

TESIS



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Escuela de Doctorado

# **Emergency Early Warning and Decision Making under Uncertainty**

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# Chapter 1

## Introduction

### 1.1 Motivation

Emergency events (EEs) are sudden occurrences that can lead to significant loss of life, injuries, property damage, ecological harm, and social risks [109], such as natural disasters, accidents, public health events and social security incidents and so on [62].

In recent years, various emergencies, such as earthquakes, floods, hurricanes, and terrorist attacks, etc., have exerted huge and severely negative impacts on human life, social stability and economic development. So, it is necessary to find some ways to mitigate and reduce the negative impacts caused by EEs, which many researchers put a lot of efforts on it. According to the analysis on the existing studies, the main research on EEs can be roughly sorted and summarized into following five topics:

- ◇ *Related features of EEs.* EEs often involve dealing with uncertain, incomplete, and insufficient information, as well as dynamic evaluation processes and other factors. Many existing studies have proposed various methods to handle these features, such as, information incomplete/inadequate [16, 60, 97, 113, 153]. Others have proposed various approaches to address dynamic evaluation of EEs, such as game theory-based dynamic models [134, 143], fault tree analysis method [67, 125], machine learning [54, 158] and so on.
- ◇ *Critical factors identification of EEs.* Identifying the critical factors of EEs can help decision maker (DM) to understand the EEs deeply and make comprehensive response to EEs successfully and effectively. Many existing studies have proposed various methods based on multi-criteria decision making (MCDM) to identify critical factors of EE, such as, DEMATEL method [29, 90], WINGS [69, 115], System Dynamics (SD) [87] and so forth.
- ◇ *Emergency early warning.* Emergency early warning system plays a vital role

in mitigating the risk of fatalities, property damage, and ecological harm in EEs [121]. Thus, researches from diverse perspectives related to early warning have been undertaken and achieved successful results [2, 3, 17]. For example, development and enhancement of early warning systems [3, 9, 22], monitoring and gathering hazards related information [2, 13], methods or frameworks for constructing early warning systems.

- ◇ *Emergency plan generation.* When managing emergency situations, emergency plans play a pivotal role as they directly impact the success of handling such events. Hence, existing researches on generating emergency plans have been approached from various views, such as assessment of emergency plans [71, 79, 157], formalization of emergency plan by mathematical programming [10, 75, 122], emergency plan generation based on case-based reasoning [142, 154, 155, 156], and hierarchical task network [63, 77] and so on.
- ◇ *Emergency decision making (EDM).* EDM is a crucial endeavor aimed at mitigating and minimizing damages or losses, including those to property, lives, and the environment caused by EEs. As a result, EDM has emerged as a highly active and significant research domain within the field of emergency studies [37, 59, 94, 113]. Such as, classical EDM problems typically involve a single DM engaged in the EDM process [23, 50, 52, 105], group emergency decision-making (GEDM) problems involve multiple experts acting as a think tank to support the DM in making emergency responses [34, 88, 92, 128, 137].

With the rapid development of disruptive innovations in technology, economy and many other areas related to the modern society in last decade, EEs are increasingly diversified, complicated and full of uncertainty, hence, it is important to study how to represent the real situation information accurately. The existing studies usually represent the uncertain information by interval values [50], fuzzy linguistic terms [113] or hesitant fuzzy linguistic term sets [5, 38].

To enhance the emergency response more pertinent, effective, and successful, the critical factors of different types of EEs should be identified prior to other emergency activities. Because of the advantages on critical factors identification and cause-effect relationship visualization among factors, different MCDM methods have been used to identify critical factors of EEs [90, 123, 131, 160, 161], and fuzzy MCDM methods are often used in fuzzy and uncertain circumstances [6, 58, 90, 112, 117, 131]. And the results of the analysis can be used in other emergency activities, such as, emergency early warning, emergency plan generation and EDM.

The successful generation of emergency warnings can give DMs more time to respond to emergencies, which can potentially avoid casualties and property losses.

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However, it is not possible to warn successfully all types of EE. Thus, when the emergency early warning fails and an EE occurs, the emergency plans would generate and prepare a respond to the EE. Then, the problem of which plan DMs should use to prevent emergencies and save losses will be answered by the EDM process.

In despite of the large number of models and approaches have been proposed to address relevant problems in the previous topics, and the significant contributions developed for emergency management, as of now, the research results obtained are insufficient for handling complex real world emergency problems adequately: new challenges such as experts' hesitation, dynamic evolution of EEs, and information loss have emerged, requires further in-depth study to enhance current solutions/proposals in existing studies. The enumeration of these new difficulties and challenges motivate this research memory:

- ◇ *Neglecting experts' hesitation behavior*: Hesitation is a common and unavoidable behavior in our daily lives, particularly when humans encounter complexity and uncertainty. [82]. Because of the incomplete information or lack of experience, the experts may hesitate to provide their assessments and opinions [20, 21]. However, such a crucial topic has rarely been addressed in existing studies on critical factors identification and emergency early warning.
  - ◇ *Losing information*: Regarding the lost of information, it might come from two different ways:
    - (1) Losing information in critical factors identification. Extant fuzzy MCDM methods defuzzify fuzzy input information into crisp values [123, 160, 112, 117] by means of a defuzzification process to achieve initial matrix information. Such a defuzzification process may cause the loss of important information [112, 117].
    - (2) Losing information in experts' opinions fusion [14, 128]. Fusion of experts' opinions is a critical process in GEDM problems, in which the wisdom of each expert is aggregated into a collective group to assist DM in making decisions. Different models and methods are employed to do such a aggregation from various perspectives. However, current GEDM studies might lose valuable information during the initial aggregation process. A significant challenge for GEDM is to retain as much information as possible and avoid such loss [129, 130].
  - ◇ *Neglecting dynamic evolution features of EEs*: Dynamic evolution is a typical feature of real-world problems, in which the problem might dynamically change across the time and because of information update, meanwhile, the interrelations among factors vary with the such a dynamic evolution of problem. So
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far, seldom extant studies on critical factors identification and emergency plan generation consider the dynamic evolution of EEs.

- ◇ *Tackling heterogeneous information*: Information plays a crucial part in all emergency activities. However, both existing critical factors identification approaches and emergency early warning approaches handle the single information domain: crisp values [76, 132], intervals [148], or linguistic terms [29, 58, 65, 151]. However, real-world information about EEs encompasses various types (crisp values, intervals, linguistic terms, hesitant information, and so on) simultaneously. Yet, none of the existing proposals in critical factors identification and emergency early warning takes into account heterogeneous information.
- ◇ *Neglecting DMs' psychological behavior*: Human beings often exhibit bounded rationality when faced with risk and uncertainty, making their psychological behavior a crucial factor in decision-making processes [51]. However, this critical issue has not been addressed in existing EDM approaches yet [38, 56, 88, 120, 137, 153]. Hence, it appears imperative to propose a model capable of handling EDM problems more effectively.

Aforementioned challenges indicate that current approaches dealing with EEs cannot adequately meet the demands and requirements of real emergency situations. Consequently, this research memory conducts further and in-depth researches to bridge these gaps.

## 1.2 Objectives

Based on the challenges highlighted in existing researches, as outlined in the previous section, the aim of this study is to enhance current research efforts. Building upon this aim, the following five research objectives are considered:

1. To propose a new fuzzy MCDM approach, specifically fuzzy DEMATEL [152], that considers experts' hesitation behavior and avoids losing information during the defuzzification process. A case study and related comparisons are introduced to show the advantages, validity and feasibility of the proposed method.
  2. To improve information modelling in fuzzy DEMATEL approach that considers heterogeneous information and dynamic evolution feature of EEs. The
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proposed method overcomes the limitations in current critical factors identification approaches by incorporating a novel dynamic perspective and heterogeneous information. This method will be used to an extremely major production safety liability accident showing its superiority and novelty.

3. To develop a novel emergency early warning approach [145], multiple types of information will be modelled using heterogeneous information. Such a proposal will be applied to a landslide emergency early warning to show its validity and performance.
4. To develop a dynamic emergency plan generation approach [146] that considers different possible emergency situations and limited resources. Illustrative example and descriptive comparisons will be presented to illustrate its novelty and superiority.
5. To develop a hesitant GEDM approach [147] that enhances information fusion and considers hesitant uncertainty along with experts' behavior. This GEDM method is expected to yield improved results as the information fusion process retains more information than classical aggregation processes. It will be used to an example to demonstrate its validity and performance.

### 1.3 Structure

To realize these goals displayed in Section 1.2, and taking under consideration the article 23, point 3, of the current directions for Doctoral Studies at the University of Jaén, in understanding with the program set up within the RD 99/2011, this memory will be developed as a compendium of articles that have been published by the Ph.D candidate during her Ph.D period.

Four articles have been published in international journals indexed by JCR database, and another article is under review in an JCR international journal.

The organization of this memory is briefly introduced below:

- ◇ Chapter 2: Some basic concepts and methods that are used in our proposals to achieve the different objectives pointed out in Section 1.2 are revised, such as, related concepts of critical factors identification of EEs, emergency early warning, emergency decision making, hesitant fuzzy sets (HFS), hesitant fuzzy linguistic term sets (HFLTS) and related methods of fuzzy evidential reasoning method, fuzzy DEMATEL method, prospect theory and so on.
  - ◇ Chapter 3: The different and novel proposals the obtained this research memory are briefly introduced, together discussions of the obtained results obtained
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to clarify the achievements reached in our research.

- ◇ Chapter 4: It is the core of the doctoral thesis, which includes the publications that conform the research results obtained across our research. For each publication, detailed information of the journal in which the proposal has been published is indicated.
  - ◇ Chapter 5: The conclusions obtained from this research and possible promising future works are pointed out.
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## Chapter 2

# Basics Concepts and Background

This chapter establishes the framework of concepts and tools related to our research throughout this memory which consists of different papers that introduce and revise the essential background to make our proposals easier to understand. In this chapter, a brief and structured revision of the crucial concepts related to our proposals will be provided. The crucial concepts include decision making, emergency decision making, the modelling and managing of uncertainty in decision making and several MCDM methods under uncertainty, such as Fuzzy TOPSIS and Fuzzy TODIM. Each of these concepts, tools and methods is further detailed in each respective papers of the compendium provided in this research memory (see Chapter 4).

### 2.1 Critical factors identification of EEs

Here, critical factors identification of EEs are briefly introduced as the fundamental knowledge within this memory, which paves the way for the coming researches.

