A Framework for Evaluation of Resilience of Disaster Rescue Networks

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Abstract. Disasters by their very nature are unpredictable so being prepared to react in short time and with high efficiency is vital. The adoption of the collaborative networks paradigm in disaster management can lead to a new generation of rescue teams so called Disaster Rescue Network (DRN). During the first hours after a disaster, and before external help can arrive, it is the DRN implanted in the incident area that can perform the first rescue tasks. But the DRN is itself affected by the disaster and often gets its operational level drastically reduced. The main objective of this work is to propose an evaluation model, through employing experts' knowledge, for measuring a resilience index in DRNs. In this paper, a Fuzzy Inference System is used to achieve the mentioned objective. This will help in evaluating the resilience of DRNs and provide the opportunity to simulate policies to improve that resilience.

Keywords: Resilience, Fuzzy Inference System, Disaster Rescue Network

1. Introduction

In the first hours after a large scale disaster and before a disaster rescue team is operational, social networks play crucial roles [1]. This means that professional rescue teams implanted in the incident area are not resilient enough to recover and accomplish their mission. Recently this problem has attracted the attention of researchers as on one hand professionals are empowered to deal with crisis situations and on the other hand response time is crucial. Having an effective recovering process after being impacted could make huge difference.

Rescue networks due to their functionality and mission have to face challenges which are not predictable. In case of disasters not only we face complex and dynamic phenomena but also the multiplicity and multifunction of actors, whether individuals or organizations, needed to deal with the situation [2]. Traditional leadership structures cannot be of much help in crisis, while a resilient response needs to be institutionalized in Disaster Rescue Networks (DRN) [3]. Resilience is an important decisive factor in terms of survivability of the system in unpredictable situations. It is sourced in basic systems theory concepts such as equilibrium, adoptability and stability [4]. Both individual and collective responses to unexpected and radical changes are interesting for researchers in the area of resilience [5].

Resilience in hazard management systems has attracted the researchers' attention and many works confirm the importance of the subject when the focus is on developing strategies for building resilient societies. Macro Level is the dominant perspective in this area and achieving a resilient society the focal point. Something which is less considered is that DRNs are also affected by disasters while we are expecting them to react quickly to recover and help the victims. In all natural or human provoked disasters, the first hours are crucial and life of people depends on how the rescue networks react when the network and its members are also suffering, both as a team and as individuals, from the same disaster. Imagine there is earthquake in a big city. Most of the infrastructures could be damaged and at the same time the hierarchy and authority structure of different organizations, responsible to help in these cases, could be hardly attacked or unable to work properly due to many reasons. What is important here is the way the DRNs could recover and start to operate efficiently.

One relevant research challenge in resilient DRNs is the development of a **framework for resilience assessment**. It is clear that rescue networks have to be restructured to work as collaborative networks to increase the resilience of the system [6]. The aim is to achieve a model of resilience that keeps a record of rescue networks and how they are achieving adequate levels of resilience. Having a conceptual model with the characterization of all relevant factors is a necessary but not sufficient step. To fulfill the mission, a quantitative model is also needed. A conceptual model could provide a big picture of what is essential and the strategy to be adopted. However, with no measuring system it is not possible to understand the weaknesses and strengths as the basis for improvement. The main concern of this paper is thus the measurability of DRNs' resilience in case of natural or human provoked disasters.

The paper is organized as follows: in next section the related literature is reviewed; section three deals with a conceptual model and in section four the process of developing hybrid intelligent system for evaluating resilience of DRNs is introduced. In section five the applicability of the model is presented by an illustrative example and implementing the proposed model into a real case study. Section six presents the discussion and future direction of the work.

2. Literature Review

It is claimed that Collaborative Networks could help achieving better operation against threats and risks and bringing a new approach to adapt to crisis situations [2]. Typically emergency management networks have multiplex relationships, follow flat decision-making process, and involve both formal and informal groups with a combination of vertical and horizontal relations [7]. Rescue teams, seen as a form of collaborative network, need a strategic and operational plan to enhance the capacity of the system to deal with critical situations. Traditional risk-based approach is insufficient and resilience analysis should be part of all catastrophe management plans [8]. The main difference between these two approaches is the way they look into future. In risk-based approaches the centre of attention is risk factor identification and mitigation, while in the resilience-based approach the assumption is that hazards are indefinable and internal preparedness and readiness for unexpected situations are necessary.

