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Decision Aid Models for Disaster Management and Emergencies

Begoña Vitoriano, Javier Montero

Universidad Complutense de Madrid
Facultad de Ciencias Matemáticas
Plaza de las Ciencias 3
28040 Madrid, Spain

Da Ruan †

Belgian Nuclear Research Centre (SCK • CEN)
Mol, Belgium

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Da Ruan unexpectedly passed away on July 31, 2011, once this book was already launched. Born in Shanghai, September 10, 1960, Da Ruan got his Ph.D. at the University of Ghent, Belgium, 1990, Etienne Kerre being his Ph.D. advisor. He had been working at SCK • CEN, Belgium, since 1991, launching in 1994 the FLINS conference series, and the ISKE conference series in 2006. Da Ruan was the founder of the International Journal of Computational Intelligence Systems, currently the official journal of European Society for Fuzzy Logic and Technologies (EUSFLAT), and he has also served as Editor of this Atlantis Press' Computational Intelligence Systems series. Da Ruan was the editor of 36 books and the author of more than 270 papers in journals and conferences. Leader of many fuzzy logic projects within nuclear science, decision systems and risk analysis, Da Ruan was a hard worker, helpful and inspirative colleague, good friend and an honest and warm-hearted person. His friends and his beloved family will miss him forever.

Preface

Decision aid models for disaster management and emergencies

Begoña Vitoriano [1,*], Javier Montero [1,2,*], and Da Ruan [3,†]

[1] *Faculty of Mathematics Complutense University, Madrid 28040, Spain*
[2] *Instituto de Geociencias IGEO (UCM,CSIC), Madrid 28040, Spain*
[3] *Belgian Nuclear Research Centre (SCK•CEN), Mol, Belgium*

[*] {*bvitoriano,javier_montero*}*@mat.ucm.es*

A disaster is understood as the disruption of the normal functioning of a system or community, which causes a strong impact on people, structures and environment, and goes beyond local capacity of response. In the global world of the 21st century, a disaster that occurs anywhere of the planet affects to the whole human Society. All regions on The Earth are interconnected and any serious problem in any region will not only have direct and terrible consequences on that region, but it will also hit the social and/or economic structure of other countries. The dimension and circumstances of each disaster will determine the relief level needed (regional, national or international), but anyway they require a joint provision strategy of many regions and the concourse of International Organizations, Governmental and Non-Governmental.

Disaster management implies a number of actions to be developed before disaster happens, during the disaster and after disaster takes place. Authorities at all levels as well many businesses create some sort of preventive measures and plans to reduce the disaster effects and return to normal function as quickly as possible, and from the experience learn how to improve prevention and reaction.

[†] Prof. Da Ruan unexpectedly passed away on 31 of July 2011 after launching this book.

Response to natural disasters (e.g., floods, earthquakes) or technological (e.g., nuclear, chemical) is an extreme complex process that involves severe time pressure, various kind of uncertainties, and many stakeholders. Disaster management often requires several autonomous agencies to collaboratively mitigate, prepare, respond, and recover from heterogeneous and dynamic sets of hazards to Society. Almost all disasters involve high degrees of novelty to deal with most unexpected various uncertainties and dynamic time pressures. Existing studies and approaches within disaster management have mainly been focused on some specific type of disasters with certain agency oriented. There is a lack of a general framework to deal with similarities and synergies among different disasters by taking their specific features into account.

This book provides with various decision analysis theories and support tools in complex systems in general and in disaster management in particular. The book is also generated during a long-term preparation of a European proposal among most leading experts in the areas related to the book title.

After a general call among specialists and a standard peer review process, we sincerely hope that this book becomes a reference in the field since it addresses not only a state-of-the-art first section and third section devoted to original application oriented advances, but also a second section that offers alternative approaches to deal with the different kinds of uncertainties that appear in disaster management and emergencies.

This book starts with an introduction to the important role of information on disaster management and emergencies by A. Pedraza. In this introduction, some main challenges in humanitarian logistics are described. Among other key issues, the author points out the collaboration needed between different parties collaborating in disaster response and the need of incorporating dynamic forecast of disasters in decision aid models. Three specific examples involving the use of information in humanitarian operations are discussed more in detail, involving techniques from operations research, operations management, and management science.