The concept of "critical factors" was introduced by Rockart [80] and the Sloan School of Management, and defined as those crucial areas of activity, usually means conditions, characteristics or variables, in which favorable outcomes are indispensable and have a significant impact for a specific company to achieve its objectives. Theierauf [96] states that if the results in these crucial areas are not adequate, the organization's efforts for the period will be below the desired level. When critical factors are sufficiently implemented, they will ensure the progressive development of an organization. Thus, critical factors identification becomes an activity research topic in recent years, and have been widely used to various fields, such as, project management [80], complex systems analysis [12, 114], emergency management [29, 160], and so on.

As aforementioned, identifying the critical factors of complex problems is essential for making right decisions. EEs are such complex problems that need to make

right decision to respond timely and effectively, so as to mitigate the losses of humans and society resulting from EEs. Thus, it is necessary to conduct critical factors identification of EEs to figure out the key elements or factors that cause EEs or are affected by EEs. On such basis, the DMs can understand EEs comprehensively, and can focus on the priority factors to make right responses.

Since the significant importance of critical factors identification, many researches have developed many MCDM based approaches to identify critical factors [70]. One of the most common approaches is DEMATEL, which states the significance of a factor is proportional to the sum of influence it exerts and the impact it incurs [39, 40]. DEMATEL is widely used to visualize the causal-effect relationships among factors by means of a cause-effect relationship diagram. To handle the complex decision problems under uncertainty, fuzzy DEMATEL method was proposed to accommodate the various types of fuzzy information, such as, linguistic information [58, 123], interval-valued intuitionistic fuzzy information [1], 2-dimension uncertain linguistic information [29], 2-tuple linguistic information [65], linguistic Z-number information [48], intuitionistic fuzzy information [15], D number information [161], interval type-2 fuzzy information [8, 26, 98] and so on.

Despite the great contributions to critical factors identification in current fuzzy DEMATEL methodologies, they have the following four limitations:

- *Information missing.* Existing fuzzy DEMATEL methods typically involve converting fuzzy input information into crisp values [123, 160] by means of a defuzzification process to obtain an initial direct-relation matrix. Indeed, such a transformation can potentially result in the lose of crucial information during the defuzzification process [112, 117]. Therefore, it seems necessary to to find a method of handling the fuzzy input information from a more rational perspective rather than opting for defuzzification.
  - *Experts' hesitation neglecting.* Although current fuzzy DEMATEL methodologies have taken into account the fuzzy input information from quantitative or qualitative contexts, they often neglect the hesitancy inherent in experts with diverse knowledge, experiences and background, which might leading experts to hesitate when providing their judgments or assessments [20, 21, 82]. Hesitancy is an unavoidable and practical issue in our daily lives [82], and should be taken into account particularly under uncertain and fuzzy environment.
  - *Heterogeneous information ignoring.* Although the different DEMATEL studies have been proposed to identify critical factors of different real-world problems, the experts' assessments can be only represented by either quantitative or qualitative information. However, experts might prefer to employ differ-
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ent information types to provide their assessments due to the features of a given problem or their individual preferences, particularly handling complex problems under uncertain in the practical situations.

- *Dynamic evolution ignoring.* Dynamic evolution is a typical feature of real-world problems, in which the problems might dynamically change alongside with the time and information update, meanwhile, the identified critical factors might vary with the dynamic evolution of problem. So far, seldom extant DEMATEL studies consider aforementioned issues at the same time, i.e., both considering different information types and the dynamic evolution of the problem.

Aforementioned limitations will be overcome in the critical factor identification regarding fuzzy DEMATEL method.

## 2.2 Emergency early warning brief introduction

In this section, a brief introduction and review of emergency early warning is revised as the fundamental knowledge within this memory, aiming to facilitate the understanding of the proposals presented.

### 2.2.1 Emergency early warning

The word "early warning" was originated from the military field. It originally refers to discovering, analyzing and judging the enemy's attack signals in advance through early warning, and reporting the threat level of such attack signals to the command department to take countermeasures in advance. Later on, this concept was gradually applied to emergency fields as an effective and potent method for forecasting and issuing warnings for hazards, which plays a pivotal role in preventing and mitigating the likelihood of fatalities, property damage, and ecological harm in disaster risk management [121], such as early warning on large-scale public health emergency [72], early warning on heavy metal pollution accident [68], early warning on natural disasters [35, 55] and so on.

Generally speaking, the emergency early warning usually includes four processes that can be shown in Figure 2.1:

1. *Risk identification process:* The early warning objects will be determined and related information will be collected in this process;
2. *Indicator evaluation process:* The information collected in the risk identification process will be analyzed and evaluated by suitable methods to obtain the risk level of the early warning objects;

3. *Early warning alarm process*: The risk level of the early warning objects obtained in the indicator evaluation process will be sent to related DMs in a timely and accurate manner according to the actual situation, usually by a warning alarm system;
4. *Risk resolution process*: According to the information sent by the early warning alarm system, DMs will take corresponding countermeasures to deal with emergencies to mitigate the effect caused by EEs.

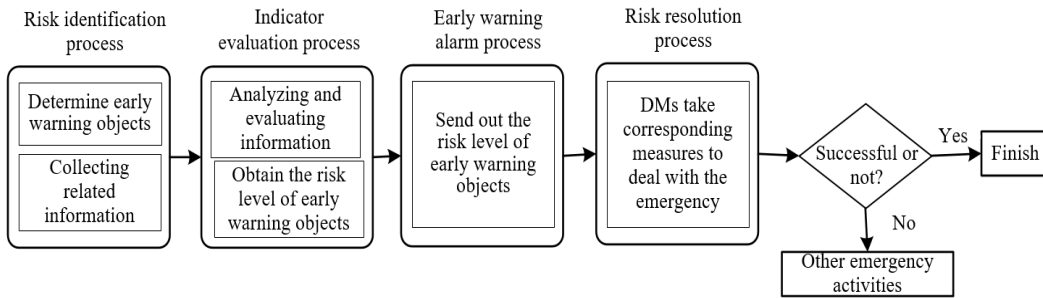


Figure 2.1: General scheme of emergency early warning

Due to its crucial importance and practical significance in the real world situations, early warning has drawn great attention from both governmental agencies and academic researchers, leading to a highly active and significant research field. Different topics related to the four processes mentioned above have been undertaken, and obtained valuable and fruitful results [2, 3, 17, 44, 45, 46, 95]. In the risk identification process, the existing studies focus on developing and improving the information collecting methods [2, 13, 57, 73, 135, 144]. In the indicator evaluation process, the existing studies focus on the development and improvement of methods and models that can analysis and evaluate the collected information effectively and accurately [17, 18, 33, 41, 61, 76, 107, 126, 132]. In the realm of the early warning alarm process, existing studies primarily concentrate on the development and enhancement of emergency early warning alarm systems, which can help to send the alarm information timely and accurately [3, 9, 11, 22, 24, 43, 55, 102, 103, 139]. The risk resolution process of emergency early warning consists of measuring to prevent or respond to emergencies in advance before the emergency occurs, meanwhile, the EDM process takes measures to contain and respond to emergencies after the emergency occurs. Therefore, the existing researches rarely study the risk resolution process of emergency early warning.

### 2.2.2 Limitations in current emergency early warning

In our research memory, we focus on the indicators evaluation process. Despite the great number of contributions in the existing studies about the indicators evaluation of emergency early warning, they have two important limitations:

- Existing emergency early warning studies [76, 132, 148, 151] do not consider experts' hesitation. In the current researches, information related to EEs is typically acquired through sensors, monitoring devices or experts' assessments to evaluate and forecast the occurrence of EEs. It is quite common that information regarding EEs is difficult to acquire by sensors or monitoring devices comprehensively, especially in uncertain and complex environment. In such situations, experts might feel hesitation because of the uncertain environment or their experience. However, seldom existing studies try to model and represent this kind of situation.
- Existing studies [2, 11, 18, 107, 151] only consider one type of information regarding EEs, such as numerical values [76, 132], interval values [148] or linguistic information [151]. However, in real world situations, there are various types of information regarding EEs from both quantitative and qualitative contexts that should also be taken into account [109], i.e. hesitant fuzzy linguistic term sets.

For successful early warning, information regarding EEs is an indispensable and important element [46]. Therefore, it is reasonable and essential to take into account the heterogeneous information regarding EEs during the indicators evaluating process of emergency early warning.

## 2.3 Emergency plan generation

In this subsection, a brief revision introduction of emergency plan generation is provided to facilitate the understanding of the following proposals.

Emergency plans play a critical role in EDM process, such plans are typically selected based on different attributes to handle the emergency situations, which aims at minimizing losses and mitigating negative impacts as much as possible when an EE occurs. The emergency plans are the key elements for the successful management of the emergency situations. Therefore, because of the significance and influence of emergency plans, different studies have been conducted from various perspectives [146].

Even though, the related researches on emergency plan generation have achieved valuable and fruitful results, they neglect a critical feature of EEs that is the dy-

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dynamic evolution, in which the changes in emergency situations update the related information, available resources, and so on. Information, especially the dynamically updated information, plays a critical role in all different decision activities, no exception for emergency plans generation. Therefore, it is essential to consider during the generation process. Moreover, the emergency plans still have obvious drawbacks because they are not flexible enough due to the fact that, most of them are predefined, hence they can not handle emergency situations that does not match perfectly the plan because of the dynamic evolution of EEs [4, 36].

To overcome these drawbacks, the dynamic feature of EEs has been discussed in the previous studies [49, 78, 89, 149, 150], however, regarding the emergency plan generation, although few studies [49, 78, 89] have considered different situations, and [89] has addressed the dynamic feature from a singular perspective, i.e., feedback-based dynamic feature. While, dynamic evolution of EEs encompasses various perspectives, e.g., information updating related to situations, available resources, etc. However, such changeable information has been neglected in the existing studies. Thus, it is essential to take into account such dynamic information during the the process of emergency plan generation.

## 2.4 Emergency decision making brief introduction

In this section, EDM is briefly revised because it serves as the foundation of our research. Subsequently, the limitations inherent in current EDM approaches are identified to demonstrate the significance and necessity of our proposals.