Adaptability is one of the most important capabilities which would guarantee the survival of a system while agility and resilience are the representatives of this capability of the system [9]. Resilience, as an emerging research field, is being analyzed from different perspectives and as a result there are different meanings and perceptions which sometimes are contested or contrasted [10][11]. Resilience is used in different contexts, including ecology management, psychology, supply chain management, safety engineering, crisis management, and collaborative networks [5][12]. Nevertheless it is important to avoid common pitfalls of synonyms and distinguish between resilience and other characteristics of the system such as flexibility, agility, and robustness [13]. In this work, a definition from [14] is taken as more appropriate to present the concept of resilience for Disaster Rescue Networks:

> "*Resilience can be understood as the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance)*" [14].

The benefit of a holistic perspective is the relation-hood view, so needless to say that the collective capability of a system is not just the additive composition of individuals, but more related to interactions and interrelations between individuals. To take advantage of the synergies in DRNs as collaborative networks, we are aiming resilience at both individual and collective levels [15]. This brings complexity and dynamism to the resilience evaluation model. Resilience is more than just capacity to provide sufficient response to uncertainty, which is the minimum expectation. It is a process of learning from doing and building a knowledge repository from tough experiences [16]. The nature of all systems is imperfect and, as such, resilient networks need to adopt a process of improvement through learning from events [17]. Furthermore, and unlike traditional views, resilience is not any more limited to the concept of distinctive and discontinuous events but it is recognized as a capability or capacity of organizations related to ordinary adoptive practices that lead the system to higher levels of efficiency [18]. Resilience in disaster management could be discussed at different levels, while most research works are focused on the resilience of the society or citizens especially in the first hours and days after large scale disasters [3].

Measurement systems associated to resilience indicators could be classified in two categories, pre-event or post-event models [4]. Pre-event models endeavor to use indicators to present the estimated level of resilience and post-event models show the actual level of resilience after analyzing the reaction of the system to real cases when a catastrophe actually happens [19]. Developing a model for pre-event estimation is a hard task that includes designing process, measurement of specific factors, and an aggregation model.

Planning, benchmarking, or a strategic move to enhance the resilience of any type of organization need an assessment model, including clear indicators. The aimed model should present the resilience of the system in a way to enable decision makers to have a clear picture of what the current situation is and the gap to meet desired state. It is difficult to develop a general mathematical model due to the variety of classes of affecting variables, while dealing with imprecise data is also indispensable [20].

The number of proposed models in the literature is still limited when most of the works concentrate on meaning, and on the conceptual part of the resilience model. There are also some attempts to use fuzzy logic, or statistical methods by employing questionnaires [4][20][21][22][23]. The scope of our work, different from previous approaches, can be summarized as follows: First, it considers the concept of resilience at micro-level (comparing with society level), targeting Disaster Rescue Networks in case of large scale catastrophes and second, developing an intelligent decision-support system to measure the level of resilience in DRNs.

3. Conceptual Model for Resilience Evaluation

There are several evaluation frameworks offering different methodologies for resilience evaluation in an organization or network [14][15]. Some of them are more focused on organizations, while some others try to propose a wider perspective to make it appropriate to cover from individuals to collective systems, such as teams, organizations, or societies. The main challenge in the proposed models is the **measurability** of the adopted criteria. This requires a trade-off analysis, as on one hand we need a comprehensive model with enough criteria covering all aspects and domains, while on the other hand non-measurable criteria are tricky. If we cannot measure it, it could not help us in reality to evaluate the level of resilience and thus it is useless for strategy selection.