The first section of this book, devoted to an overview of the state-of-the-art, contains four papers. In the first paper, M.T. Ortuño *et al.* state main definitions concerning disasters, emergencies and humanitarian logistics, and focus the review on decision aid models and systems developed until now in the area. In the second paper, F. Liberatore *et al.* offer a general overview of the different problems that become a source for uncertainty in humanitarian logistics in the context of disaster management, as well as the main techniques used until now (risk mappings, probability, stochastic programming, optimization, simulation and fuzzy models), offering a brief description of main references. In the third paper, B. Öztaysi *et al.* focus on Fuzzy Inference Systems and their applications for disaster management, showing an example in order to allow a quick and flexible solution for spontaneous volunteer management. In the fourth paper of this section, D. Tang *et al.* present a literature review in security based operations, focussing in current and expected future research in container line supply chains divided into three categories (general regulations, specific security issues and risk analysis tools).

The second section presents four different alternatives to deal with uncertainties in disaster management and emergencies. In the first paper of this section, L. Zou *et al.* present two approaches for fuzzy risk analysis in order to handle both comparable and incomparable linguistic information by means of information aggregation techniques and taking into account 10 linguistic evaluation values. In a second paper, J. Liu *et al.* offer a belief rule-based generic risk assessment framework for modelling, analyzing and synthesizing risk-related information with various uncertainties, where risk factors are described using linguistic variables in order to capture uncertain casual relationship between the risk factors and the special risk estimate. In a third paper, M.A. Abchir *et al.* stresses again that report and descriptions of the disaster that will support emergency management in their first stages are usually expressed linguistically by witnesses, so the authors offer a procedure to help to express diagnosis of the catastrophic event based upon such a natural language. In the fourth paper, in order to deal the lack of information of decision makers, H. Bustince *et al.* present a new method to amalgamate the opinions of several experts based upon interval-valued information.

Finally, last section in devoted to applications, containing this time five papers. Since a precise numerical evaluation of a potential disaster is unrealistic, the first paper by J.T. Rodríguez *et al.* reformulates this problem as a severity classification procedure, offering a bipolar classification methodology based upon the notions of semantic antagonism and dissimilarity structure. In a second paper, the problem of transhipment multi-commodity supply chain flow for humanitarian relief operations is addressed by A. Clark *et al.*, offering a model to assist policy makers and planners to design an effective supply chain so that goods and service can reach those in need as quickly as possible, a model validated with real life data from the South Asian Earthquake of October 2005. In the third paper of this section, M. Leon *et al.* take advantage of Fuzzy Cognitive Maps to represent the behaviour and operations of transport managing, showing how travellers base their decisions on their perception of available information. A hierarchical assessment framework for evaluating safety against fire and explosion hazards in container line supply chains is presented by Y.W. Chen *et al.*, following a Evidential Reasoning approach which is tested data collected from the Port of Liverpool. Finally, M. Naderpour *et al.* develop a Human Situation Awareness Support System which has the ability to support the operators' understanding and assessing the disaster, and by applying fuzzy risk assessment concepts allow a better inference of the real situation and project its status in the near future.

We have to finish this preface acknowledging the key role that our missed friend Da Ruan played in the conception of this book. In fact, the idea of this book emerged while he was spending two months as Distinguished Visitor at Complutense of Madrid, invited by B. Vitoriano within a program that pretends to bring to this University extremely qualified researchers with leadership to launch new projects. Da Ruan perfectly fitted this description, and devoted a long time discussing with us ideas about common fields of interest. This book is one of the projects we discussed, launched while he was still in Madrid, focussed on researchers and practitioners demanding new approaches, particularly those coming from Non Governmental Organizations. Along his short life, Da showed a tremendous capability to launch new projects, putting together people from many different fields, either at the academy or at the industry. Da was a taught worker, a kind person and a friend we could always count on. We miss him.

We deeply appreciate the support of members of Spanish Red Cross, Action Against Hungry and other Non Governmental Organizations that have been collaborating with us. We hope that this book will be helpful for their objectives and bring more researchers into this complex and multi facet field by means of a book that intends to become a reference text for research and practice within disaster management and emergencies.