### 2.4.1 Emergency decision making

When an EE takes place, some measures are selected and taken to minimize or decrease the potential losses resulting from EE, such a process is usually called EDM process. In this process, there are three key issues need to be resolved:

(1) *The accurate representation of the information.* There are two kinds of information, the crisp information and the fuzzy information. In the real situations, when an EE occurs, most information is uncertain and need to be correctly modelled to deal with the EE successfully. Hence, the topic about modelling information by fuzzy models have attracted many researchers to study on it, such as, interval values [113], interval type 2 fuzzy numbers [19], triangular fuzzy numbers [53], trapezoidal fuzzy numbers [136], hesitant fuzzy numbers [27] and so on.

(2) *The multiple information processing.* In real world situations, the EEs are really complex and changeable, thus, it is difficult for only one individual to deal with EEs successfully. The participation of multiple individuals is likely to be a

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powerful and effective way to deal with EEs. Therefore, how to handle the multiple information provided by multiple individuals is one important problem in EDM processes, and a lot of approaches have been proposed to cope with the multiple information, such as, the conflict information processing approach [28], the interactive information processing approach [104], the approaches for aggregating information [47, 115, 137], and so on.

(3) *The emergency plan selection.* When an EE occurs, it is essential to select the best plan to make an effective emergency response in a short. Therefore, both governments and scholars have increasingly focused their attention on selecting the most suitable emergency plan in recent years. MADM method is considered an effective method to support DMs to select the most suitable emergency plan among multiple plans [30, 42]. In existing studies, there are many MADM methods that have been developed and applied to solve EDM problems, such as, Prospect theory [113], TOPSIS [91], PROMETHEE [74], GRA [66], VIKOR [111], QUALTFLEX [32], TODIM [27], and the combination of different approaches [50], and so on.

#### 2.4.2 Limitations in current emergency decision making

Even though, the related researches on emergency plan generation have achieved fruitful results, two limitations in current EDM studies have been identified and show as follows:

1. *Losing information in the multiple information processing.* When there are multiple individuals involved EDM problems, most existing studies focus on consensus reaching process, in which an acceptable agreement among all involved experts or DMs is obtained [14, 93]. In such a case, in order to obtain the acceptable agreement timely, some experts need to revise or adjust their initial opinions [85]. This might provoke to lose information during the process. Therefore, it seems need to consider such an problem in EDM process.
2. *Neglecting experts' psychological behavior in emergency plan selection process.* Different studies have shown that experts exhibit bounded rationality under uncertainty and their psychological behavior has great impact on the process of emergency plan selection [51, 100]. However, such an crucial issue is rarely taken into consideration in current methods for emergency plan selection [38, 56, 120, 127].

Taking into account the previous limitations, this research memory will propose some theoretical methods for EDM to overcome such limitations.

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## 2.5 Methods and models

In this section, various methods and models utilized in this research memory are briefly introduced and revised, which includes hesitant fuzzy sets, hesitant fuzzy linguistic term sets, fuzzy evidential reasoning, fuzzy DEMATEL, prospect theory and so on. All these methods and models are pertinent to diverse proposals that will be developed in this research to attain our objectives.

### 2.5.1 Hesitant fuzzy sets and hesitant fuzzy linguistic term sets

In 2010, Torra [99] proposed the concept of Hesitant fuzzy sets (HFS) for modeling the hesitancy in quantitative contexts. In 2012, hesitant fuzzy linguistic term sets (HFLTS) was proposed by Rodríguez et al. [82] as an extension of HFS to model the hesitancy in linguistic contexts. These two theories are popular to deal with real world hesitant information, in which HFS will be used to fuse experts' quantitative hesitant information, and HFLTS will be employed to represent experts' qualitative hesitant information respectively. Thus, in this section, HFS and HFLTS will be introduced in short.

#### 2.5.1.1 Hesitant fuzzy sets

The concept of HFS introduced by Torra [99] is defined as follows:

**Definition 1** [99] *Let  $M = \{\mu_1, \dots, \mu_n\}$  be a set of  $n$  membership functions. The HFS associated with  $M$ , denoted  $h_M$ , is defined as:*

$$h_M : X \rightarrow \wp([0, 1]) \quad (2.1)$$

$$h_M(x) \rightarrow \bigcup_{\mu \in M} \{\mu(x)\} \quad (2.2)$$

where  $X$  is a reference set,  $x \in X$ .

In 2011, Xia and Xu [124] extended and formalized the definition of HFS to hesitant fuzzy element (HFE). In their proposal, the concept of HFS was expressed as follows:

$$E = \{\langle x, h_E(x) \rangle : x \in X\} \quad (2.3)$$

where  $h_E(x)$  is a set of values in  $[0, 1]$ , which denotes the possible membership degrees of the element  $x \in E$  to the set  $E$ . In Xia and Xu's proposal,  $h_E(x)$  was defined as the HFE,  $H = \cup h(x)$  was defined as the HFSs, and a HFE is a subset of HFSs.

The concept of the envelop of a HFE was proposed and proved by Torra [99] that is an intuitionistic fuzzy value (IFV), which defined as follows:

**Definition 2** [99] Let  $h$  be a HFE, the IFV  $A_{env}(h)$  is the envelop of  $h$ , in which  $A_{env}(h)$  can be represented as  $(h^-, 1 - h^+)$  being  $h^- = \min \{\sigma | \sigma \in h\}$  and  $h^+ = \max \{\sigma | \sigma \in h\}$ .

Different properties and operations for HFSs has been defined in [99]. These properties and operations together the managing of intuitionistic fuzzy sets and intervals [84] enable us to interpret HFEs as intervals.

### 2.5.1.2 Hesitant fuzzy linguistic term sets

Different researches [81, 82, 83] point out that human beings often utilize linguistic expressions to articulate their preferences/opinions instead of numerical values because the vagueness and imprecision of the information. In such cases, the application of the fuzzy linguistic approach [138] has achieved successful outcomes [106]. Nevertheless, experts involved in the decision making problems may sometimes hesitate when they provide their preferences, and a single linguistic term might not suffice to represent their preferences accurately. In such case, the concept of HFLTS was introduced by Rodriguez et al [82] to model this hesitation in qualitative contexts, which has attracted great attention of many researchers [64, 108, 110, 118, 119].

**Definition 3** [82] Let  $S = \{s_0, s_1, \dots, s_g\}$  be a linguistic term set, a HFLTS,  $H_S$ , on  $S$  is an ordered finite subset:

$$H_S = \{s_i, s_{i+1}, \dots, s_\zeta\}, s_\zeta \in S, \zeta \in \{i, \dots, j\} \quad (2.4)$$

**Example 1** Let  $S = \{\text{absolute weak, very weak, weak, medium, good, very good, excellent}\}$  be a linguistic term set and  $\delta$  be a linguistic variable, then,  $H_S^1(\delta) = \{\text{good, very good}\}$  and  $H_S^2(\delta) = \{\text{very weak, weak, medium}\}$  are two HFLTSs on  $S$ .

HFLTS serves as a powerful and valuable tool for modeling experts' hesitation. The application of context-free grammars [82] enables to generate comparative linguistic expressions close to the natural language utilized by human beings in real world [82, 83], which can be effectively modeled by HFLTS. This approach has found wide application in dealing with various decision making problems.

**Definition 4** [82] Let  $S = \{s_0, s_1, \dots, s_g\}$  be a linguistic term set and  $G_H$  be a context-free grammar. The elements of  $G_H = (V_N, V_T, I, P)$  are defined as below:

$V_N = \{\langle \text{primary term} \rangle, \langle \text{composite term} \rangle, \langle \text{unary relation} \rangle, \langle \text{binary relation} \rangle, \langle \text{conjunction} \rangle\}$

$V_T = \{\text{lower than, greater than, at least, at most, between, and, } s_0, s_1, \dots, s_g\}$

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$$\begin{aligned}
I &\in V_N \\
P &= \{I:: = \langle \text{primary term} \rangle | \langle \text{composite term} \rangle \\
\langle \text{composite term} \rangle &:: = \langle \text{unary relation} \rangle \langle \text{primary term} \rangle | \langle \text{binary relation} \rangle \\
\langle \text{primary term} \rangle &\langle \text{conjunction} \rangle \langle \text{primary term} \rangle \\
\langle \text{primary term} \rangle &:: = s_0 | s_1 | \dots | s_g \\
\langle \text{unary relation} \rangle &:: = \text{lower than} | \text{greater than} | \text{at least} | \text{at most} \\
\langle \text{binary relation} \rangle &:: = \text{between} \\
\langle \text{conjunction} \rangle &:: = \text{and} \}
\end{aligned}$$

$S_u$  represents the comparative linguistic expressions generated by  $G_H$ , which might be single linguistic terms or either linguistic expressions .

**Example 2** Considering the context-free grammar,  $G_H$ , introduced in Definition 4 and the linguistic term set  $S$  from Example 1, the comparative linguistic expressions might be obtained as follows:

$$\begin{aligned}
S_{u_1} &= \text{at least good} \\
S_{u_2} &= \text{at most medium} \\
S_{u_3} &= \text{between good and very good}
\end{aligned}$$

The comparative linguistic expressions,  $S_u$ , provided by DMs or experts can be transformed into  $H_S$  by the transformation function  $E_{G_H}$ , which is defined as follows:

**Definition 5** [83] Let  $E_{G_H}$  be a transformation function that transforms  $S_u$  into  $H_S$ .

$$E_{G_H} : S_u \rightarrow H_S \quad (2.5)$$

Based on  $E_{G_H}$ , there are different ways to transform different expressions,  $S_u$  into HFLTSs according to their meaning:

$$\begin{aligned}
E_{G_H}(s_i) &= \{s_i | s_i \in S\}, \\
E_{G_H}(\text{at most } s_i) &= \{s_j | s_j \leq s_i \text{ and } s_i \in S\}, \\
E_{G_H}(\text{at least } s_i) &= \{s_j | s_j \geq s_i \text{ and } s_i \in S\}, \\
E_{G_H}(\text{between } s_i \text{ and } s_j) &= \{s_k | s_i \leq s_k \leq s_j \text{ and } s_k \in S\},
\end{aligned}$$

In this research, to prevent loss of initial information and carry out computations with comparative linguistic expressions, fuzzy numbers are utilized as the transformed information from  $H_S$ , in which fuzzy envelop is employed (see [64] for details).

2.5.2 Fuzzy evidential reasoning

In 1967, Dempster [25] developed the method of evidence theory firstly. Shafer [86] extended and refined the evidence theory to evidential reasoning in 1976. The evidential reasoning is a popular method for utilizing a unified distributed modeling framework to deal with complete or incomplete information successfully. Moreover, it is also powerful for handling various uncertain information by Dempster’s combination rule. Because of the advantages of dealing with uncertainty, the evidential reasoning has been widely applied to solve different problems, such as, MADM problems [7, 159], risk assessment [116, 140] and so on.

