Resilience and Brittleness in a Nuclear Emergency Response Simulation: Focusing on Team Coordination Activity

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ABSTRACT: The current work presents results from a cognitive task analysis (CTA) of a nuclear disaster simulation. Audiovisual records were collected from an emergency room team composed of individuals from 26 different agencies as they responded to multiple scenarios in a simulated nuclear disaster. This simulation was part of a national emergency response training activity for a nuclear power plant located in a developing country. The objectives of this paper are to describe sources of resilience and brittleness in these activities, identify cues of potential improvements for future emergency simulations, and leveraging the resilience of the emergency response system in case of a real disaster. Multiple CTA techniques were used to gain a better understanding of the cognitive dimensions of the activity and to identify team coordination and crisis management patterns that emerged from the simulation training.

1 INTRODUCTION

1.1 Safety in Nuclear Power Plants

Since the first atomic reactor created by Enrico Fermi in 1942, safety aspects are an important part in the development and operation of Nuclear Reactors (Martin, 2002). Three decades passed from the development of the first nuclear power reactor to the viable exploitation of this kind of energy, and in 1979 the Three Mile Island accident, the most significant accident in the history of the American commercial nuclear power generating industry, created public skepticism and uncertainties about the safety and viability of nuclear power generation (Woods and Hollnagel, 2006).

Nowadays the Nuclear Energy industry is one of the safest in the segment with less fatal accidents than the Coal Energy industry, the Hydro Energy industry and the Natural Gas Energy industry (World Nuclear Association, 2008).

However, growing public concern over the potential catastrophic harm to humans and the environment from a nuclear accident led governing and regulatory authorities to assess their own emergency response systems. This included reviewing the need for improvements in safety regulations, consistent plant emergency systems and procedures, and to continue the utilization and development of the energy generated in Nuclear Power Plants (Union of Concerned Scientists, 2007).

1.2 Simulation to improve emergency response

In order to handle a nuclear disaster and ease the potential damage it can cause, response agencies must be prepared and capable to stabilize an accident, protect life and the environment, and be prepared for command, control and coordination of a response in order to coordinate efforts toward a common goal (FEMA, 2006).

Due to the scarce number of real accidents occurring in a Nuclear Power plant, simulation of possible real situations proved to be helpful preparing agencies and people to better respond to a real emergency. Simulations are used in very safe domains such as aviation, where the simulation prepares agents for events that are unlikely to occur in real situations. Some simulation can offer high fidelity, even in a controlled environment, to better reproduce rare and critical situations, and have been used to assess emergency response decision making in Nuclear Power plant simulation (Murphy et al, 2007).

1.3 External Emergency Plan (EEP)

Each Nuclear Power plant must have emergency plans to respond to a nuclear incident. One of them is the EEP, where local governments, agencies and people concerned work together in a previously defined place, outside the Nuclear Power plant, to follow the evolution and consequences of the accident, to classify and distinguish local ranges of accidents and to take measures and procedures to mitigate the consequences of a Nuclear accident for people and for the environment. (Bari, 2007)

1.4 Sources of Resilience and Brittleness as cues to improve the simulation

Resilience is needed to achieve high levels of performance in complex systems (Hollnagel et al, 2006). Organizations attempt to enhance resilience by anticipating and practicing how to handle rare but difficult events by practicing emergency response. A critical aspect of these run-throughs is practicing team work and coordination over multiple groups in different facilities as the simulated disaster evolves and cascades (Woods and Hollnagel, 2006). In addition, how well teams work together and the difficulties they encounter in these simulated cases provide information about sources of resilience and brittle points in the emergency response system.

The deployment of an Emergency Plan requires complex cognitive and collaborative skills, and a variety of Cognitive Task Analysis (CTA) techniques were utilized to extract information about these skills from the resources available (Woods and Hollnagel, 2006; Crandall et al., 2006). Based on this analysis, the research team looked for sources of resilience and brittleness in how the team handled the emergency response. Identifying the sources of resilience and brittleness helps provide indicators of the emergency response system's level of resilience, helps enhance future training exercises, and suggests design directions to enhance team performance.