Contents

Chapter 1

Introduction

On the Use of Information in Humanitarian Operations

Alfonso J. Pedraza-Martinez

Department of Operations and Decision Technologies, Kelley School of Business, Indiana University, 1309 E. 10th Street, Bloomington IN 47405, USA

E-mail: alpedraz@indiana.edu

1.1 Introduction

Obtaining reliable information for decision-making to prepare and respond to disasters is difficult. Governments and humanitarian organizations often have to plan complex disaster responses based on forecasts or without having reliable field assessments. Decision aid models can help governments and humanitarian organizations by improving their forecasts during disaster preparedness and by facilitating data collection during field assessments in disaster response. Decision aid models can also facilitate collaboration and coordination between different parties involved in disaster management. This book is an academic study of decision aid models for disaster management.

The interest of academics in disaster management and humanitarian logistics has increased significantly over the last decade. This is related to the fact that many of the challenges humanitarian systems face during disaster response are related to operations research, operations management and management science. For example, disaster management deals with scarce resources. This is because the impact of disasters on human life seems to be increasing at a higher rate than the resources dedicated to disaster preparedness and response. Also, high levels of uncertainty following disasters impose additional pressure on the use of available resources. The complex challenges of disaster management have motivated prominent academic institutions like Universidad Complutense in Spain,

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INSEAD in France and Cranfield in England as well as Tufts University, Georgia Tech and Rensselaer Polytechnic Institute in the United States, to create research groups aimed at improving the capacity of humanitarian systems for disaster management.

Academic journals and societies have also exhibited increased interest to topics of disaster management and humanitarian logistics. Journals like the *European Journal of Operational Research* and *OR Spectrum* have dedicated special issues to the topic. In addition, The *Journal of Humanitarian Logistics and Supply Chain Management* published its first issue in 2011. The journal is *targeted to academics and practitioners in humanitarian, public and private sector organizations working on all aspects of humanitarian logistics and supply chain management* (emeraldinsight.com). The remarkable increase of academic production in humanitarian operations makes literature reviews like the ones included in the first part of this book timely.

Additionally, the Production and Operations Management Society (POMS) founded the College of Humanitarian Operations and Crisis Management (HOCM) in 2011. The establishment of the HOCM College at POMS was followed by a call for papers for a special issue on humanitarian operations in *Production and Operations Management*, still under review when this article was written. Another important milestone of the HOCM College was its first mini-conference, held in Chicago, USA in April 2012.

Plenary sessions at the HOCM mini-conference included high-level practitioners and academics. Dr. Louis Uccellini, the President of the National Centers of Environmental Prediction of the United States – and president of the American Meteorological society –, spoke about the evolution of weather forecast and how accurate information on weather prediction helps reducing disaster uncertainty. Professor Peter Walker, the president of the International Humanitarian Studies Association, and Professor Luk Van Wassenhove, President of POMS and INSEAD Humanitarian Research Group, also commented on the value of information and pointed out that there is a need for inter-sector collaboration and interdisciplinary research in the area of disaster management. We elaborate on the needs identified by the HOCM mini-conference and discuss various examples involving the use of information in humanitarian operations. The discussion is preceded by a short description of different levels of disaster response used as a framework in the examples.

1.2 Levels of Disaster Response

The disaster management cycle includes at least four stages: preparedness, response, rehabilitation and mitigation [1, 2]. Based on the objectives, uncertainty and duration, the former two stages can be classified as 'relief' operations while the latter two stages can be classified as 'development' operations. Pedraza-Martinez *et al.* [3] discuss that relief and development operations result in different logistics challenges. On the one hand, relief operations focus on life-saving objectives via first aid, evacuation, food and water distribution, and shelter provision, subject to a budget constraint. Relief operations also face high uncertainty regarding supply and demand. Demand uncertainty results from the lack of information regarding the impact of the disaster in the affected population. Supply uncertainty has different sources including: (i) destruction of local inventories and services during the disaster, and (ii) difficulties to access the disaster area due to blockages. Finally, relief operations also have short duration that typically lasts up to three months. The duration of operations can be extended up to six months like the one following the Haiti earthquake in 2010.