In the approach of evidential reasoning, there is an assumption regarding the assessment grades  $H_1, H_2, \dots, H_N$  that are crisp and independent to each other. However, in practice, the assessment grades are typically interdependent and usually be represented by fuzzy and uncertain information. In order to handle such an issue, a fuzzy evidential reasoning approach was proposed by Yang et al. [133] to manage fuzzy and interdependent situations between different assessment grades. A brief introduction of the fuzzy evidential reasoning approach is provided as follows.

Without loss of generality, there is an assumption that only two adjacent fuzzy assessment grades within the frame of discernment are interdependent on each other. Let  $H_n$  represents the fuzzy assessment grades in the discernment frame, and will be represented by triangular or trapezoidal fuzzy numbers or their combinations, see Fig. 2.2. Let  $H_{n,n+1}$  represents the intersection subset between  $H_n$  and  $H_{n+1}$ , see grey area  $H_{1,2}$  in Fig. 2.3.

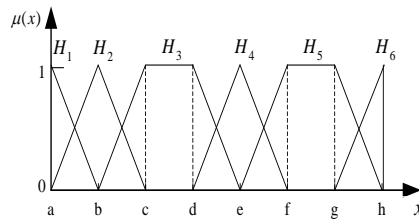


Figure 2.2: Fuzzy assessment grades

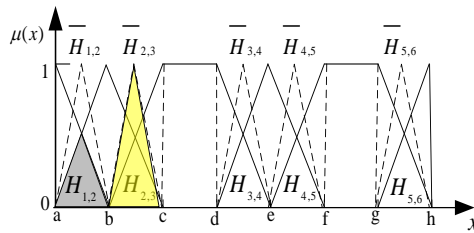


Figure 2.3: Intersection subset  $H_{n,n+1}$  and normalization fuzzy set  $\bar{H}_{n,n+1}$

The main advantage of the fuzzy evidential reasoning approach proposed by Yang et al. [133] is to handle the intersection part  $H_{n,n+1}$ , the maximum membership degree of  $H_{n,n+1}$  is usually less than one, denoted by  $\mu_{H_{n,n+1}}^{max}$ . The way to handle the intersection part in the fuzzy discernment framework can be summarized as: firstly, the intersection part,  $H_{n,n+1}$ , is normalized into  $\bar{H}_{n,n+1}$ , its maximum membership degree is one, so that  $\bar{H}_{n,n+1}$  can be regarded as an assessment grade equivalent to  $H_n$ , see yellow area in Fig. 2.3; secondly, the analytical fuzzy evidential reasoning algorithm will be used to calculate the belief degree  $\beta_{n,n+1}$  with respect to the assessment grade  $\bar{H}_{n,n+1}$ ; finally, the grade match method (see literature [133] for detail information) will be utilized to reassign the belief degree  $\beta_{n,n+1}$  to  $H_n$  and  $H_{n+1}$ .

### 2.5.3 Fuzzy DEMATEL method

Fuzzy DEMATEL method [123, 160] is an extension of DEMATEL [39, 40] proposed to tackle complex real-world decision problems under fuzzy and uncertain circumstance, in which experts' their assessments are expressed by fuzzy information. It is outlined below [123, 160].

Step 1: *To determine the decision objective and establish a committee.* The decision objective, along with expert committee is established according to the given problem.

Step 2: *To identify assessment factors and associated fuzzy information.* Assessment factors with respect to the given problem are identified, and fuzzy information associated fuzzy numbers are provided in Table 2.1 [123].

Table 2.1: Fuzzy linguistic terms with related fuzzy numbers

Linguistic terms	Triangular fuzzy numbers
Very high influence	(0.75,1.0,1.0)
High influence	(0.5,0.75,1.0)
Low influence	(0.25,0.5,0.75)
Very low influence	(0,0.25,0.5)
No influence	(0,0,0.25)

Step 3: *To consolidate evaluations from experts..* Experts provide their assessments regarding different factors  $C = \{C_k | k = 1, 2, \dots, K\}$  by using fuzzy linguistic terms as shown in Table 2.1. Upon this, the fuzzy linguistic terms is defuzzified into crisp values, and then the initial direct-relation matrix  $X = [x_{ij}]_{K \times K}$  is established, in which  $x_{ij}$  indicates the impacts of factor  $C_i$  over  $C_j$  ( $i, j = 1, 2, \dots, K$ ),  $x_{ij} = 0$  when  $i = j$ .

Step 4: *To achieve total-relation matrix.* According to Eq. (2.6),  $X = [x_{ij}]_{K \times K}$  is normalized into  $\bar{X} = [\bar{x}_{ij}]_{K \times K}$ , e.g.,

$$\bar{X} = \frac{1}{\max_i \sum_{j=1}^K x_{ij}} X \quad (2.6)$$

Then, total-relation matrix,  $T = [t_{ij}]_{K \times K}$ , is obtained by Eq. (2.7), e.g.,

$$T = [t_{ij}]_{K \times K} = \bar{X}(I - \bar{X})^{-1} \quad (2.7)$$

where  $I$  is an  $K \times K$  identify matrix.

Step 5: *To compute the sum of rows and columns of  $T$ .* According to Eqs. (2.8) - (2.9), the sum of  $i$ -th row and  $j$ -th column of  $T$  is achieved respectively, e.g.,

$$D_i = \sum_{j=1}^K t_{ij} \quad (2.8)$$

where  $D_i$  indicates the degree of influential impact that means all direct and indirect influence given by factor  $i$  to all other factors.

$$R_j = \sum_{i=1}^K t_{ij} \quad (2.9)$$

where  $R_j$  indicates the degree of influenced impact that means the direct and indirect impact received by factor  $j$  from all other factors.

When  $i = j$ ,  $D_i + R_i$  represents both the impact of factor  $i$  on the entire system and the impact of other system factors on factor  $i$ , in other word, it encapsulates all effects exerted and received by factor  $i$ . Thus,  $D_i + R_i$  is viewed as the degree of importance of factor  $i$  on the entire system. While,  $D_i - R_i$  represent the net effect of factor  $i$  on the entire system. When  $D_i - R_i \geq 0$ , the factor  $i$  exhibits a net causal effect on the entire system, conversely  $D_i - R_i < 0$ , the factor  $i$  indicates a net effect on the entire system.

Step 6: *To creat a causal relationship diagram.* Based on  $(D_i + R_i, D_i - R_i)$ , related causal relationship diagram is pictured, and their relationship can be analyzed accordingly.

#### 2.5.4 Prospect theory

Prospect theory (PT) was first introduced in 1979 [51] and extended in 1992 [101] by Daniel Kahneman and Amos Tversky as a behavior economic theory. PT can describe the behavioral characteristics of human beings and offers a methodology for calculating gains, losses, and prospect values. Therefore, it has found widely application in dealing with different EDM problems considering psychological behaviors of human beings [31, 37, 113, 141].

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The "*reference point*" (RP) is one of the key concepts in PT, which is defined as a neutral position asset or expectation value of individuals anticipate gaining or avoiding losing. RP play a crucial role in determining the feeling of gains or losses based on the difference between expectation and outcomes. Moreover, the value of the RP is affected by individual's expectations [51].

Gains and losses are defined on the basis of the RP, in which Figure 2.4 can help for a better understanding of RP. According to Figure 2.4, RP is analogously defined for cost attributes.

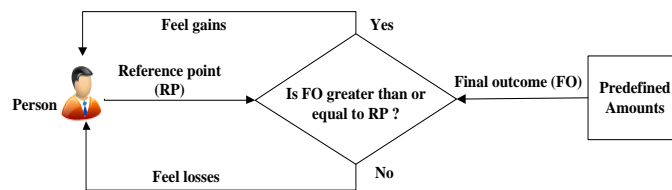


Figure 2.4: Gains and losses based on reference point and predefined amounts

According to literature [51, 101], DM's psychological behavior exhibits a risk-aversion tendency for gains and a risk-seeking tendency for losses. For measuring the magnitude of gains and losses, a value function is used in PT, which is defined on deviations from the RP with a concave and convex S-shape for losses and gains, respectively (see Figure.2.5) and it is expressed in form of a power law according to the following expression [51].

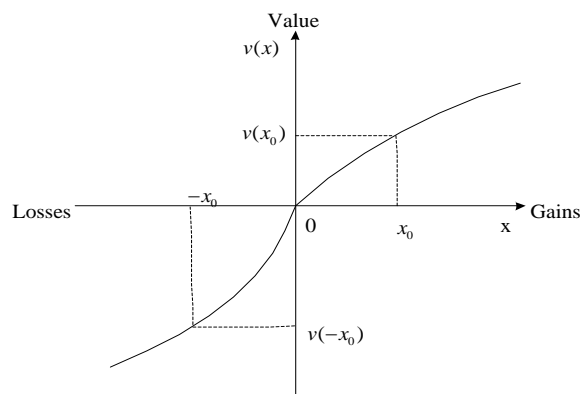


Figure 2.5: S-shaped value function of prospect theory

$$v(x) \in \begin{cases} x^\alpha, & x \geq 0 \\ -\lambda(-x)^\beta, & x < 0 \end{cases} \quad (2.10)$$

where  $\alpha$  is power parameters related to gains,  $\beta$  is for losses,  $0 \leq \alpha, \beta \leq 1$ , where  $x$  represents the gains with  $x \geq 0$  and losses with  $x < 0$ .  $\lambda$  denotes the parameter of risk-aversion,  $\lambda > 1$ .

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## Chapter 3

# Research Results

This chapter offers an overview of the main achieved proposals in this research memory. Research findings and results of each proposal are briefly reviewed. Five proposals associated with relevant objectives mentioned in the Introduction chapter are as follows:

1. A novel alpha-level sets based fuzzy DEMATEL method considering experts' hesitant information.
2. Dynamic critical factors identification: A novel fuzzy DEMATEL method considering heterogeneous information.
3. An early warning method based on fuzzy evidential reasoning considering heterogeneous information.
4. A dynamic emergency plan generation method considering different situations and limited resources.
5. A hesitant group emergency decision making method based on prospect theory.

