2013 International Nuclear Atlantic Conference - INAC 2013
Recife, PE, Brazil, November 24-29, 2013
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 978-85-99141-05-2

A FUZZY LOGIC BASED METHOD TO MONITOR ORGANIZATIONAL RESILIENCE: APPLICATION IN A BRAZILIAN RADIOACTIVE FACILITY

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ABSTRACT

Resilience is the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under expected and unexpected conditions. This definition focuses on the ability to function, rather than on being impervious to failure, and thereby overcomes the traditional conflict between productivity and safety. Resilience engineering (RE) has fast become recognized as a valuable complement to the established approaches to safety of complex socio-technical systems and methods to monitor organizational resilience are needed. However, few, if any, comprehensive and systematic research studies focus on developing an objective, reliable and practical assessment model for monitoring organizational resilience. Most methods cannot fully solve the subjectivity of resilience evaluation. In order to remedy this deficiency, the aim of this research is to adopt a Fuzzy Set Theory (FST) approach to establish a method for resilience assessment in organizations based on leading safety performance indicators, defined according to the resilience engineering principles. The method uses FST concepts and properties to model the indicators and to assess the results of their application. To exemplify the method we performed an exploratory case study at the process of radiopharmaceuticals dispatch package of a Brazilian radioactive facility.

1. INTRODUCTION

Contemporary view on safety based on resilience engineering (RE) principles emphasizes that safety critical organizations should be able to proactively evaluate and manage safety of its activities [1]. This new safety paradigm must be endorsed by the organizational safety management to be successful. Therefore we need new methods to measure safety according to RE principles, considering that safety is a phenomenon that is hard to describe measure, confirm, and manage.

Scientists in the field of safety critical organizations state that safety emerges when an organization is willing and capable of working according to the demands of their tasks, and when people understand the changing vulnerabilities of their work activities [1], [2], [3], [4]. Based on this point of view managing the organization and its sociotechnical phenomena are the essence of safety management [5], [6]. Thus, safety management relies on a systematic anticipation, monitoring and evolution of organizational performance, in which various safety indicators play a key role in providing information on current organizational safety performance. An increasing emphasis has been placed also on the role of indicators in providing information to be used in anticipation and evolution of organizational performance. These indicators are called leading indicators.

The safety performance indicators that have commonly been used in traditional safety management have often been lagging indicators, measuring outcomes of activities or things and events that have already happened (e.g., injury rates, radiation doses and incidents). These indicators are reasonably objective, easy to quantify, and can be used requiring costly changes to the existing system, but it can be questioned whether they really indicate the actual safety of organization processes. Lagging indicators may be more useful to confirm effects after a while, in long term, than to manage immediate changes in dynamic environments. To quickly monitor such changes, the effects of good work practices, as well as, to anticipate vulnerabilities, the organizations should define leading indicators. Those should be able to grasp organizational practices and processes that antecede (lead) changes in safety performance of people in the organization.

Studies on leading safety performance indicators [7], [8] and resilience measurements [9] pointed out to the excessive subjectivity in assigning scores to each indicator evaluated. Furthermore, leading indicators is not directly related to measure organizational resilience. Thus, this study sets out to remedy these deficiencies, adopting a Fuzzy Set Theory (FST) approach to develop a method for resilience measurement in organizations using leading safety performance indicators. The FST, presented in Section 3, provides an appropriate logical-mathematical framework to deal with uncertainty and imprecision of reasoning processes and situations. Other specific limitation indicated in previous studies was the need to use specific measures to assess consistency between different evaluators, to minimize subjective judgments and evaluations. We describe the use of the proposed method in a process of radiopharmaceuticals dispatch package to illustrate the proposed improvements.

2. PRINCIPLES OF RESILIENCE ENGINEERING

The term resilience engineering (RE) represents a new way of thinking about safety. Whereas conventional risk management approaches are based on hindsight and emphasize error tabulation and calculation of failure probabilities, RE looks for ways to enhance the ability of organizations to create processes that are robust yet flexible, to monitor and revise risk models, and to use resources proactively in the face of disruptions or ongoing production and economic pressures.