2 METHODOLOGY

This case study research uses multiple CTA methodologies in its analysis. Yin (1984) defines the case study research method as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident, and in which multiple sources of evidence are used.

The data analysis in this paper is based on the simulation of a nuclear power plant emergency where the EEP was employed to test and better prepare agencies and people for a real event.

The nuclear power plant where the simulation was conducted and where the studies took place is located in a developing country. This is specifically interesting because of the unique challenges not often considered in emergency response simulation research. For example, the infrastructure and the organization of different agencies play an important role in a nuclear emergency response.

This Nuclear Power plant is located close to a high density population area, and the protection of people living in the neighborhoods and the preservation of the environment are the main goals of the EEP.

The EEP was first developed by the Department of General Civil Defense over 10 years ago. This plan has been modified and revised multiple times by the involved agencies to become more complete and consistent.

Currently the EEP is a guideline to ease the articulation of the Complementary Emergency Plan developed and implemented by each participating agency. The EEP is a synthesis of threats, vulnerabilities, scenarios and role assignments to agency in a real nuclear accident.

Among the agencies participating in the simulation are local state and national levels providing police, communication, transportation, health, coordination services as well as several other private companies like buses, water, energy, power distribution.

The observed emergency simulation is part of a national exercise program that takes place each year and is based on scenarios developed by the national civil defense organization to test the response capabilities of the multiple agencies. The simulation starts when the first scenario, a warning of a small emergency in the nuclear power plant, is sent to the Emergency Calls Center. Following this first message the EEP is deployed to mobilize the representatives from all the agencies.

A previously prepared crisis management situation room receives all the agencies' representatives, as described in the EEP. At predetermined times, reestablished scenarios are sent to the coordinator of the EEP, in pre-determined hours. The simulation reported here occurred over one day in 2007 from 8:00 am until 5:00 pm with a small break for lunch. The event used, rose in difficulty as the simulation progressed, escalating from local problems in the beginning to a nuclear release into the environment in the last and worst event.

During the different events used in the simulation, the participants were aware that all their moves and their consequences were grounded in real decisions with deployed resources which contributed to the realism of the simulation.

2.1 Cognitive Task Analysis

The main CTA approach applied in this paper is described by Crandall et al. (2006) as a set of tools that if employed wisely can help researchers understand how cognition makes it possible for humans to get things done in order to help people to get things done better.

Many methods and tools are presented by Crandall et al (2006), from knowledge elicitation to the redesign of a system or task. The use of several methods and tools in an adequate combination can lead researchers to understand and solve different types of problems involving cognition (Crandall et al., 2006).

2.2 Data Collection

Data collected in this research originated mostly from "think aloud" procedures. The "think aloud" methodology let us generate verbal reports of task performance for further analyze thought processes (Ericsson and Simon, 1993). The "think aloud" part of this research corresponds to the simulation of the EEP of the Nuclear Power plant mentioned above.

Interactions among the participants, problem solving and decision making processes are captured in almost four hours of audiotape recordings which were transcribed and translated.

In addition to the "think aloud" method, interviews conducted with experts on the EEP simulation to better understand details. This combined data collection provided a deeper understand of the case and enhanced the analysis process.

2.3 Protocol Analysis

To analyse the cognitive work in the case studied, a Protocol Analysis was used. The PA is a rigorous method for eliciting verbal reports of thought sequences as a valid source of data on thinking (Ericsson and Simon, 1993).

PA is also referred to as a general data analysis procedure, where each statement in the protocol is coded according to a model of reasoning that reflects the goal of the research. This model of reasoning has coding categories that can include expressions of goals, observations, hypotheses and decisions, leading to analytic and representational formats that can reveal important aspects of cognitive processes (Crandall et al, 2006).