### **3.1 Emergency critical factors identification based on fuzzy DEMATEL method**

Emergency critical factors identification plays a vital role in analyzing the interrelationship among factors that are associated to specific EEs, which helps DMs to understand the EEs comprehensively and deeply, and handle it effectively. Therefore, it is an important topic in emergency management.

One of the most popular used methods to identify emergency critical factors is DEMATEL [39, 40] because of its easy and simple computations regarding the analysis on interrelations among different factors and visualization of cause-effect

relationship. However, the DEMATEL method [39, 40] faces a challenge in handling complex decision problems under uncertain circumstance, where expert judgments are usually expressed by crisp values. Consequently, it has been expanded to fuzzy circumstance [123].

### **3.1.1 Related limitations in current fuzzy DEMATEL method**

According to such demands, fuzzy DEMATEL method [123] has been proposed to analyze the interrelationships among different factors under uncertainty, and fruitful results from different aspects have been produced [6, 48].

In spite of this, existing fuzzy DEMATEL methods have remarkable drawbacks because they defuzzify fuzzy input information into crisp values. Such a defuzzification may provoke information loss [112, 117]. Therefore, it appears essential to approach tackling fuzzy input information from a more rational view, rather than to defuzzify it originally.

Moreover, while existing fuzzy DEMATEL methods have taken into account fuzzy input quantitative or qualitative information, they ignore that experts are bounded rational and may hesitate when providing their opinions due to varying knowledge, experiences and background [20, 21, 82]. Hesitancy is an important and unavoidable topic in humans daily life [82], and should be taken into account under fuzzy circumstance.

To address the aforementioned limitations, we have proposed a novel fuzzy DEMATEL method from the view of alpha level sets, instead of employing defuzzification way. Meanwhile, it handles the DM's hesitation from qualitative view by using HFLTS.

### **3.1.2 Proposed novel fuzzy DEMATEL method**

The new proposed method has several novelties and advantages, they are briefly listed below (more comprehensive information seen Chapter 4):

1. The proposed novel fuzzy DEMATEL method points out a new view to tackle fuzzy assessments, it avoids the defuzzification process and provides more reasonable results due to the more information kept during the analysis process. This innovative way to tackling fuzzy assessments empowers our proposal from a new view to analyze the interrelationships among factors.
  2. The proposed novel fuzzy DEMATEL method incorporates experts' hesitation, which is an important and unavoidable topic in humans daily life. By doing so, it broadens the scope and applicability of the fuzzy DEMATEL method and makes it closer to the real-world scenarios.
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3. The proposed novel fuzzy DEMATEL method offers two distinct options for analyzing the interrelationship among factors. Those two options have not been discussed in previous fuzzy DEMATEL studies. It provides new analysis views on the tendency and changes among factors.

To highlight the proposed method, we have conducted related comparisons with previous studies to illustrate its performance, feasibility, validity and superiority.

The detail information related to the proposed method is:

Z. X. Zhang, L. Wang, Y. M. Wang, L. Martínez. A novel alpha-level sets based fuzzy DEMATEL method considering experts' hesitant information. *Expert Systems With Applications*, 2023, 213: 118925.

## 3.2 Dynamic fuzzy DEMATEL method considering heterogeneous information

On the basis of Section 3.1, it is found that dynamic evolution is a typical feature of real-world problems, in which the problem might dynamically change alongside with the time and information update, meanwhile, the identified critical factors might vary with the dynamic evolution of the problem. However, such a dynamic feature has not been drawn attention by existing studies, we propose an approach that considers the dynamic evolution of the problem.

### 3.2.1 Dynamic evolution with heterogeneous information in fuzzy DEMATEL

In the real-world, there is a practical and inevitable issue that experts may have different attitudes or opinions over different factors, due to varying different background and knowledge. Moreover, factors under consideration in a given problem may exhibit varying nature, qualitative or quantitative. Hence, experts may opt to use different information types to provide their assessments according to their knowledge, individual preference and factor nature. Nevertheless, there is only one information type (e.g., crisp values or linguistic terms) provided for experts to express their assessments in the existing fuzzy DEMATEL studies.

So far, seldom existing DEMATEL studies consider different information types and dynamic evolution of problem at the same.

To overcome these limitations, a novel dynamic fuzzy DEMATEL method is proposed to tackle heterogeneous information and dynamic evolution of given problems.

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**3.2.2 Dynamic critical factors identification: A novel fuzzy DEMATEL method considering heterogeneous information**

The new proposed method takes into account both the dynamic evolution of problem, and the heterogeneous information employed by experts to express their assessments. The novelties and advantages are briefly listed below (further details seen Chapter 4):

1. The proposed method presents a new view to identify the critical factors from dynamic evolution, which enriches the research perspectives and extends the scope of the existing studies. Such a novel dynamic perspective of identifying critical factors provides a new insight to explore the interrelationship among factors deeply and comprehensively.
2. The proposed method takes in account heterogeneous information, in which experts can provide their assessments according to their knowledge, individual preference and factor nature.

To illustrate the feasibility, superiority and validity of the proposed method, an example and related comparisons are carried out.

The detail information related to the proposed method is:

Z. X. Zhang, L. Wang, X. Y. Xie, Q. D. Wu, Y. M. Wang, R. M. Rodríguez. Dynamic critical factors identification: A novel fuzzy DEMATEL method considering heterogeneous information. *Expert Systems with Applications*, under review.

**3.3 Emergency early warning method based on fuzzy evidential reasoning**

To achieve the third objective outlined in Section 1.2, the significance of the role of emergency early warning and heterogeneous information in early warning process was highlighted, and then the drawbacks in current early warning studies were pointed out. Afterwards, a fuzzy evidential reasoning method is utilized to deal with the heterogeneous information to improve current early warning studies and a real early warning problem is used to demonstrate its superiority and reliability.

**3.3.1 Heterogeneous information in emergency early warning**

As mentioned previously, the information used and its modelling affect the emergency early warning results directly, therefore, it plays a critical and important role handling successfully forecast and warn the hazards in advance [121]. Consequently,

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several emergency early warning studies have considered different types of information either collected by sensors, monitoring devices or provided by experts.

Nevertheless, when the hazards was characterized by uncertain and complex information, it is quite hard to collect information related to hazards by sensors or monitoring devices. In such a situation, experts' assessments regarding the hazards serve as valuable supplementary information. However, current researches rarely take into account the combinations of information, which includes different types of information from qualitative and quantitative contexts.

To address such drawbacks in the current early warning researches, we have introduced a new proposal that considers fuzzy evidential reasoning and heterogeneous information.

### 3.3.2 Proposed emergency early warning method

This proposal has several superiority and novelties, which are briefly listed as follows (further details seen Chapter 4):

1. This proposal developed a new early warning approach that takes into account the heterogeneous information which consist of precise values, interval values, linguistic information and HFLTS. The new early warning approach not only enriches the incorporation of various types of information but also brings the early warning research closer to real world problems.
2. Due to the advantages of avoiding loss important information in the fusion process, the fuzzy evidential reasoning approach is employed in our proposal to fuse the heterogeneous information. This new approach ensures the reasonableness of the early warning results, and shows the superiority of considering the heterogeneous information and enriches the methods and models of current researches on emergency early warning.
3. The fuzzy evidential reasoning method enables the more safety status information regarding early warning objectives, this can allows experts in analyzing the safety tendencies of early warning objectives more effectively.

In addition, we have demonstrated an early warning example about a landslide early warning problem to illustrate the feasibility and validity of the proposed approach.

The detail information related to the proposed method is:

Z. X. Zhang, L. Wang, J. L. Duan, Y. M. Wang. An early warning method based on fuzzy evidential reasoning considering heterogeneous information. *International Journal of Disaster Risk Reduction*, 2022, 82, 103356.

### **3.4 Dynamic emergency plan generation method considering different situations and limited resources**

EDM is vital to alleviate losses and negative impacts, when an EE takes place. Emergency plans are chosen to deal with the possible situations aiming at preventing or minimizing potential losses. Hence, emergency plans are crucial component of EDM. Thus, how to generate emergency plans is an worthy topic to study.

#### **3.4.1 Limitations in current emergency plan generation studies**

The emergency plans serve as pivotal elements in EDM, exerting direct impact on the successful handling of emergency situations. Therefore, given the significance and impact of emergency plans, related studies have been undertaken from diverse perspectives.

Even though previous related studies have yielded valuable findings, they ignored a critical feature of EEs: dynamic evolution. This involves information updating (e.g., changing of emergency situations, available resources) along with the evolution of EEs, where information is vital component during the process of emergency plan generation. Such critical feature of EEs should be considered during the emergency plan generation, aiming at overcoming the drawbacks that the predefined emergency plans are lack of flexibility to adapt to various emergency situations.

Inspired by the drawbacks, this study provides a new method for dynamically generating emergency plans, which describes the dynamic feature by changing of possible emergency situations, available limited resources, and relevant information.

#### **3.4.2 Dynamic emergency plan generation method**

To accomplish the fourth objective of this research, a novel method for dynamically generating emergency plan is introduced. The method takes into account the dynamic feature from diverse aspects, e.g., changing of possible emergency situations, available limited resources, and relevant information.

This new proposal has several superiority and novelties, which are briefly listed below (further details seen Chapter 4):

1. The proposed method introduces a new way by considering both various emergency situations and the constraints of limited resources during the process of emergency plan generation. It makes the study closer to the real-world situations.
  2. The proposal generates emergency plans by utilizing integer linear programming. This method is not only straightforward and easy to comprehend, but
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also easy and fast to calculate. Such simplicity and efficiency enable the method to perfectly tackle complex practical problems.

Finally, a dynamic emergency plan generation example is included to illustrate the feasibility and validity of this proposal. Moreover, a comparison with existing studies is carried out to show its robustness.

The detail information related to the proposed method is:

Z. X. Zhang, L. Wang, J. Y. Lai, Y. M. Wang. A dynamic emergency plan generation method considering different situations and limited resources. *Sustainability*, 2023, 15, 5996.

### 3.5 A hesitant group emergency decision making method based on prospect theory

Because of the complexity and uncertainty inherent in EDM problems, the experts usually exhibit bounded rationality and may hesitate to provide their assessments and opinions. However, experts' psychological behavior and hesitancy behavior in quantitative contexts have not been put much attention in existing GEDM approaches. Therefore, it is worthy to develop a new GEDM approach capable of addressing experts' psychological behavior and handling hesitant information in quantitative contexts. A novel GEDM approach was developed aiming at modelling of hesitancy in quantitative contexts through hesitant fuzzy sets (HFSs) and handling experts' psychological behavior through prospect theory. The fifth goal is reached with this proposal.