There are several studies that have proposed properties or principles of resilient organizations [4], [10], [11], [12]. These studies have identified characteristics of organizations that perform high-risk activities in complex environments and even so maintain excellent safety performance and operational efficiency. In this study six principles were considered more relevant. These principles are presented below:

- **<u>Top-level commitment</u>:** Top-level commitment is a powerful influence on many organizational management themes. Top management recognizes human performance concerns and tries to address them, infusing the organization with a sense of significance on how human performance influence safety, and on how the organization can provide resources for a safer work. Without the attention and support of the senior management, resilience and safety cannot be effectively managed.
- **<u>Learning culture</u>:** The learning culture principle involves how an organization identifies better ways of carrying out its business, based on past and current experience, and its ability to identify when new issues and problems may appear. Organizations that fail to learn from small events or weak signals resisting beyond a reasonable level, without changing the way they are doing things, probably are at greater risk to have major accidents than organizations that learns and reform [11].
- **<u>Flexibility</u>:** Flexibility represents the ability of an organization to adapt to new or complex problems with adequate resources, in a way that maximizes its ability to solve problems without disrupting overall functionality. It requires that people at the working level have the resources (technical and human) to be able to make important decisions without having to wait unnecessarily for high level instructions or new equipment. In short, flexibility represents the ability of the system to restructure itself using already available resources in response to external changes or pressures.
- **<u>Just culture</u>:** A just culture is paramount for resilience due to its supporting role in the reporting of weak signals up through the organization, yet not tolerating culpable behaviors. Without a just culture, the willingness of the workers to report problems will be much diminished, thereby limiting the ability of the organization to learn about weaknesses in its current defenses. According to Reason [13], just culture clearly defines where the line between acceptable and unacceptable actions should be drawn.
- **<u>Awareness</u>:** The focus of this principle is on how the system facilitates data gathering and understanding to provide people and overall management with insights about what is going on in work activities. It is related to the quality of human performance in the organization, to the extent that it can be a problem, and the current state of defenses [14].
- **<u>Preparedness</u>:** Preparedness refers to "being ahead" of the problems in human performance and their consequences [7], [12]. The organization actively anticipates problems and it is prepared to deal with them. The principle emphasizes that there must be up-to-date realistic response plans in place to cover the major types of safety concerns.

Considering the principles above, the true challenge to measure resilience is to translate the principles into observable actions – leading indicators – that can be monitored.

3. FUZZY LOGIC FOR MODELING OF LEADING INDICATORS

Fuzzy logic provides an appropriate logical-mathematical framework to handle problems with such characteristics [14], since: (1) it deals with uncertainty and imprecision of reasoning processes and situations; (2) it allows the modeling of the heuristic knowledge that cannot be described by traditional mathematical equations and; (3) it allows the computation of linguistic informations.

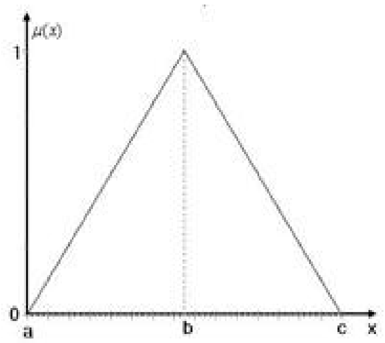
Several studies have introduced the FST approach for performance assessment of health, safety and environment in organizations [15], [16]. These studies show important reasons to use FST: reduction of human error, creation of expert knowledge and interpretation of large amount of vague data.

Fuzzy set theory (FST) is an extension of classical set theory where elements have degrees of membership. Let *X* be the universe of discourse and *x* a generic element of *X*, a fuzzy subset $\tilde{A}$, defined in *X*, is one set of the dual pairs:

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \mid x \in X\} \tag{1}$$

where $\mu_{\tilde{A}}(x)$ is the membership function or membership grade *x* in *A*. The membership function associates to each element *x* of *X*, a real number $\mu_{\tilde{A}}(x)$, in the interval [0, 1].

A fuzzy number is a special fuzzy subset of real numbers. Its membership function is a continuous mapping from *R* (real line) to a closed interval [0, 1]. Among the various shapes of fuzzy number, the triangular fuzzy number is the most popular one [17]. A triangular fuzzy number $\tilde{A}$ can be denoted by *(a, b, c)* (Fig. 1) and its membership function is described in Eq. 2.