In this paper, the conceptual model introduced in [24] is adopted and used as a basis to develop a quantitative model. The mentioned model is well accepted by experts in the area and provides a comprehensive framework for understanding resilience. In fact, in several other research works, the same model was employed on different occasions. As a result, there is an adequate number of empirical studies and satisfactory guidelines for measurability of the used criteria, which is very important for quantitative models [4][15][16][18][24]. Fig. 1 presents the mentioned model.

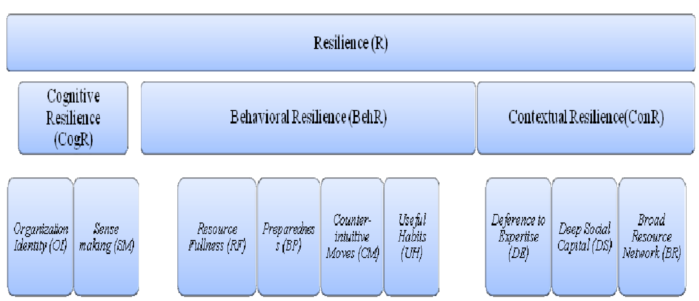

Fig. 1 - Resilience Evaluation Model (adapted from [24])

The value of each main criterion is a result of aggregation of sub-criteria values which could make the process of measurement applicable. Table 1 presents all criteria in the model and their description.

Table 1. Explanation of Resilience Evaluation Model

Criteria	Definition	
Organization Identity (OI)	OI encompasses the core values and beliefs of an organization that its members deem to be the most central, distinctive, and symbolic, through which an organization reveals its identity to stakeholders [25].	Mission, core values, Common vocabulary, Group commitment
Sense making (SM)	The process through which individuals work to understand novel, unexpected, or confusing events [26].	Balance of confidence and scepticism, Positive perception, Experience interpretation
Resource Fullness (RF)	The ability to identify problems, establish priorities, and mobilize resources when disaster occurs; resourcefulness can be further regarded as flexible plans, strategies and procedures to apply or coordinate resources [27].	Creativity, Balance of originality and initiative
Preparedness (BP)	BP is taking actions and making investments before they are needed to ensure that an organization is able to benefit from situations that emerge [24].	Prepared infrastructure, Cooperation in noncritical situations, Training
Counter-intuitive Moves (CM)	The ability to follow a dramatically different course of action from the one which is the norm [15].	Variety of strategies, Scenario planning, Non-aligned activities, Learning from events
Useful Habits (UH)	Useful, practical habits, especially repetitive, over-learned routines that provide the first response to any unexpected threat [15].	Flat decision process, Power of experts
Deference to Expertise (DE)	DE in a mindful organization manifests itself in the under specification of structures, relaxation and departure from formal hierarchical decision structures to one that gives the flow of authority to people who possess the required expertise to deal with the problem at hand [28].	Flat decision process, Power of experts
Deep Social Capital (DS)	DS is attained through well-maintained interpersonal relationships within an organizational community. It focuses on long term partnership that benefits parties beyond immediate transaction interests [29].	Member communication & cooperation, Resource sharing
Broad Resource Network (BR)	Resilient firms are able to utilize relationships with supplier contacts, loyal customers, and strategic alliance partners to secure needed resources to support adaptive initiatives [24].	Resource network, Meta organizational resources

4. Developing a Hybrid Intelligent System for Evaluation

One of the main problems in social or human based systems is the lack of tools to map from an input space to an output space. This is due to the complexity of the system and shortage of knowledge about its components and their relations. It is a challenging mission when there is neither sufficient historical data nor knowledge about the structure of the system. To tackle these types of problems, the knowledge of experts could be the only source of information.

Fuzzy Inference System (FIS) is a powerful tool to deal with expert's knowledge and for approximate reasoning [30]. To develop a FIS, knowledge is extracted and represented in a set of rules that express the relations between components of the system. For the case of resilience measurement, due to the lack of information and unclear equation between the criteria, FIS seems to be more effective comparing with other possible methods. Most of the other methods need historical behavior (information) or clear relation for aggregating. In this work, FIS is employed to develop an evaluation model for DRNs' resilience. As it can been inferred from Fig. 1, we need to have a hybrid system including four FISs to aggregate the criteria in two steps. In the first step, three FISs are built to aggregate the sub-criteria to determine the three main criteria, Cognitive Resilience, Behavioral Resilience, and Contextual Resilience. In a second step, the result will be the output of criteria fusion from first step. To do that, and for each FIS, we follow the procedure presented in Fig. 2.

