Modeling a Decision Making Process in a Risk Scenario: LOCA in a Nucleoelectric Plant Using Fuzzy Cognitive Maps

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Abstract. Decision making in a nucleoelectric plant is a complex process, due to many elements involved in its operation, and the permanent attention demanded by its maintenance. Presently, the decision making process in the plant is analyzed and developed by a human operator, using diagrams whose main characteristic is a linear representation of events within a scenario. That is a slow process, and can lead to the generation of new failures. We propose the development of an expert system that will help in the decision making, In this paper our main objective will be the design of the of knowledge representation and the design of reasoning through the latter. The dominion is located in the failure events in a nuclear plant. To automate the decision making process, a representation of knowledge is developed using Fuzzy Cognitive Maps (FCM), which allow us to model an expert's behavior, in decision making with uncertainty.

1 Introduction

An important part of fuzzy logic and possibility theory is centered in aspects such as: representation of knowledge, approximate reasoning and reasoning with uncertainty, main topics of Artificial Intelligence [3].

Fuzzy control logic is very close to the experts' spirit, and is known as artificial intelligence–based control. A byproduct of this theory are fuzzy cognitive maps [4, 5].

Fuzzy cognitive maps are digraphs used to represent causal reasoning. The fuzzy part allows us to have degrees of causality, represented as links between nodes of these digraphs, also known as concepts. This structure allows the forward and backward propagation of causality, allowing the knowledge base to increase when

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increasing nodes and links between them. Causality is represented as a fuzzy relation between nodes. For this type of representation a causal algebra that allows the implementing of this type of knowledge representation has been developed[7, 9, 12].

In a nuclear plant whose objective is to generate electric power, an important feature could be some critical situations due to failures in control systems; in this case the effects of mechanical and/or electrical failures of the different variables that keep the reactor in operation must be attenuated, and and if equilibrium needs to be restored through preventive decision making [10, 11, 13]. In this paper we use FCMs to model the behavior of an expert in decision making [2].

In AI, there is a variety of techniques used for representing knowledge: production rules, semantic networks, frameworks, scripts, statements logic and fuzzy cognitive maps, among others [3]. The choice of a particular technique depends on two factors: the nature of the application and the user's choice. In this case, fuzzy cognitive maps (FCMs) were chosen to represent behavior. The behavior to be modeled is centered in the decision making process, whose reasoning implies to reach a predefined goal, coming from one or more initial states; hence, the less number of transitions to reach the final goal, the most efficient the reasoning system will be. Thus, increasing efficiency implies to minimize intermediate states, and that is represented in the organization of the knowledge base. The former is accomplished by a fast and efficient implementation of the inference engine; in other words, the circuit between perception and action is closed in a faster way [3]. Cognitive maps allow us to represent many rules efficiently through links.

As a first step we must detect by means of a behavior analysis, the elements generating that behavior and its process. Elements will be represented by nodes and behavior by the links between this nodes [6, 8].

2 Fuzzy Cognitive Maps

Fuzzy cognitive maps (FCMs) comprise a new approach to the model of behavior and operation of complex systems. They were introduced by Bart Kosko in 1986 to describe the behavior of a system in terms of concepts and causal relations between those concepts [4, 5, 7, 12].

FCMs are represented by a diagram, in which nodes are concepts describing the main characteristics of the process, and the edges between the nodes establish causal relations (positive or negative) between the concepts. This graphical representation illustrates the influence that each one of the concepts has on the rest [7].

Concepts in a FCM are events, whose values change in time and originate in the system. Concepts take values in the interval [0,1], and the interconnection weights in the interval [-1,1] (see [2, 7]).

Positive causality implies a directly proportional relation[1] between one concept and the other, whereas the negative one implies an inversely proportional relation[2] [2, 7].

1 **A directly proportional relation b**etween two elements means that if one **increases** its possibility of being present the other is **incremented** proportionally. And if this possibility **decreases** in one of them, then the possibility of the other **decreases** proportionally.