#### 3.5.1 Limitations in current group emergency decision making methods

When an EE has occurred, some measures must be implemented to minimize the losses of lives and properties. Because EDM is typically characterized by incomplete information and time pressure in real world, it has big challenges for a DM to make comprehensive judgments and to forecast the evolution of EEs accurately under emergency situations. However, such problems will be easier for group wisdom and this leads to GEDM problems. In GEDM problems, multiple experts with diverse array of professional backgrounds (such as sociological, demographic, hydrological, meteorological, geological, etc.) are essential to help the DM to make a correct decision.

Even though, the current GEDM approaches have obtained significant achievements in the fields of emergency management, there are still two limitations that

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need to be well addressed:

1. *Losing information in aggregation process.* The aggregation process employed in existing GEDM researches may result in the loss of valuable information at the very beginning. Hence, it is a significant challenge for GEDM approaches to keep as much information as possible provided by group, avoiding such kind of information lost.
2. *Neglecting DM's psychological behaviors in selection process.* Different studies have demonstrated that DMs exhibit bounded rationality when they are under risk and uncertainty. Moreover, DM's psychological behavior plays crucial role in GEDM processes. However, this critical issue has been overlooked in existing GEDM approaches.

To address such limitations, we have proposed a novel GEDM method with application of HFSs and PT, which incorporates diverse experts' opinions to represent group hesitancy and fuses them into HFSs and incorporates DM's psychological behaviors through PT.

#### 3.5.2 Proposed GEDM method

This proposal put emphasis on keeping as much information as possible at the every beginning of the decision process with application of HFSs, which can denote the group hesitation by HFE constructed through the fusion of experts' assessments. These HFSs will be integrated as inputs of the GEDM process, which also take into account the experts' psychological behavior through PT. The contributions of this approach are the following ones:

1. This proposal incorporates diverse experts' assessments to represent group hesitancy and fuses them into HFSs.
2. Simultaneously, in the selection process, this proposal incorporates the DM's psychological behaviors through PT for its advantages of describing psychological behaviors of human beings under risk and uncertainty.

The superiority of this proposal has been demonstrated through the part of case study and comparisons, and consequently, the fifth objective of our researches is reached.

The detail information related to the proposed method is:

Z. X. Zhang, L. Wang, R. M. Rodríguez, Y. M. Wang, L. Martínez. A hesitant group emergency decision making method based on prospect theory. *Complex & Intelligent Systems*, 2017, 3, 177-187.

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## Chapter 4

# Publications

### 4.1 A novel alpha-level sets based fuzzy DEMATEL method considering experts' hesitant information

- State: Published.
- Title: A novel alpha-level sets based fuzzy DEMATEL method considering experts' hesitant information.
- Authors: Zi-Xin Zhang, Liang Wang, Ying-Ming Wang and Luis. Martínez.
- Journal: Expert Systems With Applications
- Volume: 213. Pages: 118925. Date: March 2023.
- DOI: <https://doi.org/10.1016./j.eswa.2022.118925>
- Online ISSN: 1873-6793
- Print ISSN: 0957-4174
- Impact Factor (JCR 2022): 8.5.
  - Quartiles:
    - \* Quartile 1 in Computer Science, Artificial Intelligence 22/192.
    - \* Quartile 1 in Operations research and Management Science 7/104.

## **4.2 Dynamic critical factors identification: A novel fuzzy DEMATEL method considering heterogeneous information**

- State: Under review.
- Title: Dynamic critical factors identification: A novel fuzzy DEMATEL method considering heterogeneous information.
- Authors: Zi-Xin Zhang, Liang Wang, Xianyu Xie, QinDe Wu, Ying-Ming Wang and Rosa M. Rodríguez.
- Journal: Expert Systems with Applications
- Online ISSN: 1873-6793
- Print ISSN: 0957-4174
- Impact Factor (JCR 2022): 8.5
  - Quartiles:
    - \* Quartile 1 in Computer Science, Artificial Intelligence 22/192.
    - \* Quartile 1 in Operations research and Management Science 7/104.

### 4.3 An early warning method based on fuzzy evidential reasoning considering heterogeneous information

- State: Published.
  - Title: An early warning method based on fuzzy evidential reasoning considering heterogeneous information.
  - Authors: Zi-Xin Zhang, Liang Wang, JinLi Duan and Ying-Ming Wang.
  - Journal: International Journal of Disaster Risk Reduction.
  - Volume: 82. Page:103365. Date: October 2022.
  - DOI: <http://doi.org/10.1016/j.ijdrr.2022.103356>
  - Online ISSN: 2212-4029.
  - Impact Factor (JCR 2022): 5.
    - Quartiles:
      - \* Quartile 1 in Geosciences, multidisciplinary 32/202.
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#### 4.4 A dynamic emergency plan generation method considering different situations and limited resources

- State: Published.
  - Title: A dynamic emergency plan generation method considering different situations and limited resources.
  - Authors: Zi-Xin Zhang, Liang Wang, Jiayan Lai and Ying-Ming Wang.
  - Journal: Sustainability
  - Volume: 15. Pages: 5996. Date: March 2023.
  - DOI: <https://doi.org/10.3390/su15075996>
  - ISSN: 2071-1050.
  - Impact Factor (JCR 2022): 3.9
    - Quartiles:
      - \* Quartile 2 in Environmental sciences 114/275.
      - \* Quartile 2 in Environmental studies 48/128.
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#### 4.5 A hesitant group emergency decision making method based on prospect theory

- State: Published.
  - Title: A hesitant group emergency decision making method based on prospect theory.
  - Authors: Zi-Xin Zhang, Liang Wang, Rosa M. Rodríguez, Ying-Ming Wang and Luis Martínez.
  - Journal: Complex Intelligent Systems
  - Volume: 3(3). Pages: 177-187. Date: October 2017.
  - DOI: [10.1007/s40747-017-0045-9](https://doi.org/10.1007/s40747-017-0045-9)
  - ISSN: 2199-4536.
  - Indexed in JCR without impactor factors in 2017.
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## Chapter 5

# Conclusions and Future Works

The main conclusions obtained thorough proposals and possible promising future works in our research memory are revised and provided in Chapter 5.

### 5.1 Conclusions

In recent years, the human beings' daily lives and social development received serious threats because of the frequently occurrence of EEs. Hence, related issues of emergency management have drawn great attention from both government agencies and academic researchers, and have obtained notable achievements and outcomes.

Since the significance of related issues in emergency management, many models and methods have been developed by different researchers to deal with the problems from various perspectives. However, there still have drawbacks in current researches on such fields of critical factors identification, emergency early warning, emergency plan generation and EDM considering DM's psychological behavior together with dynamic views among others, which have outlined in Chapter 1.

Throughout our efforts, we have obtained innovative, noteworthy, and pertinent outcomes with regard to those drawbacks in existing studies. These outcomes not only meet the objectives outlined in Section 1.2, but also offer new perspectives and avenues for future exploration.

Consequently, the outcomes of our research was summarized as follows:

1. The application of alpha-level sets for overcoming the limitations in critical factors identification is a useful tool that may improve the existing fuzzy DEMATEL studies for providing more reasonable and reliable results. Additionally, dynamic views have also been considered in the critical factors identification process that enhances the applicability of our studies to real-world situation.

2. Emergency early warning plays an important role in reducing the occurrence possibility of EEs in advance, in which information modelling is vital to the quality of forecast. Different information types are usually associated to EEs in real world, which has been considered in the early warning process.
3. Emergency plans are the measures that are selected to handle the emergency situations, which have been discussed from novel perspectives that are generated based on the consideration of limited resources and dynamic evolution. The considered novel perspectives make the emergency plans more flexible and targeted. Such a generation way improves the handling efficiency of EDM process.
4. In recent years, the EEs and EDM problems have becoming increasingly complex and uncertain, which may imply higher requirements on processing different types of uncertainties. Therefore, the development of EDM deals with multiple types of information, considering experts' hesitancy and DM's bounded rational as it has been shown in the obtained results in this research.

## 5.2 Future Works

Despite the novel methods and approaches have been developed in this research memory, there are still some challenges in the research fields of emergency early warning and emergency decision making that should be solved in the future. In future studies, we will put emphasis on the extension of the proposed approaches and on the development of solutions for new challenges:

1. An important extension of our proposals is the integration of the proposed approaches into a decision support system aimed at enable the implementation of emergency early warning approaches in real world situation.
2. A potential research perspective in EDM problems could focus on the exploration of data-driven decision models aimed at streamlining, automating, and enhancing existing EDM frameworks.
3. A more ambitious research perspective could focus on establishing the platform, which can integrated the early warning process and EDM related issues into a more comprehensive decision support system for improving emergency management.

### **Additional Publications**

Despite the publications outlined in this research memory, the following contributions were highlighted for the diffusion of our scientific results:

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- International Journals
    - Z. X. Zhang, L. Wang, Y. M. Wang. An emergency decision making method based on prospect-theory for different emergency situations. *International Journal of Disaster Risk Science*. 2018, 9(3): 407-420.
    - L. Wang, Z. X. Zhang, A. Ishizaka, Y. M. Wang, L. Martinez. TODIM-Sort: A TODIM based method for sorting problems. *Omega-International Journal of Management Science*, 2023, 115, 102771.
  
  - International Conferences
    - L. Wang, J. Y. Lai, Z. X. Zhang. A dynamic multi-criteria sorting method for modern renewable energy consumption. International Conference on Intelligent Systems and Knowledge Engineering (ISKE-2023), 17-19 Nov, 2023, Fuzhou, China.
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## Appendix A

# Resumen escrito en Español

**Título de la tesis:** *Alerta temprana de emergencias y toma de decision bajo incertidumbre*

Este apéndice incluye el título, introducción, resumen y conclusiones escritas en español, como parte de los requisitos necesarios para obtener el doctorado según el artículo 23.2 del Reglamento de Estudio de Doctorado de la Universidad de Jaén.

Se introduce de forma breve la investigación llevada a cabo, indicando motivación, objetivos y la estructura de los capítulos que la componen. Seguidamente, se presenta un resumen de la misma, para finalmente concluir con el apartado de conclusiones obtenidas y trabajos futuros.