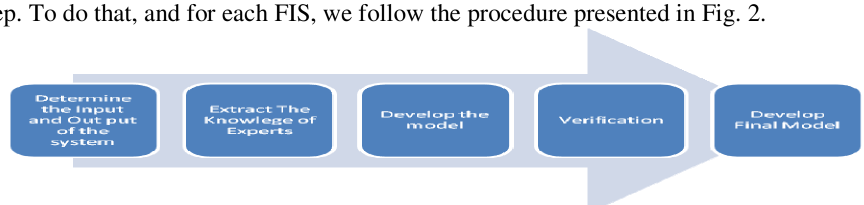

Fig. 2. The process of Developing FIS for Evaluation of Resilience in DRN

The first step is to determine input and output, for which two important decisions should be taken: the number of fuzzy sets and the membership function. In this work we selected five fuzzy sets and a Gaussian membership function. This membership function is more complex in comparison with a triangle-shaped function, but with better results in most cases [31]. Afterwards, the experts' knowledge, in a form of a set of rules, is extracted. This is based on the experts' experience, using questionnaires/interviews. The final rule set can be refined using an experts' panel. Below some sample rules for Cognitive Resilience FIS are presented:

a) If "*Organization Identity*" is very high and "*Sense making*" is very high then the "*Cognitive Resilience*" is very high.
b) If *"Organization high*" is high and *"Sense making"* is medium then the "*Cognitive Resilience"* is Medium.
c) If *"Organization Identity"* is very how and *"Sense making"* is very low then the *"Cognitive Resilience"* is Medium.
d) If *"Organization Identity*" is high and *"Sense making"* is Low then the *"Cognitive Resilience"* is Medium.
e) If "*Organization Identity*" is very Low and *"Sense making"* is very Low then the "*Cognitive Resilience*" is very Low.

The last three steps comprise an iterative process to make sure that the model will work properly.

In order to confirm the validity of the model, a typical three-step process was used which includes face validity, extreme conditions test, and behavior analysis. In "face validity" the rules are rechecked to make sure they are acceptable and satisfy the logic of relationships between the variables. Extreme conditions test is used to make sure that the model could respond properly to critical situations which are usually on the border, such as extreme conditions of variables. Finally, behavioral analysis is a way to analyze the behavior of the system when values of input variables are increasing, at a constant rate, from their minimum to their maximum (or from max to min) one by one while the others remain constant. This can provide detailed information about the system and its performance so any deviation from expected situation or illogical behavior should be analyzed and by imposing new rules the model could be corrected to be acceptable. Fig. 3 shows the high-level view of the model.

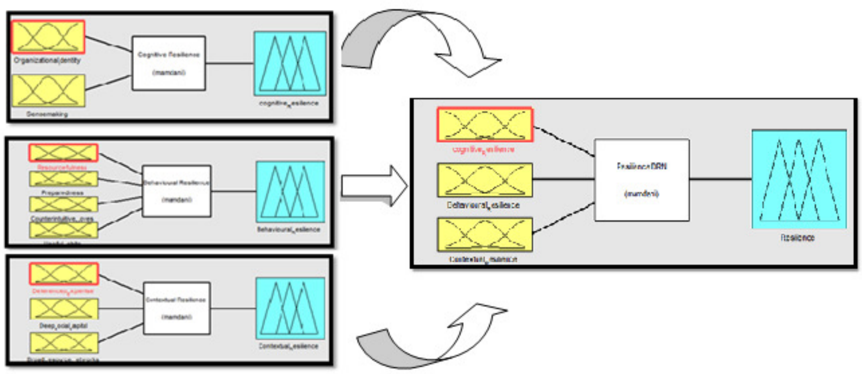

Fig. 3. Architecture of Resilience Evaluation Model (Hybrid Intelligent system)

As mentioned above, four FISs are developed and all should be analyzed one by one, while the hybrid system also needs to be verified as it could be an erroneous infusion model. Fig. 4 depicts the rules and output surface for "Behavioral Resilience", presenting the relation between "Preparedness" and "Resourcefulness". This is an example and by analyzing each relation unacceptable conditions/rules could be recognized.