This qualitative approach allows observing the general behavior of the system. However, quantification must be taking into account the causal relation in the map. How much does a node cause another? This is where fuzzy logic proves its worth.

The state of a given node is derived from all the other nodes causing it. These states are multiplied by the weight of the arc between the two nodes, and the sum is used as the input of a threshold function, transmitting a non bound input in a bound signal, which allows the comparison of nodes. Different threshold functions can be used; in this paper the following logistic signal function is used [5]:

$$S(x) = \frac{1}{\left(1 + e^{-cx}\right)} \qquad (1)$$

3 Application case: Accident by Loss of Coolant (LOCA)

A small LOCA (*Loss Of Coolant Accident*) is a rupture in liquid flow, small enough so that low capacity systems are sufficient to compensate the loss of coolant. The size of this LOCA category can be approximated to a relief/security valve stuck in the open position. Within this category are considered liquid leaks less than 0.004 sq. ft. and vapor leaks less than 0.005 sq. ft. Arriving to this LOCA scenario implies an initial failure of loss of coolant. Although LOCA's have not happened in nuclear plants according to operational experience, this kind of initiators scenarios are examined because they represent a menace to the core integrity and to the primary contention [1].

4 Elements of the Model of the HPCS System Within a Small LOCA

The behavior model is conformed by 6 elements, and this model is inspired in the physical system of Fig. 1: a) A1 (Reactor valve failure); b) A2 (Tank valve failure); c) M (Pool manual valve failure); d) B (Pump failure); e) HPCS operational; f) Vessel in good condition.

The reactor valve allows feeding water from the deposits (tank and pool) to keep a stable temperature of the reactor by means of cooling it when its temperature surpasses acceptable levels. Besides, this valve, given the relation existing between the variables temperature and pressure, also influences the keeping of pressure inside the reactor vessel. Because of the former, a *reactor valve failure (A1)* becomes a first order failure[3], and thus leaves the *High Pressure Core Spray (HPCS)* cooling system inoperative, which consequently leaves the vessel in a bad condition.

2 **An inversely proportional relation b**etween two elements means that if the possibility of one of them being present **increases**, then the possibility of the second element **decreases** proportionally; and again, if the possibility of one **decreases** then the possibility of the second element **increases** proportionally.

3 **First order failure**: one whose effect causes a total failure of the system, leaving it non operational.

The tank valve (Tx Valve) allows feeding water from this deposit (Tx) to the reactor, and so it is part of the cooling system; in other words, if a *tank valve failure (A2)* is present, this affects the operation of the HPCS system. However, this relation is not determining, because the tank is not the only deposit available to supply the water necessary to keep the HPCS system operational.

The pool valve (Ax Valve) allows feeding water from the second deposit (Pool) available to the cooling system towards the reactor. Hence, a *pool valve failure (M)* affects the operation of the HPCS system, and, like the former relation, it does not so in a determining way, since the pool is not the only deposit available to supply the water necessary to keep the HPCS system operational.

The pump allows the suction of water from any of the two deposits available for the HPCS system to provide the necessary cooling, and then a *pump failure (B)* first order one, it affects the reactor directly.

The *operation of the HPCS system* is the main element of the model, it has a positive effect on the objective element, that is, to keep the vessel in good condition. The rest of the elements of this system: pump and valves, contribute to keep the HPCS system in good working order, and hence a failure in such elements affects the overall operation of the system.

The *good condition of the vessel* implies a reactor operating properly, and this state is directly dependent on the operation of the HPCS system, which means a correct operation of the pump and the valves contained in the system.

Fig. 1 shows in a general way the operation of a nucleoelectric plant: generating electric power by means of the vapor obtained from the heating of water by the reactor nucleus.

Keeping the reactor operation in a failure scenario implies the activation of the systems attenuating such a failure scenario [1, 10, 11].

In our model, the attenuating system is the HPCS and the failure scenario is the loss of coolant (known as small LOCA) [1].