$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-a}{b-a}, & \text{if } a \le x \le b \\ \dfrac{c-x}{c-b}, & \text{if } b \le x \le c \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Figure 1: Triangular fuzzy number

An important concept in fuzzy set theory is the concept of linguistic variables. A linguistic variable is a variable whose values are words or sentences in natural language, which can be represented as fuzzy sets. We can consider a leading indicator as a linguistic variable represented by set of four linguistic terms (Unimportant, Little Important, Important and Very Important) which correspond to the importance degrees used to assess the weight of this indicator by experts.

4. METHOD FOR RESILIENCE MONITORING

The method has the following phases:
(1) Selection of the leading indicators;
(2) Determination of a resilience ideal pattern;
(3) Assessment of the actual resilience level compared with the pattern.

4.1. Selection of leading indicators

Selection of leading indicators should always start from the consideration of what are the key issues to monitor, manage and change [7], [8], [12]. The leading indicators are utilized as part of the resilience monitoring process, not as an independent goal or function as such. The operationalization of an indicator is called "metric". A metric denotes how the indicator is measured, whereas an indicator denotes something that one wishes to measure with the use of one or more metrics. The selection of the resilience themes addressed and leading indicators used in the radiopharmaceuticals dispatch package sector was based on a previous ergonomic study [18] and are described in table 1.

Table 1: Themes and leading indicators

Themes	Indicators	Themes	Indicators
Top-level commitment	1.1 Human resources 1.2 Material resources 1.3 Safety commitment 1.4 Safety policy 1.5 Procedure management 1.6 Training programs 1.7 Competence selection	**Awareness**	4.1 Reports of problems 4.2 Information security 4.3 Communication 4.4 Team work 4.5 Workload 4.6 People relations 4.7 Tasks and skills 4.8 Awareness of limitations 4.9 Preventive maintenance 4.10 Proactive actions
Learning culture	2.1 Information dissemination 2.2 Information flow 2.3 Work management 2.4 Actual working practices 2.5 Local adaptations 2.6 Content of documentation 2.7 Availability of documentation 2.8 Analysis of incidents 2.9 Investigations of incidents and accidents	**Just culture**	5.1 Reporting of deviations/worries 5.2 Understanding of errors 5.3 Perception of errors 5.4 Actions are not punitive 5.5 Peer assessments 5.6 Professional recognition
Flexibility	3.1 Ability to cope with the unexpected 3.2 Capacity for flexibility 3.3 Safe working limits 3.4 Reports on adaptations 3.5 Incorporation of adaptations	**Preparedness**	6.1 Emergency plan 6.2 Identification of risks 6.3 Safety equipments 6.4 Alarm system 6.5 Proactive procedures 6.6 Emergency training

4.2 Determination of a resilience ideal pattern

The second phase of the method is to obtain from experts in radiopharmaceuticals production and resilience engineering issues the degree of importance of each indicator metric, so that the organization sector can be considered resilient. This means that the degree of importance assigned to each indicator by the specialist should show how the sector should be to achieve an ideal resilience level. Thus, it is not evaluating the sector, but the ideal of resilience that it should have. The phase has the following steps: 1) Experts selection; 2) Calculation of each expert relative importance, based on knowledge and experience; 3) Choice of linguistic terms and membership functions; 4) Determination of the importance degree of each indicator, 5) Aggregation of fuzzy opinions; 6) Resilience pattern.

Calculation of experts' relative importance. The relative importance of the expert was calculated on the basis of experts' attributes (experience, knowledge of radiopharmaceuticals production safety and knowledge of the package radiopharmaceuticals dispatch). We used a questionnaire (Q) to identify the profile. Each questionnaire contains information of a single expert. The relative importance (RI) of expert E_i (i = 1, 2, 3,…, n) is a subset μ_i (k) Є [0,1] defined by Eq. 3. Referring to Eq. 3, *tQi*, is the total score of expert *i*.

$$RI_i = \frac{tQ_i}{\sum_{i=1}^{n} tQ_i} \qquad (3)$$

Choice of linguistic terms and membership functions. Each leading indicator can be seen as a linguistic variable, related to a linguistic terms set associated with membership functions. These linguistic terms are represented by triangular fuzzy numbers to represent the importance degree of each indicator (Fig. 2). It is suggested that the experts employ the linguistic terms, U (Unimportant), LI (Little Important), I (Important) and VI (Very Important) to evaluate the importance of each indicator.