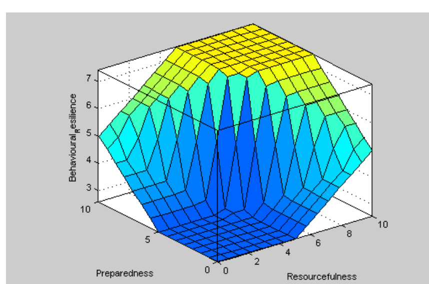

Fig. 4. Graphical representation of the rules for Behavioral Resilience

Fig. 5 shows the example of behavioral analysis which is used in this work. As it can be seen, the behavior of the system when one of the indicators (preparedness) is increasing from minimum to maximum value (0 to 10) and the others are fixed (5) is presented. Similarly, different combinations should be analyzed to verify the model.

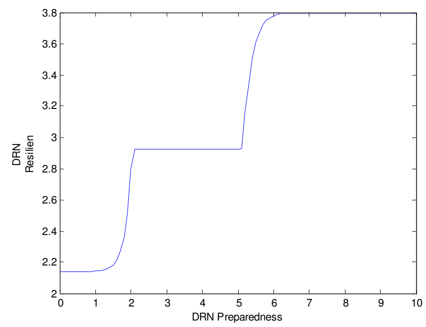

Fig. 5. The behavior of the system in case of change in preparedness while all other indicators remain constant

The key benefits of the introduced model, more than measuring the level of resilience, is the ability to simulate different scenarios to recognize which indicator could affect more the resilience of the network in each condition to be investigated. This can help managers to select appropriate combinations of solutions to enhance the resilience of the network in an efficient way.

5. Case Study

In this section, the applicability of the proposed model is demonstrated by using an illustrative example and real case study. For numerical example four types of DRNs with the following information are considered.

Table 2. Initial information for a numerical example

DRN_i	OI	SM	RF	PP	CM	UH	DE	DS	BR
DRN_1	1	1	1	1	1	1	1	1	1
DRN_2	4	8	8	4	4	3	4	6	7
DRN_3	3	5	6	5	6	6	6	4	5
DRN_4	7	7	7	7	7	7	7	7	7

By employing a hybrid decision-support system, the result is as below:

Table 3. Result of Numerical example

DRN_1 Resilience	DRN_2 Resilience	DRN_3 Resilience	DRN_4 Resilience
0.9084	2.6323	3.7788	7.5883

As discussed in previous section, the advantage of the proposed model is the ability to simulate different scenarios to investigate which indicator affects more the resilience in each case and should be in priority of investment to increase the level of resilience of the network. To show this ability DRN_2 and DRN_4 are selected and in each iteration one of the indicators is increased by 30% to see the behavior of the system. This can help managers of the networks to check possibilities of enhancing the level of resilience and find an optimal solution as limited sources should be invested wisely. Table 2 presents the result of the illustrated test to show the impact of increasing each indicator (one by one).

Table 4. Result for the illustrative example with 30% increase in each indicator

	OI 30%	SM 30%	RF 30%	PP 30%	CM 30%	UH 30%	DE 30%	DS 30%	BR 30%
DRN_2	2.6324	2.6323	2.6323	2.6323	2.6323	2.6323	6.736	7.3716	2.6323
DRN_4 Resilience	7.5883	8.5746	7.5883	7.5883	7.5883	7.5883	7.5883	7.5883	7.5886

As it can be seen, for $DRN_{2,}$ the best strategies are investment on Deference to Expertise (DE) and Deep Social Capital (DS), while for DRN_4 Sense Making (SM) is the best investment target.