On the other hand, development operations usually focus on minimizing a cost function, subject to minimum acceptable service levels to meet demand. Development operations also face demand uncertainty, but this uncertainty is lower than that faced by relief operations. Demand uncertainty may result from the mobility of potential beneficiaries, weather conditions or localized security problems. Development operations may face some supply uncertainty but it is typically negligible when compared to the one faced in relief operations. Supply uncertainty may result from lack of local inventory. Finally, development operations typically have a longer duration, which can range from six months to several years. Despite the differences in terms of objective, uncertainty and duration, relief and development operations often share the same logistics networks. The multi-objective problem resulting from simultaneous relief and development operations is quite challenging for the humanitarian sector [4]. Nevertheless, this problem has not been sufficiently studied by academics.

Disaster response usually occurs on three levels: local, national, and international (Figure 1.1). Local response begins immediately after the disastrous event. Operational staff in charge of the local response system coordinate search and rescue activities [5]. Sometimes international humanitarian organizations have presence in the area of disaster and take part in the local response. For example, *Medecins Sans Frontiers* set up an open-air hospital to treat emergencies the day following the 2010 earthquake in Haiti.

If the magnitude of the disaster overwhelms local capacity then the national system is activated. The national system usually includes donors of cash and basic items like medicines, water, food, and shelter. It also includes logistics and heavy equipment for debris removal. The national system often faces difficulties in delivering supplies in the affected area, which causes a response delay. Depending on the magnitude of the disaster, the national system may not have enough capacity to offer a complete response. In such scenario the national government is responsible for requesting the activation of the international system.

Fig. 1.1 Different Operational Levels of Disaster Response

The international system is composed primarily of donors, international humanitarian organizations and NGO—although in recent operations like the Haiti response in 2010 the military forces of donor countries like the United States have also supported the system. The first issue faced by the international system is access to information regarding the disaster. When international humanitarian organizations have existing programs in the disaster area, they may receive field information within minutes following the event. Otherwise, they must rely on their forecasts, previous experience, the media and other organizations until their own disaster response teams are able to reach the affected area and send information back to the headquarters.

There is a number of coordination challenges within each level of disaster management. Sometimes different parties involved in disaster management have different concerns. Take the example of response operations involving the international level. As mentioned above, these operations include donors and humanitarian organizations. While donors prefer to earmark their funds in order to increase the accountability of their donations, international humanitarian organizations would prefer no-earmarked funds to avoid exogenous constraints—imposed by donors—to the use of resources. The coordination of donors and humanitarian organizations is an interesting problem that has not been investigated sufficiently.

There are also coordination challenges between different levels of disaster response. Different response levels may have distinct opinions while participating in disaster response operations. Take the example of the earthquake in Colombia, in 1999. The immediate response to that disaster occurred at the local level. When the national level got involved it intended to take control of the operation, but the local level was reluctant to give up control to the national level arguing that they—the locals—had been directly affected by the disaster and had better knowledge of the field [5]. Achieving coordination between local and national levels consumed precious time that could have been used by staff to reach the demand of humanitarian aid.

Additionally, there are third parties that do not participate but support disaster response operations. Commercial suppliers and academics collaborate during different stages of the disaster management cycle. Nevertheless, the objectives of these parties may not be aligned with the ones of the parties directly involved in disaster response. For example, humanitarian staff working on disaster response have very tight time constraints and must prioritize different tasks. As expected, they allocate most of their time to life-saving activities and sacrifice less important activities like data collection. While data collection may be secondary to humanitarian staff during disaster response, it is a critical input for decision aid models developed by academics.

In the following sections we discuss three examples on the use of information in humanitarian operations. These examples are presented using the framework introduced above. We focus on examples that involve national and international levels of response instead of those involving local response. The first example is on the National Centers for Environmental Prediction (NCEP) in the United States and their remarkable work on weather forecasting. This example refers to preparedness for disaster response at the national level (Figure 1.2).

