later on it was suggested to apply in the field of safety analysis of electrical installations [3].

Fuzzy relations between the symptoms of failure observed in a transmission line and the failure they may cause and between the failure types and safety levels are to be estimated. This will be achieved from the analysis of investigated (or published) technical information [4 - 10] and from a survey of the views of a group of experts. These relationships are incorporated in the program FIRECAB (Fire Evaluation of Cables), developed to get the safety-value of each line.

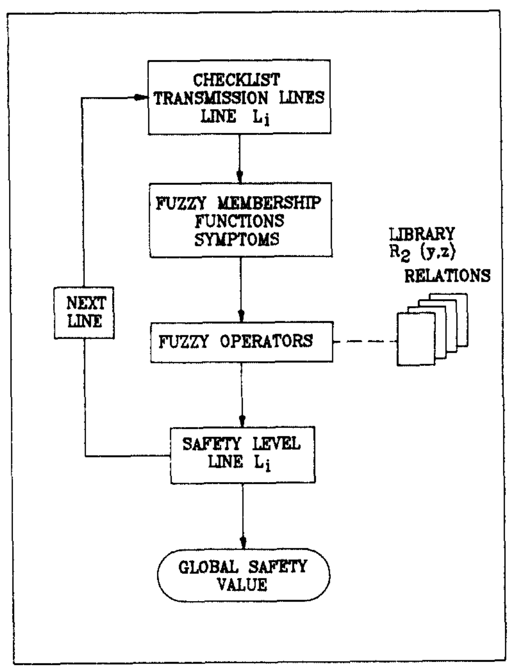

Figure 1 : Flowchart of FIRECAB

The proposed methodology will result in a reduction in a degree of subjectivity of the safety evaluation·process. The basic idea of this approach is outlined in brief.

Let x be a set of symptoms of a given transmission line, y a set of failure types and z a set of safety levels.

$R_1(x,y)$ and $R_2(y,z)$ are denoted as two (fuzzy) relations between symptoms and failure types, and between failure types and safety levels respectively. Therefore a new (fuzzy) relation for a certain transmission line between symptoms and safety levels denoted R(x,z) can be obtained as :

$$R(x,z) = R_1(x,y) * R_2(y,z) \qquad (1)$$

where * is a compositional operator of fuzzy relations.

If one gives the inspectors a checklist for each transmission line with possible observable symptoms x, then one gets easily a safety level z for each transmission line.

This relationship also holds for the classical approach, naturally the fuzzy approach seems to have an important advantage of reducing the degree of subjectivity of the human observer.

It's easy to say that one makes a checklist of symptoms x, but in the classical approach this results directly in the list with too much detail, thereby loosing the final goal of a safety evaluation in an economic manner.

However, the fuzzy approach takes a given set of symptoms x related to a given set of failures y. Due to the fact that this relation $R_1(x,y)$ holds for every installation, this fuzzy relation $R_1(x,y)$ has to be done only once. Additions or changes can be modified easily.

The set of symptoms includes many different aspects, i.e. for some type of equipment the degradation of materials and parts is reflected in a corresponding reduction of functional capability ; for other types of equipment, the degradation of materials and parts may progress without noticeable functional degradation until a trigger event causes sudden failure of the equipment.

An indicative example of a study-case gives a global idea :
Let

x = set of symptoms = $\{x_1,x_2,...,x_9\}$

where :

x_1 = no obvious isolation damage
x_2 = small isolation damage
x_3 = excessive isolation damage
x_4 = no rust
x_5 = small rust
x_6 = excessive rust
x_7 = no resistance change
x_8 = small resitance change
x_9 = excessive resistance change

and

y = set of failure types
= $\{y_1,y_2,...,y_6\}$

where :

y_1 = no loss of isolation
y_2 = small isolation leaks
y_3 = isolation leaks
y_4 = no transmission signal change
y_5 = small transmission signal changes
y_6 = high transmission signal change

The set of symptoms needs to describe in a very comprehensive manner all the possible observable symptoms, so that an inspector can point out which are valuable for each line. A good preparation of the relation $R_1(x,y)$ helps inspectors as well as for the final safety result. Clearly, this relation is common for each installation if these x- and y-set are well chosen.

The relation $R_2(y,z)$ is however typical for each installation and known safety study. If one is considering the safety against fire, the set of safety-levels z describes the safety against fire in the installation. Therefore this relation has to be established for each installation itself. Moreover this relation can also describe interference between several lines, which makes that it's surely installation-dependent.

Let

z = set of safety levels
= $\{z_1,z_2,z_3\}$

where :

z_1 = unsafe against fire
z_2 = questionably safe against fire ; needs corrective measures
z_3 = safe against fire

All these relations are written in a matrix-form (see fig. 2) and the final R(x,z) relation is computed by the FIRECAB program.