2.4 Analysis and Representation

With all the data records completed and reviewed, it is time to move into the analysis and representation phase. Crandall et al (2006) defined the analysis and representation phase as a process of exploration and discovery locating what is important in the data set, and a moment to organize and structure those discoveries in order to communicate them well.

The main data analysis and representation was conducted by means of a timeline analysis. In this timeline analysis, all the activities of the people in the room involved in the EEP simulation were represented in a chart, to create an overarching view of all the simulation activities.

To represent the various activities of the teams, categories of actions were created based on separate analyst review. Common categories were then labelled to express analyst agreed-upon key moments of the simulation as well as to simplify the representation for analysis. These categories are listed in table 1.

In the representation, for each minute of the simulation there is a line with multiple boxes to be filled. For example, between 9:45 and 9:46 of the simulation activities involving Question, Request for Silence and People arrival are observed. The boxes corresponding to each one of these subcategories would then be checked in corresponding to the time 9:45.

Table 1. Categories of actions and descriptions

Categories	Actions	Description
Comunication	Conversation in small groups	People speaking in small groups
	Messages from plant/new information	New events, scenarios, information
	Explanation of details / specific knowledge	Technical explanation to share knowledge
	External comunication (cell phone)	Comunication outside de External Emergency Room
	Repeating known information	Briefings to mantain common ground
	Question	Doubts of the participants
Order/comand	Comand to team members	Orders given by the coordinator or another leader
	Aproving and making decisions	Decisions concerning what to be done in each case
	Request for silence	To avoid dispersion of the group
	Request for information	To avoid unclear informations
Physical/ technology	Technology problems	Inadequate technology resources
	People arrival	Replacements, lunch break, arrival of people

To more accurately analyze the data, colours were allocated to each participant agency in the simulation. While there should be a total of 26 colours in the complete timeline, due to limitations in the range of recording, only actions of individuals appearing in the videos were represented in the timeline. Figure 1 shows a sample of the structure of the timeline analysis from 10:30 am to 11:00 am.

For analysis and comprehension purposes, comments on specific important actions were done in some boxes that have a red signal on the right top. Numbers were also allocated for each sequence of actions that had the same origin, i.e. a new message arrives to the team. This new message corresponds to the series 24 in the sequence of actions observed. So the series 24 will be written in the box of this action. Following this message there will be some other actions involving explanation of details, questions, and decision making. Each of these actions in this same sequence will get the series 24. When a new event arises, series 25 will be given to the first action of this event.