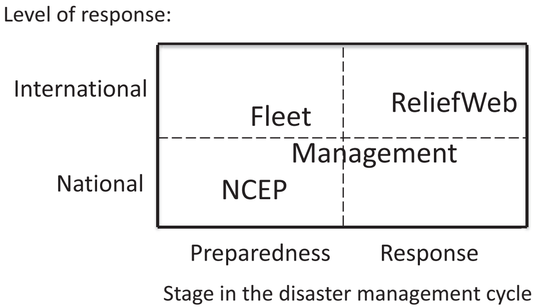

Fig. 1.2 Classification of examples according to level of response and stage in the disaster management cycle

The second example is on collaboration between humanitarian organizations and academics to improve vehicle fleet management in humanitarian operations. This example touches on preparedness at the international level and response at the national level. The third example is on Reliefweb and its role in information dissemination. ReliefWeb is an information-sharing platform primarily used by the international level of disaster response. The ReliefWeb example describes an initiative to improve access to information for disaster response at the international level.

1.3 Disaster Preparedness at the National Level: Centers for Environmental Prediction (NCEP)[1]

Weather related events like floods, storms, cold waves and wildfires counted for 71% of the total number of disasters covered by ReliefWeb in 2010. Fortunately, weather related events can be predicted with enough accuracy to minimize their impact on human life [6]. The National Centers for Environmental Prediction (NCEP) are responsible for forecasting weather related events in the United States. As part of their mission, NCEP "*deliver national and global weather, water, climate and space weather guidance, forecasts, warnings and analyses to its Partners and External User Communities.*" (ncep.noaa.gov). NCEP is composed of 9 centers: Aviation Weather Center (AWC), Climate Prediction Center (CPC), Environmental Modeling Center (EMC), Hydrometeorological Prediction Center (HPC), NCEP Central Operations (NCO), National Hurricane Center (NHC), Ocean Pre-

[1]This example is based on the presentation given by Dr. Louis Uccellini, Director of the National Centers for Environmental Prediction at the first Mini-Conference of the College of Humanitarian Operations and Crisis Management, at the Production and Operations Management Society (POMS), 2012.

diction Center (OPC), Space Weather Prediction Center (SWPC), and Storm Prediction Center (SPC). NCEP produce the majority of the weather related information in the United States.

Weather forecasting is based on four components: Global Observing System, Computers, Data Assimilation & Modeling/Science, and forecasters [7]. The global observing system has evolved substantially during the last few decades. Kistler *et al.* [8] divide the evolution of the global observing system into three phases: (i) *early period*, from the 1940s to 1957, when the first upper-air observations were made and numerical models were introduced; (ii) *modern rawinsonde period*, from 1958 to 1978; (iii) *modern satellite period*, from 1979 to the present, when real time numerical prediction models were introduced. The modern satellite based system allows forecasters to obtain accurate predictions of storms several days in advance. Based on millions of data records, forecasters use mathematical and numerical models to estimate possible duration, trajectories and intensity of weather related events. The improvement in forecast models has positively impacted disaster response in the United States. While in the 1970's accurate forecasts were only available hours before the event, in 2010 accurate forecasts allowed decision-making several days before the potential disaster occurs.

NCEP participate actively in disaster preparedness and response at the national level in the United States. From February 4 to 7, 2010 a major snowstorm affected the west cost of the country. It produced up to 75 cm of snow in some areas of Maryland. From February 9 to 11 the storm was followed by a blizzard, which produced up to 60 cm of snow in northern Maryland. According to Reuters [9] it could have been the worst storm in Washington in 90 years. President Barack Obama named the storm "snowmageddon". NCEP predicted the storm system more than seven days in advance. Accurate warnings were emitted by NCEP three to five days in advance, depending on the geographic area.

As a result of NCEP early alarms, the affected States had time to prepare for the storm. Following NCEP recommendations, these States implemented contingency plans for disaster response. Furthermore, NCEP information helped airlines to decide the cancellation of flights well in advance preventing thousands of passengers from getting stranded at airports. Regarding supply chain management, NCEP weather forecast allowed retailers to preposition inventory to face the potential disruption. This was particularly important because the storm coincided with the "Super Bowl", the American football match to be played on Sunday, February 7, 2010. Retailers knew several days in advance that they had to advertise "pre-storm" sales because mobility problems could deter consumers from purchasing during the day of the football match. Due to the joint action of NCEP and State governments, 2010 snowmageddon did not have a major impact on human lives, travel or gross national product, as opposed to other major snowstorms during the nineties [7].