Failure types

	y_1	y_2	y_3	y_4	y_5	y_6
x_1	0.9	0.1	0	0.9	0.1	0
x_2	0.7	0.4	0.1	0.6	0.3	0.1
x_3	0.3	0.9	0.5	0.3	0.5	0.2
x_4	0.1	0.3	0.9	0.1	0.4	0.6
x_5	0.9	0.2	0.1	0.9	0.2	0.1
x_6	0.3	0.2	0.1	0.5	0.3	0.1
x_7	0.1	0.3	0.5	0.3	0.4	0.5
x_8	0.1	0.1	0.2	0.1	0.5	0.7
x_9	0.9	0.1	0.0	0.9	0.1	0.0

Safety levels

	z_1	z_2	z_3
y_1	0.9	0.5	0.1
y_2	0.5	0.9	0.1
y_3	0.1	0.1	0.9
y_4	0.9	0.5	0.1
y_5	0.5	0.9	0.1
y_6	0.1	0.1	0.9

Figure 2 : $R_1(x,y)$ and $R_2(y,z)$

These relations then hold for each line where the coefficients in the last 'matrix' are changed according to the line.

There are lots of additional possibilities which need another seperate study in the classical approach.

Besides the concepts of fuzzy relations, compositional operations of fuzzy relations, the other concepts of fuzzy set theory, such as afterset and foreset, can be applied in this study too. In particular the use of afterset and foreset enables us to give more information about the safety itself, and points out the importance of the lines.

- the R-afterset of element x of X, denoted xR: $Y \rightarrow [0,1]$; $y \rightarrow R(x,y)$, for all element y of Y,
i.e., the R-afterset of x associates to every element y of Y the degree in which x is R-related to y.

- the R-foreset of element y of Y, denoted Ry: $X \rightarrow [0,1]$, $x \rightarrow R(x,y)$, for all element x of X,
i.e., the R-foreset of y associates to every element x of X the degree in which x is R-related to y.

Suppose L represents a set of transmission lines $L=\{l_1,l_2,l_3,\ldots,l_5\}$ and X a set of symptoms $X=\{x_1,x_2,x_3,x_4\}$ that have to be related. Very often it is impossible to decide that some transmission line definitely has some symptom or definitely has not some symptom. Just as for fuzzy sets this problem can be overcome by allowing partial degrees for the strength of the link between elements. The corresponding fuzzy relation may be represented by the following fuzzy relation S(l,x):

S	x_1	x_2	x_3	x_4
l_1	1.0	0.2	0.9	0.8
l_2	0.2	0.3	0.2	0.9
l_3	0.1	0.9	1.0	0.9
l_4	0.8	0.2	0.7	0.9
l_5	0.9	0.1	0.1	0.2

Figure 3 : S(l,x)

One easily finds by checking the domain and range of the relation S, the degree of membership of some transmission line l_i (i=1,2,...,5) in the domain of S is the highest degree to which this transmission lines shows one of the symptoms, and the degree of membership of some symptom x_j (j=1,2,...,4) in the range of S is the highest degree to which this symptom appears in one of the transmission lines.

Those 'reverse' operators give a means to answer the economical problem. Indeed, it is not only interesting to know which is the safety-level associated to a certain transmission line, but also what is the cost to improve the overall safety of the installation by replacing the necessary lines.

The economical aspect of this fuzzy methodology is very interesting. Due to the simpler calculational efforts one can get much easier a sensitivity analysis. The inverse question, which cables need to be repaired first, and at which cost, to get a safer situation can be answered faster and at less costly computation time. In a very crisp description or modellisation of the fire-risk analysis, it becomes a hard matter to reverse the questions. The use of the fuzzy methodology shows a much easier way :

suppose the total set of transmission lines $L = \{l_1,l_2,\ldots,l_i,\ldots\}$, in which each line can have symptoms of the set $X = \{x_1,x_2,\ldots,x_j,\ldots\}$, finally resulting in a set of safety levels $Z = \{z_1,z_2,\ldots,z_k,\ldots\}$, one can also write :

$l_1R = \{(x_1,1.0),(x_2,0.2),(x_3,0.9),(x_4,0.8)\}$, i.e., the degree of membership of some symptom x_j in l_1R is the degree to which transmission line l_1 shows symptom x_j. The fuzzy set l_1R gives a weighted description of the state of 'illness' of transmission line l_1.

$Rx_3 = \{(l_1,0.9),(l_2,0.2),(l_3,1.0),(l_4,0.7),(l_5,0.1)\}$ i.e., the degree of membership of some transmission line l_i in Rx_3 is the degree to which symptom x_3 appears in l_i.

3. Conclusion

This paper made notice of the classical approach of fire risk analysis and also of the fuzzy approach one can follow. The study that was started seems to indicate that the fuzzy approach implements a faster methodology with accordingly lower costs involved. The fuzzy relationships between the symptoms and the failure types, and between these failure types and the safety levels have to be refined in more realistic way.

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