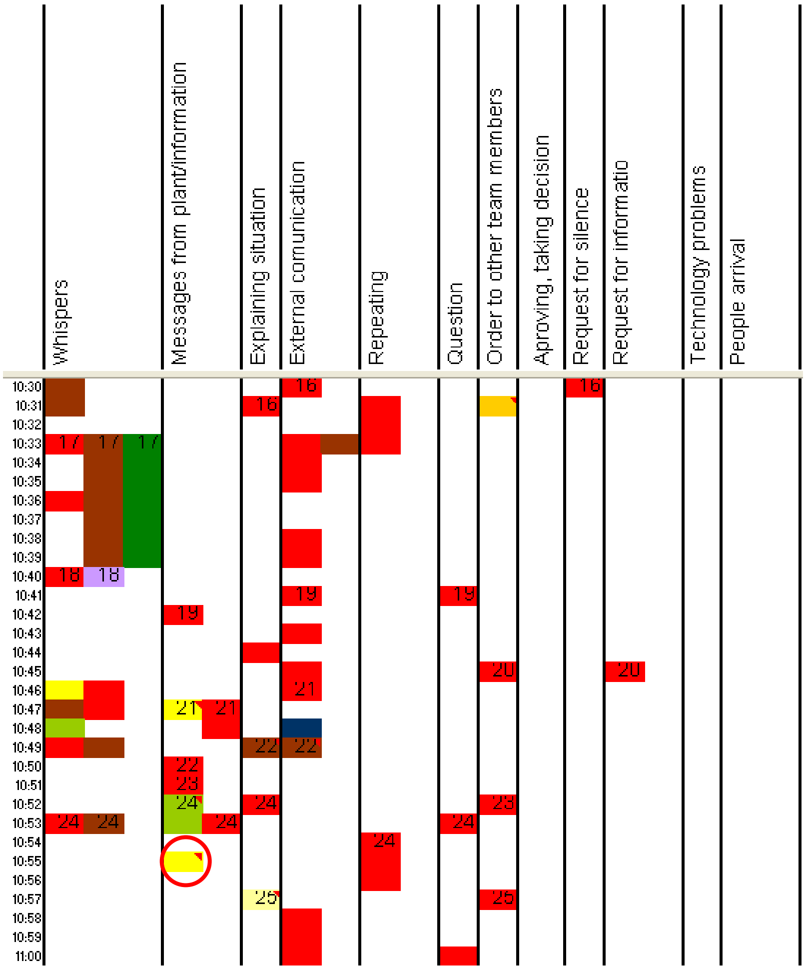

Fig. 1 Detail view from the timeline analysis

After numbering all the events and actions, analysis turned to sequences of actions to examine what actions followed one another. These numbers were summed up in the matrix shown in the table 2.

For example, if a question was asked right after an external message, the number corresponding to the line and column "External Message" and "Question was added by one. To reorganize and simplify the analysis of this information, the subcategories of actions that had the largest number of succeeding events were put along side the others. This reorganization made it easier to identify some specific patterns of the simulation concerning team organization, information and actions flow. Patterns in this case were considered as recurring events or repeated behaviours from the agents that were seen in different scenarios or events. Figure 2 shows a sequence of events that appeared often for different scenarios in the simulation.

Table 2. Number of crossed interactions

	Messages from plant/new information	Explanation of details / specific knowledge	External comunication (cell phone)	Question	Request for silence	Comand to team members	People arrival	Technology problems	Request for information	Conversation in small groups	Repeating known information	Aprovinga and taking decisions
Messages from plant/new information		16	5	5	7	9	0	0	1	9	6	7
Explanation of details / specific knowledge			10	5	4	12	0	2	2	6	9	4
External comunication (cell phone)				5	2	8	0	0	2	4	2	2
Question					1	3	0	0	0	5	4	1
Request for silence						2	0	0	0	3	1	2
Comand to team members							0	2	2	5	3	3
People arrival								0	0	0	0	0
Technology problems									0	0	0	0
Request for information										1	0	0
Conversation in small groups											3	3
Repeating known information												2
Aprovinga and taking decisions												
	65	70	40	29	22	49	0	4	8	39	30	24

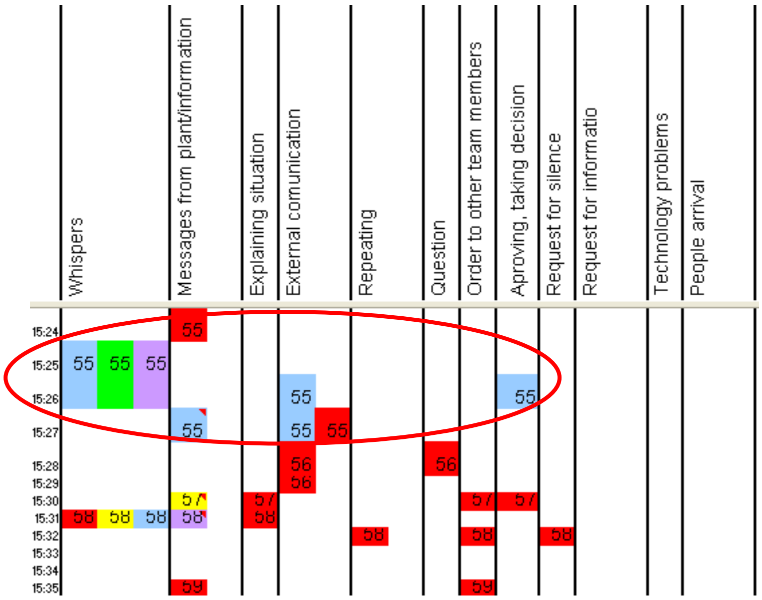

Fig. 2. Sample of actions sequence

This sequence of actions describes the mechanism how the team worked- from receiving a new problem or new information, explaining the problem throughout the group and common grounding functions (Klein et al, 2004), discussing problems in small groups, making decisions and sending orders outside the meeting room by cell phone. This is one example of a specific event, but identifying different actions with different mechanisms and patterns were extremely important to understand the reasoning process of the team.