NCEP do a remarkable job on predicting weather related events. This example shows how the reliable and accurate early warnings produced by NCEP helped to prevent a major disaster. Incorporating early warnings and forecasts into decision aid models is an interesting research area that has not received enough attention from operations research, operations management and management science academic communities. Although Ragnier [6] analyzed the impact of accurate disaster forecasts on evacuation decisions, the effect of improving forecasts on areas of research like facility location, inventory management, and transportation has not been widely explored yet.

1.4 Disaster Preparedness and Response: Fleet Management in the Humanitarian Sector

Fleet management in humanitarian operations is a complex set of tasks that involves multiple parties at local, national, and international levels. Four-wheel drive (4DW) vehicles are at the core of humanitarian fleets. Although it would be difficult to determine the exact figure due to problems in data collection, Fleet Forum[2] has estimated that the international fleet of 4WD vehicles has approximately 80,000 units. These vehicles are used to support the transportation needs of humanitarian staff in disaster response, rehabilitation and mitigation [10].

For almost 10 years Fleet Forum work has focused on developing solutions to fleet management problems regarding efficiency, safety and environmental impact in the humanitarian sector. In 2007 several Fleet Forum members agreed that some of the symptoms of their problems were excessive fleet sizes, ageing fleets, lack of fleet standardization, delays in disaster response and accidents. These organizations invited INSEAD Humanitarian Research Group (HRG) to join them to collaborate in the search for solutions[3]. In 2007 HRG began a long-term project with the aim of understanding how international humanitarian organizations manage their vehicle fleets in field operations.

Due to the lack of academic references in the area of humanitarian fleet management, the research design was built upon exploratory case studies. These cases included World

[2]Fleet Forum is an organization of more than forty members, including NGOs, international organizations, the UN, academic institutions, donors, and corporate partners (fleetforum.org, Tomasini *et al.* 2006) [11],

[3]Professor Luk Van Wassenhove created HRG in 2001 as a platform for cross-disciplinary research and engagement in humanitarian logistics

Vision International (WVI), World Food Programme (WFP), International Federation of Red Cross and Red Crescent Societies (IFRC), and International Committee of the Red Cross (ICRC). Interviews at local, national and international levels where conducted in Africa, the Middle East and Europe with collaboration of the four organizations. Based on the analysis of these interviews the research team proposed a series of hypotheses explaining the main drivers of problems in humanitarian fleet management. These drivers included the simultaneous objectives of disaster response (relief) and rehabilitation and mitigation (development), difficult operating conditions, conflicting objectives at the different levels of disaster response, decentralization, and earmarked funding [10].