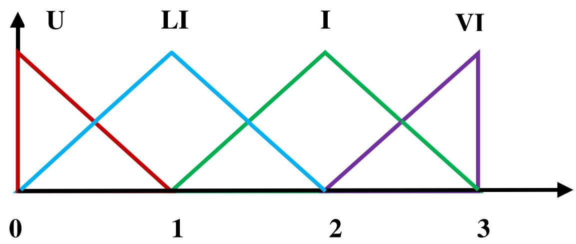


Figure 2: Membership functions

Aggregation of the fuzzy opinions. The similarity aggregation method proposed by Hsu and Chen [19] is used to combine the experts' opinions which are represented by triangular fuzzy numbers. The agreement degree (AD) between expert Ei and expert Ej is determined by the proportion of intersection area to total area of the membership functions. The agreement degree (AD) is defined by Eq. 4.

$$AD = \frac{\int_x \left(\min\left\{\mu_{\tilde{N}i}(x), \mu_{\tilde{N}j}(x)\right\}\right)dx}{\int_x \left(\max\left\{\mu_{\tilde{N}i}(x), \mu_{\tilde{N}j}(x)\right\}\right)dx} \qquad (4)$$

If two experts have the same estimates, then, AD =1. In this case, the two experts' estimates are consistent, and then the agreement degree between them is one. If two experts have completely different estimates, the agreement degree is zero. If the initial estimates of some experts have no intersection, then we use the Delphi method to adjust the opinion of the experts and to get the common intersection at a fixed α – level cut [19]. The higher the percentage of overlap, the higher the agreement degree. After all the agreement degrees between the experts are calculated, we can construct an agreement matrix (AM), which give us insight into the agreement between the experts.

$$AM = \begin{bmatrix} 1 & AD_{12} & \cdots & AD_{1j} & \cdots & AD_{1n} \\ \vdots & \vdots & & \vdots & \vdots & \\ AD_{i1} & AD_{i2} & \cdots & AD_{ij} & \cdots & AD_{in} \\ \vdots & \vdots & & \vdots & \vdots & \\ AD_{n1} & AD_{n2} & \cdots & AD_{nj} & \cdots & 1 \end{bmatrix} \quad (5)$$

The relative agreement (RA) of expert E_i (i = 1, 2, 3, …, n) is given by Eq. 6.

$$RA_i = \sqrt{\frac{1}{n-1} \cdot \sum_{j=1}^{n} (AD_{ij})^2} \quad (6)$$

Then we calculate the relative agreement degree (RAD) of expert E_i (i = 1, 2, 3, …, n) by Eq. 7 and the consensus coefficient (CC) of expert E_i (i = 1, 2, 3, …, n) by Eq. 8.

$$RAD_i = \frac{RA_i}{\sum_{i=1}^{n} RA_i} \quad (7)$$

$$CC_i = \frac{RAD_i \cdot RI_i}{\sum_{i=1}^{n} (RAD_i \cdot RI_i)} \quad (8)$$

Let Ñ be a fuzzy number for combining expert's opinions. Ñ is the fuzzy value of each leading indicator which is also triangular fuzzy number. By definition of the consensus coefficient (CC) of expert E_i (i = 1, 2, 3, …, n), $\tilde{N}$ can be defined by Eq. 9. Referring to Eq. 9, $\tilde{n}_i$, is the triangular fuzzy number relating to the linguistic terms, U (Unimportant), LI (Little Important), I (Important) and VI (Very Important).

$$\tilde{N} = \sum_{i=1}^{n} (CC_i \cdot \tilde{n}_i) \quad (9)$$

Resilience pattern. The resilience pattern as a reference for monitoring the organizational resilience is established by calculating the normalized importance degree (NID) of each leading indicator that makes up each property relevant to resilient organizations. The normalized importance degree (NID) of each leading indicator is given by deffuzification of its triangular fuzzy number $\tilde{N}$ (a_i, b_i, c_i), where b_i represents the importance degree. Then, NID can be defined by Eq. 10.

$$NID_i = \frac{NID_i}{\text{the highest numerical value of bi}} \quad (10)$$

4.3. Resilience assessment

This third phase of the method is to assess the resilience level compared to the resilience pattern. In this phase, the linguistic values are used to assess the compliance degrees of the leading indicators to the radiopharmaceuticals dispatch package sector given by workers. It is suggested that the workers employ the linguistic terms, SD (Strongly Disagree), PD (Partially

Disagree), NAND (Neither Agree Nor Disagree), PA (Partially Agree), SA (Strongly Agree) (Fig. 3).