Another analysis was carried out concerning interactions within people in the team. For that, the distribution of the members of the EEP were represented by circles in the same format as they were distributed in the External Emergency room. Based on this representation, arrows were drawn going from and coming to one participant to others. The thicknesses of the arrows represent the number of interactions each person had during the whole simulation.

Figure 3 presents this analysis, identifications are not provided in this figure because they are undisclosed. However, there was an analysis based on the role each person had in the simulation.

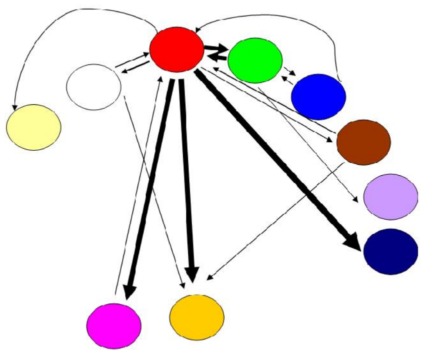

Fig. 3. Interaction between agents analysis

This analysis was important to detect how the distribution of people in the room interfered in the communication among the team, to have a better view of the information flow, to indentify overloads and bottlenecks in the simulation and to identify the most important people involved in communication, decision making activities in the simulation, and also to identify surprising patterns, function based grouping of interactions.

3 FINDINGS

3.1 Results: Sources of Resilience

Resilience is defined as the capacity of the system to successfully handle disturbances, including surprises. The following sources of resilience were identified based on the combined analysis of the data.

1- There are important efforts from the emergency team coordinator on briefing and maintaining the common ground. Due to the dynamic characteristics of an emergency response, revision and briefings are extremely important. (Woods and Hollnagel, 2006).

The ability of people in an emergency room to revise plans and assessment when evidence arrives and situations change lead to a more consistent and reliable decision making process.

Also the diversity of background and knowledge agents of the emergency response team has requires briefings to share common ground and comprehension of the incident and events. (Hong and Page, 2004)

2 - Diversity of the emergency response team might be a source of resilience. The presence of representatives from 26 different agencies represents the diversity of the group. However, Hong and Page (2004) consider that problem solver groups with diversified high skilled individuals can outperform a team of experts.

3 - The emergency response team presents some good organizational patterns. Klein (2001) defines organization as the attempt by multiple entities to act in concert in order to achieve a common goal by carrying out a plan they all understand.

In the EEP studied, agencies that compose the team bring their own plan and script for emergency response. For complex system demands, having a modular plans rather than complete complex plans makes more sense. (Klein, 2001)

4 - There is also a reorganization mechanism that emerges from the emergency response team activities. When incidents appear and require different competences, agents required to understanding and making decisions on specific domains gather together in small groups to discuss about the subject. One example happened when there was a real situation not planned in the Simulation Protocol.

There were environment activists blocking roads close to the Nuclear Power Plant area. To solve the problem, representatives from polices (highway, investigative and military) gathered together to discuss about the problem and make decisions. After that, each of them contacted their own agencies to act in coordination, and the activists were stopped a few minutes later. Klein (2001) classifies those organization mechanisms as sources of emerging marginal value to the operations.

3.2 Results: Sources of Brittleness

Brittleness is defined as a point of the system that leads it to be operating riskier than expected. Identifying sources of brittleness can help anticipate how the system can fail and helps preventing it (Gomes et al, 2008).