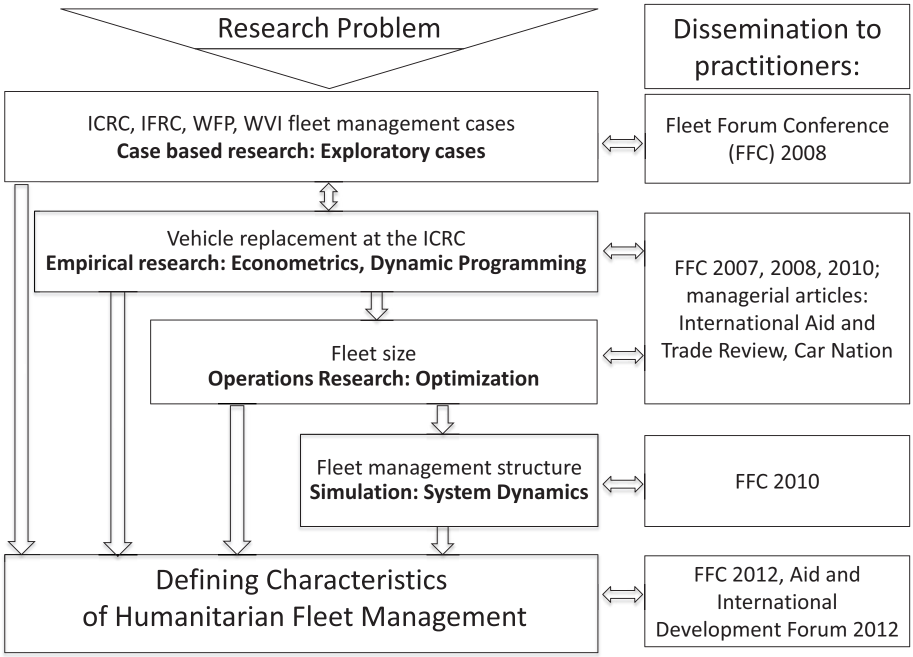

Fig. 1.3 Research Process on Fleet Management in Humanitarian Operations followed by INSEAD Humanitarian Research Group (HRG)

The results of the case-based research were presented at the Fleet Forum Conference in 2008 (Figure 1.3). At the conference humanitarian logisticians provided insightful feedback to the research team. Feedback from practitioners helped the researchers to refine the preliminary findings. Practitioners also agreed to provide more information both qualitative and quantitative to complement the initial findings. Equally important, humanitarian logisticians agreed that the research added value to their job since academics were presenting a synthesis of fleet management challenges and their causes in a format that could be clearly understood.

Parallel to the qualitative case studies, HRG team collected data on vehicle use from ICRC fleet management system, FleetWave, a web-based enterprise fleet management solution used by commercial companies like PaperCo and Coca Cola (chevinfleet.com). The ICRC data was used to test a policy suggested by the ICRC international level to the national delegations in more than 80 countries. The ICRC policy was to replace vehicles every 150,000 km or 5 years, whichever came first. Vehicle manufacturers like Toyota and Nissan recommended this replacement policy to business using their products. Nevertheless, ICRC had some special operating characteristics: difficult operating conditions and vehicle purchasing discounts due to its humanitarian orientation. Using econometrics models and dynamic programming, the research found that the optimal policy for the ICRC would be to replace their vehicles every 100,000 km or its equivalent in age [12]. Difficult operating conditions resulted in a relatively greater maintenance cost compared to commercial fleets while purchasing discounts resulted in a lower cost of capital per vehicle.

The same research found that ICRC national delegations did not follow the 150,000 km or 5 years policy. This was explained by a misalignment of incentives between international headquarters and national delegations caused by earmarked funding for vehicle procurement. The analysis on vehicle replacement was complemented with optimization models to determine the optimal fleet size to support the transportation needs of programs for rehabilitation and mitigation in cases of demand uncertainty. The results of quantitative research boosted the interest of humanitarian logisticians in collecting and analyzing data for decision-making purposes.

Next, the fleet management descriptions from case studies were combined with the quantitative data on vehicle use from ICRC in a simulation-based research. The purpose was to obtain further insights on decentralization and the effect of earmarked funding on humanitarian fleet management. The research found that when decentralization and earmarked funding are present simultaneously humanitarian organizations using national vehicle procurement might take longer to react to small and medium size disasters than those using global procurement with long lead-times [4]. This is explained by the fact that earmarked funding creates resource allocation constraints that deter the deployment of the fleet in a timely fashion.

Humanitarian logisticians have realized that there is value in carefully collecting operational data regarding the use of their fleets. They have also seen that better decisions can be made when data is rigorously transformed in information. Due to their increasing interest in gathering information regarding their fleets, some senior humanitarian logisticians started pilot projects to install satellite-tracking technologies in their fleets. These technologies will allow logisticians to collect data on vehicle use in real time and react faster to disruptions in transportation following disasters. Additionally, this data will facilitate more sophisticated analyses on fleet management using optimization techniques.

1.5 Disaster Response at the International Level: ReliefWeb

Created in 1996 by the UN Office for the Coordination of Humanitarian Affairs (OCHA), ReliefWeb aims "*to be the world's leading on-line gateway to information on humanitarian emergencies and disasters*" [13]. ReliefWeb was part of a humanitarian sector initiative in the early 1990s to improve the dissemination of information for decision-making in the humanitarian sector. Another initiative that aimed the same objective was the United Nations Joint Logistics Centre (UNJLC) Website [14, 15]. While the UNJLC Website specialized to become the logistics cluster website, ReliefWeb consolidated as a web platform offering multiple services beyond logistics to the humanitarian community.