## A.1 Motivación

Los eventos de emergencia (EE) son sucesos repentinos que pueden provocar pérdidas significativas de vidas, lesiones, daños a la propiedad, daños ecológicos y riesgos sociales [109], como desastres naturales, accidentes, eventos de salud pública e incidentes de seguridad social, etc. [62].

En los últimos años, diversas emergencias, como terremotos, huracanes y ataques terroristas, etc., han tenido enormes impactos y gravemente negativos en la vida humana, la estabilidad social y el desarrollo económico. Por lo tanto, es necesario encontrar algunas formas de mitigar y reducir los impactos negativos causados por los EE. Según el análisis de los estudios existentes, los principales campos de investigación se pueden resumir a grandes rasgos en los cinco siguientes:

- ◇ Características relacionadas de los EE. Los EE a menudo implican lidiar con información incierta, incompleta e insuficiente, así como con procesos de evaluación dinámica y otros factores. Muchos estudios existentes han propuesto varios métodos para manejar estas características, como información incompleta/inadecuada [16, 60, 97, 113, 153]. Otros han propuesto varios enfoques para abordar la evaluación dinámica de los EE, como los modelos de decisión dinámica basados en la teoría de juegos [134, 143], el método de análisis de árbol de fallas [67, 125], aprendizaje automático [54, 158], etc.
  - ◇ Identificación de factores críticos de los EE. Identificar los factores críticos de los EE puede ayudar a los tomadores de decisiones (DM) a comprender los EE en profundidad y dar una respuesta integral a los EE con éxito y eficacia. Muchos estudios existentes han propuesto varios métodos para identificar factores críticos de EE, como el método DEMATEL [29, 90], WINGS [69, 115], Dinámica de sistemas (SD) [87] etc.
  - ◇ Alerta temprana de emergencia. El sistema de alerta temprana de emergencia desempeña un papel vital en la mitigación del riesgo de muertes, daños a la propiedad y daños ecológicos en los EE [121]. Así, se han llevado a cabo investigaciones desde diversas perspectivas relacionadas con la alerta temprana y han logrado resultados exitosos [2, 3, 17]. Por ejemplo, desarrollo y mejora de sistemas de alerta temprana [3, 9, 22], monitoreo y recopilación de información relacionada con peligros [2, 13], métodos o marcos para construir sistemas de alerta temprana.
  - ◇ Generación de planes de emergencia. Al gestionar situaciones de emergencia, los planes de emergencia desempeñan un papel fundamental, ya que impactan directamente en el éxito de la gestión de dichos eventos. Por lo tanto,
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las investigaciones existentes sobre la generación de planes de emergencia se han abordado desde varios puntos de vista, como la evaluación de planes de emergencia [71, 79, 157], formalización del plan de emergencia mediante programación matemática [10, 75, 122], generación de planes de emergencia. [142, 154, 155, 156] y red de tareas jerárquica [63, 77], etc.

- ◊ Toma de decisiones de emergencia (EDM). La EDM es un esfuerzo crucial destinado a mitigar y minimizar los daños o pérdidas, incluidos aquellos a la propiedad, las vidas humanas y el medio ambiente causados por los EE. Como resultado, la EDM ha surgido como un dominio de investigación muy activo y significativo dentro del campo de los estudios de emergencia [37, 59, 94, 113]. Por ejemplo, los problemas clásicos de EDM generalmente involucran a un solo DM en el proceso de EDM [23, 50, 52, 105], problemas de toma de decisiones de emergencia en grupo (GEDM) involucran a múltiples expertos que actúan como un grupo de expertos para apoyar al DM en la respuestas de emergencia [34, 88, 92, 128, 137].

Con el rápido desarrollo de innovaciones disruptivas en tecnología, economía y muchas otras áreas relacionadas con la sociedad moderna en la última década, los EE están cada vez más diversificados, complicados y llenos de incertidumbre, por lo que es importante estudiar cómo representar con precisión la información de la situación real. Los estudios existentes generalmente representan la información incierta mediante valores intervalares [50], términos lingüísticos difusos [113] o términos lingüísticos difusos dudosos [5, 38].

Para mejorar la respuesta de emergencia más pertinente, efectiva y exitosa, se deben identificar los factores críticos de los diferentes tipos de EE antes que otras actividades de emergencia. Debido a las ventajas en la identificación de factores críticos y la visualización de la relación causa-efecto entre factores, se han utilizado diferentes métodos de toma de decisión multicriterio (MCDM) para identificar factores críticos de EE [90, 123, 131, 160, 161], y los métodos MCDM difusos se utilizan a menudo en circunstancias confusas e inciertas [6, 58, 90, 112, 117, 131]. Los resultados del análisis se pueden utilizar en otras actividades de emergencia, como por ejemplo, alerta temprana de emergencia, generación de planes de emergencia y EDM.

El éxito de una alerta de emergencia puede dar a los DM más tiempo para responder a las emergencias, lo que puede evitar víctimas y pérdidas materiales. Sin embargo, no es posible advertir con éxito todos los EE. Por lo tanto, cuando la alerta temprana de emergencia falla y se produce un EE, se deben generar y preparar planes de emergencia para responder al EE. De esta forma, durante el proceso de EDM se

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responderá a la pregunta de qué plan utilizarán los DM para prevenir el desarrollo de emergencias y evitar pérdidas.

A pesar de la gran cantidad de modelos y enfoques que han propuesto para abordar problemas relevantes en los temas anteriores, y las importantes contribuciones desarrolladas para la gestión de emergencias, hasta el momento, los resultados de investigación obtenidos no son suficientes para manejar el complejo mundo real. Para abordar adecuadamente los problemas de emergencia han surgido nuevos desafíos, como las dudas de los expertos, la evolución dinámica de las EE y la pérdida de información, se requiere por tanto, un estudio más profundo para mejorar las soluciones/propuestas actuales en los estudios existentes. La enumeración de estas nuevas dificultades y desafíos motiva esta memoria de investigación:

- ◇ *No tener en cuenta la duda de los expertos o DM*: La duda es un comportamiento común e inevitable en nuestra vida diaria, particularmente cuando los humanos se encuentran con problemas complejos e información con incertidumbre [82]. Debido a la información incompleta o a la falta de experiencia, los expertos pueden dudar en dar sus valoraciones y opiniones [20, 21]. Sin embargo, este tema tan crucial rara vez se ha abordado en los estudios existentes sobre identificación de factores críticos y alerta temprana de emergencia.
  - ◇ *Pérdida de información*: La pérdida de información se puede producir de dos formas diferentes:
    - (1) Pérdida de información en la identificación de factores críticos. Los métodos MCDM difusos existentes defusifican la información difusa de entrada en valores nítidos [123, 160, 112, 117] mediante un proceso de defusificación catiónica para lograr información matricial inicial. Tal proceso de defusificación puede causar la pérdida de información importante [112, 117].
    - (2) Pérdida de información en la fusión de opiniones de expertos [14, 128]. La fusión de opiniones de expertos es un proceso crítico en los problemas de GEDM, en el que el conocimiento de cada experto se agrega para ayudar a DM en la toma de decisiones. Para ello, se emplean diferentes modelos y métodos para realizar dicha agregación desde diversas perspectivas. Sin embargo, los estudios GEDM actuales podrían perder información valiosa durante el proceso de agregación inicial. Un desafío importante para GEDM es mantener la mayor cantidad de información posible y evitar dicha pérdida [129, 130].
  - ◇ *No considerar las características de evolución dinámica de los EE*: La evolución dinámica es una característica típica en problemas del mundo real, ya que
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el problema puede cambiar dinámicamente con el tiempo y la información es actualizada, mientras tanto, las interrelaciones entre los factores pueden variar con la evolución dinámica del problema. Actualmente, los estudios existentes sobre la identificación de factores críticos y la generación de planes de emergencia no consideran la evolución dinámica de los EE.

- ◇ *Abordar los tipos de información:* La información juega un papel crucial en todas las actividades de emergencia. Sin embargo, tanto las propuestas existentes de identificación de factores críticos como los enfoques de alerta temprana de emergencia manejan un único dominio de información: valores nítidos [76, 132], valores intervalares [148] o información lingüística [29, 58, 65, 151]. Sin embargo, la información del mundo real sobre los EE se abarca distintos tipos de información simultáneamente (valores nítidos, intervalos, términos lingüísticos, información dudosa, etc.). Sin embargo, ninguna de las propuestas existentes en materia de identificación de factores críticos y alerta temprana de emergencias tiene en cuenta información heterogénea, es decir, el uso de distintos tipos de información.
- ◇ *No tener en cuenta el comportamiento psicológico de los DM:* Los seres humanos a menudo exhiben una racionalidad limitada cuando se enfrentan al riesgo y la incertidumbre, lo que hace que su comportamiento psicológico sea un factor crucial en los procesos de toma de decisiones [51]. Sin embargo, este problema crítico aún no se ha abordado en los enfoques EDM existentes [38, 56, 88, 120, 137, 153]. Por lo tanto, parece imperativo proponer un modelo capaz de manejar los problemas de EDM de manera más efectiva.

Los desafíos antes mencionados indican que los enfoques actuales que abordan los EE no pueden satisfacer adecuadamente las demandas y requisitos de situaciones de emergencia reales. En consecuencia, esta memoria de investigación lleva a cabo investigaciones adicionales y en profundidad para cerrar estas brechas.

## A.2 Objetivos

Sobre la base de los desafíos destacados en las investigaciones existentes, como se describe en la sección anterior, el objetivo de este estudio es mejorar los esfuerzos de investigación actuales. Por tanto, los objetivos planteados en esta investigación son los siguientes:

1. Proponer un nuevo enfoque MCDM difuso, específicamente DEMATEL [152] difuso que sea capaz de modelar la duda de los expertos y evite la pérdida de
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información durante el proceso de defusificación. Para ilustrar las ventajas, validez y viabilidad del nuevo método, se llevará a cabo un caso de estudio y comparaciones relacionadas con enfoques de análisis de interrelaciones existentes.