After demonstrating the capability of the introduced model by an illustrative example, a real case study was implemented. Red Crescent/ Red Cross organizations due to their nature have to be prepared for prompt action to disasters. They are usually the first formal group to respond in natural disasters and increasing the level of resilience is part of their strategic plan. They include a combination of professionals and volunteers while, at the same time, they have several organizations to support their activities. For the case study, a Red Crescent organization from a Middle Eastern country was selected. The selected country has a long history in natural disasters such as earth quakes and floods. In several cases the rescue network was affected while as a rescue team they had to keep operation going on. The first step was to measure the level of criteria and process them to feed the model. Each criterion from Fig. 1 (details in Table 1) was "measured" by questions which were representing the sub-criteria. Seven selected managers who are experts in the organization answered questionnaires. The final scores to be used by model resulted from the aggregation of information in the questionnaires using the average of sub-criteria (which were expressed in the form of questions).

For instance, Organizational Identity (OI) had five sub-criteria which were turned into questions. Each person had to answer all questions and give a number between 0 and 100 (percentage). Below you can find an example of question:

"How strong is the sense of visions, goals and values in the organization?"

Then the average of all five criteria/ answers is calculated.

OI_{Qi} =Average(C_j) wheere C_j is representing the jth criterion, j=[1:5] & i=[1:7] .

In the last step information from all questionnaires should be aggregated and here average of the values were used. Final value, OI_{total} is the average of OI_{Qi} where max " i" is the number of filled-in questionnaires:

OI_{total} = Average (OI_{Qi}), where i=[1:7].

Table 5 presents the result of this measurement process.

Table 5. Information for the case study in percentage

DRN	OI	SM	RF	PP	CM	UH	DE	DS	BR
$DRN_{Red\ Crescent}$	62%	60%	63%	50%	56%	53%	58%	55%	59%

Table 6 presents the level of resilience using introduced model:

Table 6. Level of Resilience in the Case Study (from 0 to 10)

Resilience	Contextual Resilience	Behavioral Resilience	Cognitive Resilience
3.7920	3.2353	7.4051	5.0017

Finally, for scenario planning, the value of each criterion is increased 30% and the impact on total resilience is calculated. Table .7 shows the result and, as it can be seen, "Broad Resource Network" is the most relevant criteria for investment in this case.

Table 7. Red Crescent Resilience in case of 30% increase in each indicator (From 0 to 10)

30% increase in main criteria	OI	SM	RF	PP	CM	UH	DE	DS	BR
$DRN_{Red\ Crescent}$	3.7920	3.7920	3.7924	3.6640	3.7942	3.7942	3.7920	3.7920	7.2976

6. Discussion and Future Work

Collaborative Networks, as an emerging discipline, open a new window to enhance our capability to confront complex problems. One of the most difficult cases is to work under stressful conditions of post hazards situation. Rescue Networks have to work in critical situations while, as a member of society, they are also under the influence of the event. Disasters are unpredictable and it is crucial to make sure DRNs work as resilient structures able to recover immediately from any crisis and to start their mission with minimum delay. In this paper a conceptual model based on contextual, behavioral, and cognitive resilience was employed to develop an intelligent hybrid decision system for assessing the level of resilience of DRNs. Face validity of the rules, extreme condition test, and behavioral analysis of the system were used to verify the model. At the end, the applicability of the model was illustrated by using a case study. The model not only helps to quantify the concept of resilience for DRNs but it also gives us a tool for scenario planning/testing in a virtual environment. The most important reason to select the "Fuzzy Inference System" was its ability to deal with imprecise data and the capability to make a bridge between knowledge of experts (as the only available source of data in this case) and decision support system. Other alternatives such as MCDM or statistical methods have their own strengths and weaknesses for information fusion but are not suitable for this type of problem which has characteristics such as unclear relation between variables, no knowledge about synergies or redundancies between them and lack of historical data to recognize the pattern.

As future work, the plan is to implement the introduced model in more real cases to improve the system. Further we are planning to improve the capability of the model by considering the role of time and interrelation between resilience indicators.

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