1 - While a nuclear accident is highly complex and dynamic, the design of the current simulation that was studied was quite static. There are a finite number of pre-determined events that were sent to the emergency response team in a predetermined sequence, creating a less complex and challenging environment. There was a noticeable change on team behaviour when an unanticipated surprise real-world situation arose when a group of environment activists started blocking roads. Agency participants became noticeably more serious and there were less marginal activities between the people that were not concerned to find solutions for the problem.

For this lack on dynamics and realism, Murphy et al. (2007) propose a Learning laboratory approach which takes a design approach to large scale exercises, to abstract valuable lessons from these exercises.

2 - However there are mechanisms of briefing repeatedly used during the simulation, there is no specific briefing mechanisms to put in a common ground agents that arrive in the middle of an event or decision making process. This people’s arrival is often during the first hours of the simulation, when agencies contacted are sending their representatives, during lunch time and can be sometimes seen during the course of the simulation, when replacement of an agent is needed for any reason.

3 - Physical distribution of individuals in the room is extremely important, since there are scenarios that a combination of agencies will interfere rather than others. In shared work spaces, individuals will organize their own activities and placement in

relation to the distribution of others in the room. (Engeström and Middleton,1996)

An appropriate and flexible work space organization providing a dynamic layout of agency's representative cells could also enhance the organization mechanism already existing in the emergency response team.

4 - Activities of the simulation team coordinator are extremely important to execution and command of the EEP. However, if most part of the activities of the EEP are performed by the coordinator, there might be a cognitive overload, generating this way a bottleneck on the decision making process (Klein, 2001). Figure 3 shows that a great part of the communication between agents is done by the coordinator and it can represent an overload on his activities.

5 - The number of agents and agencies has an influence on the organization and performance of the team. After some hours in the external emergency room it seems to have a tendency of the participants to disperse and probably a lack on concentration. It is noticeable by the number of times silence were requested to the team. The number of individuals might degrade this context, especially if some of the agents do not have an active participation on the team's decisions and actions. Having a team is better off only when its performance is higher than the sum of each individual. By adding more people, the coordination cost rises, and the team can become too large (Klein, 2001).

6 - Though the agencies bring their own plans for emergency, generating a less complex modular emergency plan, it is needed an elaborated plan to identify the function and role of each agency in the Nuclear Emergency response. An analysis of the EEP existing might help to increase the simulation's resilience.

7 - There is a lack on visual and communication technology support to understand and share the emergency situation to all the agents involved in the Emergency Plan. All the description of the events and activities are done verbally. Visual and communication technology support is helpful to understand the context and make decisions when time to response is scarce. (Shoenwald et al, 2005)

CONCLUSION

In the current study we have used multiple CTA techniques to find sources of resilience and brittleness in a nuclear emergency response simulation. Our analysis found sources of resilience and brittleness related to team coordination, simulation design and dynamics, workspace design, visual and communication technology support and crisis response activities.

Knowing and understanding these sources of resilience and brittleness in a system is useful to better understand why activities are successful or unsuccessful, and what the interference in the system performance is.

Further studies and researches are planned to be done in order to further examine these sources of resilience in the emergency response simulation, and to mitigate the sources of brittleness or even transform them into sources of resilience.

It is important to remember that there were some shortcomings imposed by the materials used in the analysis due to this sensitive domain

There was not a direct recommendation for improvement of the Emergency Response simulation, but, rather, hints of issues to be improved in the next studies of the case. Most part of the studies on emergency response simulation in nuclear power plants were made in developed countries. Studies in nuclear power plant emergency in developing countries shows to be important because there are social, cultural and economic differences from developed countries that will imply in different demands for agents, organization and the system.

The results provided by this analysis suggest that areas such as team coordination, simulation design and dynamics, crisis management and correspondent development of appropriate technology to support them are areas with high potential for improvement in emergency response simulation.

ACKNOWLEDGEMENTS:

The authors gratefully acknowledge the support of Fipse/Capes Project and National Council of Scientific and Technological Development (CNPq-Conselho Nacional de Desenvolvimento Científico e Tecnológico).

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