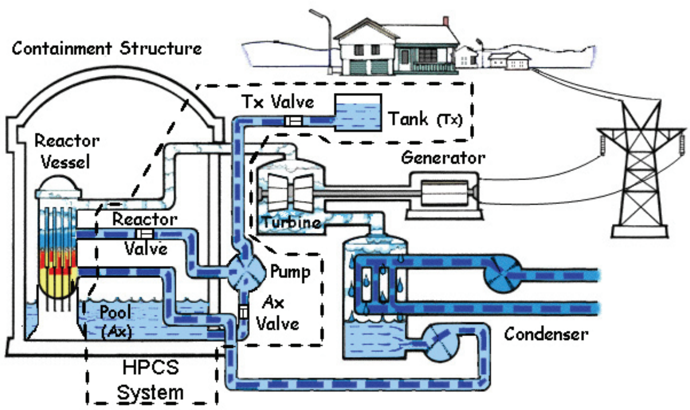

Figure 1. Operation of a nucleoelectric plant.

Our proposal associates to each possible event a possibility allowing us to make a decision based on the state of the parameters that are part of the different starting events, that is, the possible paths generated within the Small LOCA scenario. For that purpose, a representative set is implemented and analyzed (Fig. 1). The fuzzy cognitive map and the relations established between the different elements can be examined in Fig.2 .

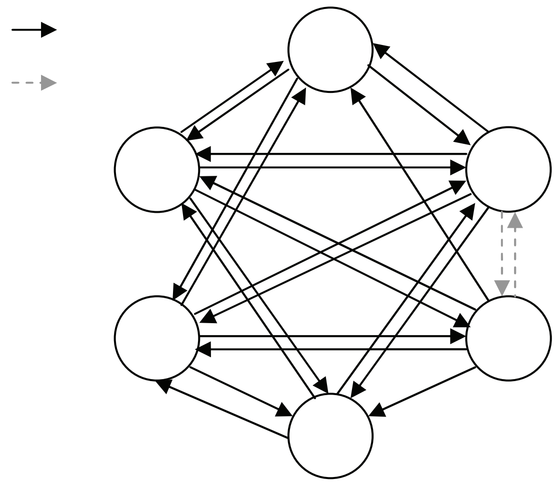

Figure 2. Fuzzy Cognitive Map of a representative set for the Small LOCA scenario.

4.1 A1 (Reactor Valve Failure)

- Once the event A1 is present, all that happens with A2 or M does not matter, because it is a first order failure, which implies affecting the system globally. In this case, the relation with those failures (A2 or M) is an excluding one (-1), *i.e.*, once the system fails, the effect of either A2 or M does not contribute to the system failure, and they are excluded.
- With regard to event B, this is independent (0). In this case, the fact that A1 is present does not affect B
- As for the operation of the HPCS system, this is in an inversely proportional relation (-1) with event A1.
- The relation between A1 and the event of the vessel being in good condition, is inversely proportional (-1).

4.2 A2 (Tank Valve Failure)

- The fact that event A2 is present, has no positive or negative effect on M (0).
- The fact that A2 is detected implies that there is no first order failure, for otherwise the effect of event A2 would have no importance, being excluded. Hence, the relation with events A1 and B is an excluding one (-1).
- The relation of event A2 with the fact that the HPCS system is in operation, has a possibility of (-0.5), although it is not determinant, for even, if event A2 were

present, the HPCS system could continue its operation, as long as events M, A1 and B are not present.

- With regard to the vessel condition, the effect can be negative if A2 is combined with event M, but it could be positive if event M is not present, and thus the resultant effect would be indifferent (0).

4.3 M (Manual Pool Valve Failure)

- The fact that event M is present has no positive or negative effect on A2 (0).
- The fact that event M is detected implies that there is no first order failure, because if there were, the effect of M would have no importance, being excluded. Thus the relation with A1 and B is an excluding one -1).
- There is a relation between event M and the operation of the HPCS system, although it is not determinant (-0.5), because, even if event M were present, the HPCS system could continue in operation if event A2 were not present, which implies that neither A1 nor B are present.
- The effect of failure M on the good condition of the vessel can be negative if it is combined with event A2, and positive if event M is not present, and thus the total effect is indifferent (0).