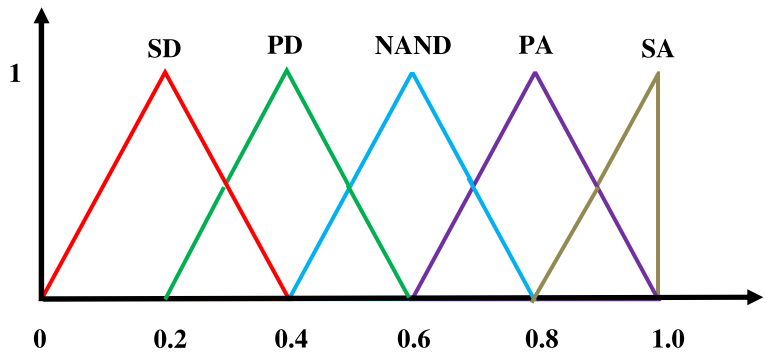


Figure 3: Membership functions for resilience assessment

Using the center of area defuzzification method we calculate the compliance degree (CD) with the resilience pattern by Eq. 11. Referring to Eq. 11, cd_j is the compliance degree of leading indicator j of theme *i* in the package radiopharmaceuticals dispatch.

$$CDi = \frac{\sum_{j=1}^{k} NID_j . cd_j}{\sum_{j=1}^{k} NID_j} \tag{11}$$

5. RESULTS

The resilience ideal pattern was obtained based on the opinion of twelve experts in radiopharmaceuticals production and organizational safety. The resilience assessment of the radiopharmaceuticals dispatch package sector was performed by seven workers. The average assessment of the resilience based on each indicator was computed and showed in Fig. 4. We consider satisfactory a compliance degree greater than 0.6, because this value already represents an agreement with the resilience ideal pattern. This represents an α – level cut at 0.6 of the fuzzy set "leading indicators". The result of the average assessment showed that the radiopharmaceuticals dispatch package sector presented satisfactory learning culture, flexibility awareness, just culture and preparedness. However, this sector presented problems related to the top-level commitment.

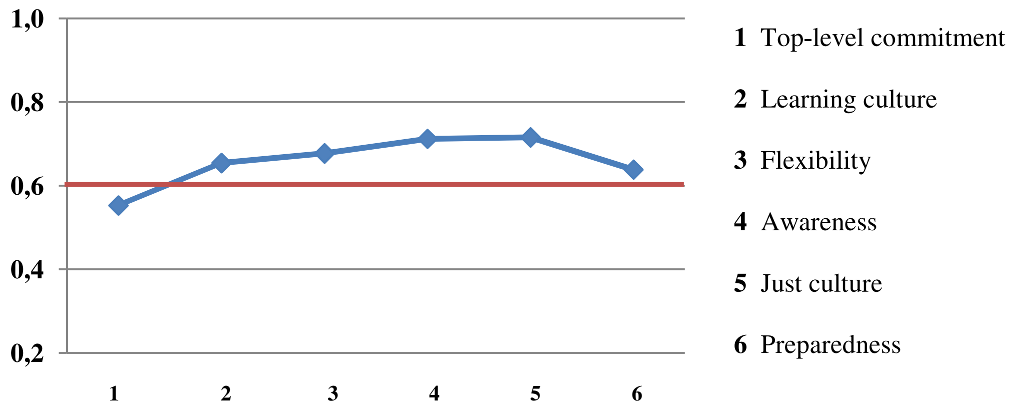


Figure 4: Average assessment of resilience

6. CONCLUSIONS

In this paper we described a method for organizational resilience assessment. We proposed a method that uses leading indicators and concepts and properties of Fuzzy Sets Theory. We developed a resilience pattern using a similarity aggregation method to aggregate fuzzy individual opinions, considering the difference of importance of each expert. A pilot study in the radiopharmaceuticals production facility shows that this method based on leading indicators and fuzzy logic offers interesting perspectives for the implementation of resilience engineering principles. This assessment method can be a proactive tool to provide a basis for action without waiting for events. Using this method we identify problems related to leading indicator metrics of the top-level commitment theme. These problems can be investigated in order to implement actions to make the process of radiopharmaceuticals dispatch package more efficient and secure besides improving the resilience in this sector.

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