2. Mejorar el modelado de información en el modelo difuso DEMATEL que considere información heterogénea y la evolución dinámica de los EE. El método propuesto supera las limitaciones de los enfoques actuales de identificación de factores críticos incorporando una perspectiva dinámica novedosa e información heterogénea. Este método se aplicará en un accidente de responsabilidad de seguridad para mostrar su funcionamiento y novedad.
3. Para desarrollar un nuevo enfoque de alerta temprana de emergencia [145], se modelarán múltiples tipos de información utilizando información heterogénea. Dicha propuesta se aplicará a una alerta temprana de emergencia por deslizamientos de tierra para demostrar su validez y desempeño.
4. Desarrollar un enfoque dinámico de generación de planes de emergencia [146] que considere diferentes situaciones de emergencia posibles y recursos limitados. Se presentarán ejemplos ilustrativos y comparaciones descriptivas para ilustrar su novedad y superioridad.
5. Desarrollar un enfoque para GEDM que modele información dudosa [147] y mejore la fusión de información considerenado información difusa dudosa junto con el comportamiento de los expertos. Se espera que este método GEDM produzca mejores resultados ya que el proceso de fusión de información es capaz de mantener más información que los procesos de agregación clásicos. Se utilizará un ejemplo para demostrar su validez y desempeño.

### A.3 Estructura

Para llevar a cabo los objetivos expuestos en la sección A.2, y teniendo en cuenta el artículo 23, punto 3, de las actuales directrices de Estudios de Doctorado de la Universidad de Jaén, en entendimiento con el programa establecido en el RD 99 /2011, esta memoria se desarrollará como un compendio de artículos que hayan sido publicados por la doctoranda durante su periodo doctoral.

Se han publicado cuatro artículos en revistas internacionales indexadas en la base de datos JCR y otro artículo se encuentra en revisión en una revista internacional JCR.

A continuación se presenta brevemente la organización de esta memoria:

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- ◇ Capítulo 2: Se revisan algunos conceptos y métodos básicos que se utilizan en nuestras propuestas para lograr los diferentes objetivos señalados en la Sección 1.2, tales como conceptos relacionados de identificación de factores críticos de EE, alerta temprana de emergencia, toma de decisiones de emergencia, conjuntos difusos dudosos, conjuntos de términos lingüísticos difusos dudosos y métodos relacionados: método de razonamiento probatorio difuso, método DEMATEL difuso, teoría prospectiva, etc.
- ◇ Capítulo 3: Se introducen brevemente las diferentes y novedosas propuestas obtenidas en esta memoria de investigación, junto con discusiones de los resultados obtenidos para esclarecer los logros alcanzados en nuestra investigación.
- ◇ Capítulo 4: Es el núcleo de la tesis doctoral, que incluye las publicaciones que conforman los resultados obtenidos a lo largo de nuestra investigación. Para cada publicación se indica información detallada de la revista en la que se ha publicado la propuesta.
- ◇ Capítulo 5: Se señalan las conclusiones obtenidas de esta investigación y posibles trabajos futuros prometedores.

## A.4 Resumen

En los últimos años, los EE se han producido con frecuencia y han causado numerosas pérdidas y daños (materiales, humanos, ambientales, etc.) que tienen un impacto negativo en la vida humana y el desarrollo de la sociedad. Hay muchas actividades de gestión de emergencias, como identificar los factores críticos de los EE, alerta temprana de emergencia, generación de planes de emergencia, EDM, etc., que pueden ayudar a los DM a conocer los EE en profundidad y responder a los EE de manera oportuna y precisa, lo que puede mitigar y reducir los daños y pérdidas causados por los EE. La gran importancia de estas actividades de gestión de emergencias, ha atraído la atención tanto del ámbito académico como político y se han convertido en temas de investigación candentes en los últimos años. Sin embargo, es innegable que aún existen limitaciones que deben estudiarse y desafíos que enfrentar, como por ejemplo, *el comportamiento dudoso de los expertos, el comportamiento psicológico de los DM, el problema de la pérdida de información, la información heterogénea, la evolución dinámica*, etc. Para superar estas limitaciones, esta investigación presenta las siguientes propuestas:

1. Un novedoso método DEMATEL difuso basado en conjuntos de nivel alfa que considera la información dudosa de los expertos. El uso de conjuntos de nivel
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alfa para manejar las evaluaciones difusas del método DEMATEL difuso puede conservar mucha más información que la que se obtiene mediante las operaciones de defusificación realizadas en los enfoques DEMATEL difusos existentes. Al mismo tiempo, el método propuesto también tiene en cuenta el comportamiento dudoso de los expertos, lo cual es un problema inevitable y práctico en la situación del mundo real.

2. Identificación dinámica de factores críticos: un novedoso método difuso DEMATEL que considera información heterogénea. El método propuesto propone un ángulo novedoso para identificar los factores críticos de la evolución dinámica. Además, considera información heterogénea, tal como, valores numéricos, valores intervalares, términos lingüísticos y conjuntos de términos lingüísticos difusos dudosos.
3. Método de alerta temprana de emergencias basado en razonamiento probatorio difuso considerando información heterogénea. Se ha utilizado el método de razonamiento evidencial difuso para fusionar información heterogénea, incluyendo valores numéricos, valores intervalares, términos lingüísticos y conjuntos de términos lingüísticos difusos dudosos con la idea de mantener la mayor cantidad de información posible durante el proceso de fusión para obtener resultados más precisos.
4. Método dinámico de generación de planes de emergencia considerando diferentes situaciones y recursos limitados. El método propuesto proporciona una perspectiva novedosa al considerar tanto situaciones dinámicas como recursos de emergencia limitados durante el proceso de generación del plan de emergencia. Este método está basado en programación lineal lo que hace que la asignación de recursos para generar los planes de emergencia sea un proceso sencillo y fácil de entender.
5. Un método de toma de decisiones de emergencia en grupo dudoso basado en la teoría de la perspectiva. Este método considera las opiniones de diferentes expertos como la duda del grupo y las fusiona en un conjunto difuso dudoso. Además, se utilizó la teoría de la perspectiva para abordar las conductas psicológicas de los DM, ya que juega un papel importante en los procesos de GEDM.

## A.5 Conclusiones y Trabajos Futuros

A continuación se exponen las principales conclusiones obtenidas a través de las propuestas presentadas, y algunos trabajos futuros.

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### A.5.1 Conclusiones

En los últimos años, la vida cotidiana y el desarrollo social de los seres humanos han recibido serias amenazas debido a la frecuente ocurrencia de EE. Por lo tanto, las cuestiones relacionadas con la gestión de emergencias ha atraído gran atención tanto de las agencias gubernamentales como de los investigadores académicos, y han obtenido logros y resultados notables.

Teniendo en cuenta la importancia de los problemas relacionadas en la gestión de emergencias, diferentes investigadores han desarrollado modelos y métodos para abordar estos problemas desde diversas perspectivas. Sin embargo, todavía existen limitaciones en las investigaciones realizadas en la identificación de factores críticos, alerta temprana de emergencias, generación de planes de emergencia y EDM considerando el comportamiento psicológico del DM junto con información dinámica, entre otros, que se describen en la sección A.1.

A lo largo de nuestros esfuerzos, hemos obtenido resultados innovadores, destacables y pertinentes respecto a aquellas limitaciones de los estudios existentes. Estos resultados no solo cumplen con los objetivos descritos en la sección A.2, sino que también ofrecen nuevas perspectivas y vías para exploración futura.

En consecuencia, los resultados de nuestra investigación se resumen de la siguiente manera:

1. La aplicación de conjuntos de nivel alfa para superar las limitaciones en la identificación de factores críticos es una herramienta útil que puede mejorar los estudios difusos de DEMATEL existentes para proporcionar resultados más razonables y confiables. Además, también se han considerado puntos de vista dinámicos en el proceso de identificación de factores críticos que mejoran la aplicabilidad de nuestros estudios a situaciones del mundo real.
  2. La alerta temprana de emergencia desempeña un papel fundamental a la hora de reducir la posibilidad de que se produzcan EE con antelación, por lo que la información es vital para la calidad de las previsiones. Generalmente se asocian diferentes tipos de información a los EE en el mundo real, lo que ha sido considerado en el proceso de alerta temprana.
  3. Los planes de emergencia son las medidas que se seleccionan para atender situaciones de emergencia, lo cual se ha discutido desde diferentes perspectivas que se generan en base a la consideración de recursos limitados y evolución dinámica. Las nuevas perspectivas consideradas hacen que los planes de emergencia sean más flexibles y específicos. Esta forma de generación mejora la eficiencia de manejo del proceso de EDM.
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4. En los últimos años, los problemas de EE y EDM se han vuelto cada vez más complejos e inciertos, lo que puede implicar mayores requisitos en el procesamiento de diferentes tipos de incertidumbres. Por lo tanto, el desarrollo de la EDM aborda múltiples tipos de información, considerando la duda de los expertos y la racionalidad acotada del DM como se ha demostrado en los resultados obtenidos en esta investigación.

### A.5.2 Trabajos Futuros

A pesar de los nuevos métodos y enfoques que se han desarrollado en esta memoria de investigación, todavía existen algunos desafíos en la línea de investigación de alerta temprana de emergencias y la toma de decisiones de emergencia que deberían resolverse en el futuro.

1. Una extensión importante de nuestras propuestas es la integración de los enfoques propuestos en un sistema de apoyo a la toma de decisiones destinado a permitir la implementación de enfoques de alerta temprana de emergencia en situaciones del mundo real.
2. Una posible perspectiva de investigación en problemas de EDM podría centrarse en la exploración de modelos de decisión basados en datos destinados a simplificar, automatizar y mejorar los marcos de EDM existentes.
3. Una perspectiva de investigación más ambiciosa podría centrarse en el establecimiento de una plataforma que pueda integrar el proceso de alerta temprana y las cuestiones relacionadas con la EDM en un sistema de apoyo a la toma de decisiones más completo para mejorar la gestión de emergencias.

**Publicaciones adicionales.** A pesar de las publicaciones reseñadas en esta memoria de investigación, se destacan los siguientes aportes para la difusión de nuestros resultados científicos:

- Revistas Internacionales
    - Z. X. Zhang, L. Wang, Y. M. Wang. An emergency decision making method based on prospect-theory for different emergency situations. *International Journal of Disaster Risk Science*. 2018, 9(3): 407-420.
    - L. Wang, Z. X. Zhang, A. Ishizaka, Y. M. Wang, L. Martinez. TODIM-Sort: A TODIM based method for sorting problems. *Omega-International Journal of Management Science*, 2023, 115, 102771.
  - Conferencias Internacionales
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- L. Wang, J. Y. Lai, Z. X. Zhang. A dynamic multi-criteria sorting method for modern renewable energy consumption. International Conference on Intelligent Systems and Knowledge Engineering (ISKE-2023), 17-19 Nov, 2023, Fuzhou, China.



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