4.4 B (Pump Failure)

- Event B is independent of event A1 (0), which implies that whether event A1 is present or not, it has no influence, since the HPCS system would have already failed upon the presence of event B.
- The relation between event B and failures A2 and M is excluding (-1); *i.e.*, once the event B is present, events A2 and M do not contribute further to the overall effect on the system, since the HPCS system would be automatically inoperative.
- The relation of event B with respect to the operation of the HPCS system is inversely proportional (-1).
- The relation of event B with regard to the fact that the vessel is in good condition, is inversely proportional (-1).

4.5 When the HPCS is Operational

- The relation of this event respective to any of the failure events is inversely proportional (-1).
- With regard to the vessel being in good condition, this is directly proportional (1), because for a good operation of the HPCS system, the vessel must be in good condition.

4.6 When the Vessel is in Good Condition

- The relation of this event respective to any of the failure events is inversely proportional (-1).
- With regard to the operation of the HPCS system, the relation is directly proportional (1), because if the vessel is in good condition, then the HPCS system is operational.

5 Tests and their Interpretation

In the next section, we give a detailed account of the tests made with the fuzzy cognitive map presented in Fig. 2, which are represented in the following matrix:

Table 1. Matrix for the HPCS System in the LOCA scenario

	A1	A2	M	B	HPCS	Vessel
A1	0.000000	-1.000000	-1.000000	0.000000	-1.000000	-1.000000
A2	-1.000000	0.000000	0.000000	-1.000000	-0.500000	0.000000
M	-1.000000	0.000000	0.000000	-1.000000	-0.500000	0.000000
B	0.000000	-1.000000	-1.000000	0.000000	-1.000000	-1.000000
HPCS	-1.000000	-1.000000	-1.000000	-1.000000	0.000000	1.000000
Vessel	-1.000000	-1.000000	-1.000000	-1.000000	1.000000	0.000000

Table 2. First scenario, with event A1 present (reactor valve failure).The result is a scenario with failing HPCS system and vessel malfunction present.

	A1	A2	M	B	HPCS	Vessel
V_i	1	0	0	0	0	0
V_1	0.500000	0.006693	0.006693	0.500000	0.006693	0.006693
V_2	0.466586	0.006262	0.006262	0.466586	0.006693	0.006919
V_3	0.467376	0.008715	0.008715	0.467376	0.009354	0.009638
V_4	0.454598	0.008420	0.008420	0.454598	0.009293	0.009689
V_5	0.455342	0.009557	0.009557	0.455342	0.010565	0.010992
V_6	0.449336	0.009367	0.009367	0.449336	0.010496	0.010980
V_7	0.449907	0.009944	0.009944	0.449907	0.011148	0.011648
V_8	0.446845	0.009824	0.009824	0.446845	0.011090	0.011620
V_9	0.447249	0.010131	0.010131	0.447249	0.011436	0.011974
V_{10}	0.445627	0.010055	0.010055	0.445627	0.011393	0.011946
V_{11}	0.445900	0.010222	0.010222	0.445900	0.011580	0.012137
V_{12}	0.445023	0.010175	0.010175	0.445023	0.011550	0.012115
V_{13}	0.445201	0.010266	0.010266	0.445201	0.011652	0.012219
V_f	0.444722	0.010238	0.010238	0.444722	0.011633	0.012204

Table 3. Second scenario, with event A2 (tank valve failure) present. The result is a correct operation of the HPCS system and the vessel.

	A1	A2	M	B	HPCS	Vessel
V_i	0	1	0	0	0	0
V_1	0.006693	0.500000	0.500000	0.006693	0.075858	0.500000
V_2	0.000378	0.049915	0.049915	0.000378	0.483274	0.577462
V_3	0.003010	0.004930	0.004930	0.003010	0.933015	0.917782
V_4	0.000091	0.000093	0.000093	0.000091	0.989378	0.990387
V_5	0.000050	0.000050	0.000050	0.000050	0.992970	0.992938
V_6	0.000049	0.000049	0.000049	0.000049	0.993063	0.993066
V_7	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_8	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_9	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{10}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{11}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{12}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{13}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_f	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069

Table 4. Third scenario, with event M (pool valve failure) present. The result is a correct operation of the HPCS system and the vessel..

	A1	A2	M	B	HPCS	Vessel
V_i	0	0	1	0	0	0
V_1	0.006693	0.500000	0.500000	0.006693	0.075858	0.500000
V_2	0.000378	0.049915	0.049915	0.000378	0.483274	0.577462
V_3	0.003010	0.004930	0.004930	0.003010	0.933015	0.917782
V_4	0.000091	0.000093	0.000093	0.000091	0.989378	0.990387
V_5	0.000050	0.000050	0.000050	0.000050	0.992970	0.992938
V_6	0.000049	0.000049	0.000049	0.000049	0.993063	0.993066
V_7	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_8	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_9	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{10}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{11}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{12}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_{13}	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069
V_f	0.000049	0.000049	0.000049	0.000049	0.993068	0.993069

Table 5. Fourth scenario, with event B (pump failure) present. The result is the failure of the HPCS system and a vessel malfunction.

	A1	A2	M	B	HPCS	Vessel
V_i	0	0	0	1	0	0
V_1	0.500000	0.006693	0.500000	0.006693	0.006693	0.006693
V_2	0.466586	0.006693	0.006693	0.466586	0.006693	0.006919
V_3	0.467376	0.006262	0.006262	0.467376	0.009354	0.009638
V_4	0.454598	0.008715	0.008715	0.454598	0.009293	0.009689
V_5	0.455342	0.008420	0.008420	0.455342	0.010565	0.010992
V_6	0.449336	0.009557	0.009557	0.449336	0.010496	0.010980
V_7	0.449907	0.009367	0.009367	0.449907	0.011148	0.011648
V_8	0.446845	0.009944	0.009944	0.446845	0.011090	0.011620
V_9	0.447249	0.009824	0.009824	0.447249	0.011436	0.011974
V_{10}	0.445627	0.010131	0.010131	0.445627	0.011393	0.011946
V_{11}	0.445900	0.010055	0.010055	0.445900	0.011580	0.012137
V_{12}	0.445023	0.010222	0.010222	0.445023	0.011550	0.012115
V_{13}	0.445201	0.010175	0.010175	0.445201	0.011652	0.012219
V_f	0.444722	0.010266	0.010266	0.444722	0.011633	0.012204

Table 6. Fifth scenario, with events A2 (valve tank failure) and M (pool valve failure) present. The result is the failure of the HPCS system and a vessel malfunction..

	A1	A2	M	B	HPCS	Vessel
V_i	0	1	1	0	0	0
V_1	0.000045	0.500000	0.500000	0.000045	0.000045	0.000045
V_2	0.006690	0.499830	0.499830	0.006690	0.006691	0.006691
V_3	0.006273	0.474932	0.474932	0.006273	0.006485	0.006485
V_4	0.008049	0.476229	0.476229	0.008049	0.008329	0.008329
V_5	0.007802	0.469505	0.469505	0.007802	0.008153	0.008153
V_6	0.008354	0.470339	0.470339	0.008354	0.008729	0.008729
V_7	0.008238	0.468245	0.468245	0.008238	0.008635	0.008635
V_8	0.008419	0.468652	0.468652	0.008419	0.008822	0.008822
V_f	0.008370	0.467969	0.467969	0.008370	0.008779	0.008779

The interpretation of the results considers the following rounding off:
0.011633, 0.012204 and 0.008779 are taken as 0.
0.993068 and 0.993069 are taken as 1.

Where:
0 means the absence of an element, or either its opposite effect.
1 means the element is present.

These results were compared with an expert's analysis; all of them were congruent. Other tests were performed, like considering: "HPCS operational" or "vessel in good condition", or "HPCS and Vessel operational", the results were, as should be expected, "HPCS and vessel functioning correctly" in all of them.

6 Conclusions

Fuzzy cognitive maps allow handling the complexities of failure analysis in the system operation, involving all the elements of the system considered as a whole, especially if we compare it with the traditional failure trees method used by the expert, where each element of the system is considered individually in the reasoning process.

The interpretation of the results obtained helps, in an automatic fashion, to the supervisor in charge of overseeing the plant performance to make decisions about critical situations. This point is of paramount importance when the available information is so extensive as to make difficult making an adequate decision. With the interpretation of the results obtained in real time according to the present state of the plant, they will allow to make a faster and more reliable decision.

The challenge will be to model most of the systems intervening in the plant operation, to have all the time assistance to make decisions automatically.

References

1. Huerta, A., Aguilar, O., Núñez, A., López, R.: Análisis de Eventos Internos para la Unidad 1 de la Central Nucleoeléctrica de Laguna Verde –Eventos Iniciadores y Secuencias de Accidentes. Comisión Nacional de Seguridad Nuclear y Salvaguardias (1993)
2. Khan, M.S., Chong, A., Quaddus, M.: Fuzzy Cognitive Maps and Intelligent Decision Support –A Review. School of Information Technology, Murdoch University, Graduate School of Business, Curtin University of Technology, GPO Box U (1987)
3. Konar, A.: Artificial Intelligence and Soft Computing –Behavioral and Cognitive Modeling of the Human Brain. CRC Press (2001)
4. Kosko, B.: Fuzzy Cognitive Maps. International Journal of Man-Machine Studies 24 (1986) 65-75
5. Kosko, B.: Neural Networks and Fuzzy Systems: A Dynamical Systems Approach to Machine Intelligence. Prentice-Hall, New Jersey (1992)
6. Laureano-Cruces, A., De Arriaga-Gómez, F., García-Alegre, M.: Cognitive task analysis: a proposal to model reactive behaviors. Journal of Experimental & Theoretical Artificial Intelligence 13 (2001) 227-239
7. Laureano-Cruces, A., Ramírez-Rodríguez, J., Terán-Gilmore, A.: Evaluation of the Teaching-Learning Process with Fuzzy Cognitive Maps. IBERAMIA-04 Advances in Artificial Intelligence. Lecture Notes in Artificial Intelligence Series, Vol. 3315. Springer-Verlag (2004) 922-931
8. Laureano-Cruces, A., Espinosa-Paredes, G.: Behavioral design to model a reactive decision of an expert in geothermal wells. International Journal of Approximate Reasoning 39 (2005) 1-28

9. Laureano-Cruces, A., Ramírez-Rodríguez, J., Mora-Torres, M., Terán-Gilmore, A.: Inference Engine to Elicit the Cognitive and Emotive Interventions of a Pedagogical Agent. International Journal of Intelligent Systems. Wiley (Submitted: March 2006)
10. Peláez, C. E., Bowles, J. B.: Applying Fuzzy Cognitive-Maps Knowledge-Representation to Failure Modes Effects Analysis. Proceedings Annual Reliability and Maintainability Symposium X. IEEE (1995) 149-144
11. Peláez, C. E., Bowles, J. B.: Using Fuzzy Cognitive Maps as a System Model for Failure Modes and Effects Analysis. Information Sciences 88. Elsevier Science Inc. (1996) 177-199
12. Stylios, C. D., Groumpos, P. P.: Fuzzy Cognitive Maps: a model for intelligent supervisory control systems. Computers in Industry 39. Elsevier Science B.V. (1999) 229-238
13. Uhrig, R. E., Tsoukalas, L. H.: Multi-Agent Based Anticipatory Control for Enhancing the Safety and Performance of Generation-IV Nuclear Power Plants During Long-Term Semi-Autonomous Operation. Progress in Nuclear Energy, Vol. 43. Elsevier Science Ltd (2003) 113-120