Originally ReliefWeb had offices in Kobe, Geneva and New York to update content in real time. Regarding cost, ReliefWeb's total budget in 1999 was $1.14 million while in 2005 the budget was $2 million, supported entirely by donations. In 2011 the offices in Kobe and Geneva were moved to the humanitarian hubs of Bangkok and Nairobi, which allowed them to lower the operating cost without sacrificing the 24-hours a day coverage. Every day the globally located ReliefWeb team contacts different sources of information and searches the web to identify the most relevant humanitarian news, reports, maps, analysis and other content [16]. These documents are filtered to avoid duplication and posted on the website. ReliefWeb services include posting vacancies, reports, emergency updates, and a map center. Regarding emergency updates, ReliefWeb covered 182 disasters in 2011, and covered 157 disasters in 2010 (Table 1.1). In 2011 the site received 9.3 million unique visits [16], and published over 55,000 posts including documents, vacancies and maps. Not surprisingly, the traffic of the website peaks in the aftermath of disasters. Following the Asian tsunami in 2004 ReliefWeb received an average of 3 million hits per day.

Table 1.1 ReliefWeb coverage by disaster type 2008-2010.*

New disasters by type	**2008**	**2009**	**2010**
Flood	47	85	72
Storm*	33	30	29
Earthquake	13	21	17
Landslide & mudslide	11	16	11
Cold Wave	3	6	6
Epidemic	0	9	6
Volcano	6	6	6
Wildfire	0	0	5
Other	11	20	5
Total	**124**	**193**	**157**

* Storm includes local storm, tropical cyclone, hurricane and storm surge.
Source: ReliefWeb Annual Statistics [17–19].

ReliefWeb has global reach consisting of visits from Europe (29%), Africa (23.7%), North America (19.4%) and Asia (18.3%). Geographic regions with lower percentages of visits are Latin America and Oceania. The top five countries in number of visits during 2010 were: USA, UK, Kenya, Canada, and France. One of the main criticisms leveled at ReliefWeb following an evaluation carried out in 2005 was the lack of access to the local level of response [12], which was partially due to language problems. One of the suggestions from users was to include content in other languages than English. In June 2012 content was available in English (399,799 posts), French (36,803 posts), Spanish (21,363 posts), and Arabic (113 posts).

The sources of postings have evolved in the last few years. In 2005 the top five sources were media outlets: Agence Fance-Presse, Integrated Regional Information Networks, Reuters, Xinhua, and UN News Service. In 2011 the top five sources were: Agence France-Pressse, Integrated Regional Information Networks, OCHA, Reuters, and the International Federation of Red Cross and Red Crescent Societies (IFRC). The evolution of the top-five source composition suggests that ReliefWeb has earned a high degree of trust from humanitarian organizations as a platform for information sharing.

During the first month of the Haiti response in 2010 ReliefWeb posted daily situation reports from organizations such as OCHA and IFRC. The first OCHA report was posted on the day of the earthquake. The report included contact details of ReliefWeb regarding donations: "*All humanitarian partners including donors and recipient agencies are encouraged* *to inform FTS of cash and in-kind contributions by sending an email to: fts@reliefweb.int*." The OCHA report also directed readers to ReliefWeb in order to get more information about the disaster.

The example of ReliefWeb shows an effort to disseminate information in the aftermath of disasters. ReliefWeb collects, filters, and publishes information related to disaster response even the same day that disasters occur. That information is public and can be easily accessed through their website. Nevertheless, ReliefWeb usually does not provide further analysis to support decision-making. It would be very interesting to see alliances between information-sharing platforms like ReliefWeb and academic researchers to incorporate real time analysis based on decision aid models in web reports.

1.6 Conclusions and Suggested Areas for Future Research

This introduction discusses three examples of information on disaster management. In doing so, it has also mentions some interesting research challenges in the areas of operations research, operations management, and management science. First, it mentions the humanitarian logistics challenges resulting from simultaneous relief and development operations. Second, it elaborates on the practical problem of conflicting objectives between different parties collaborating in disaster response. Third, it comments on the need for coordination between donors and international humanitarian organizations. Fourth, it discusses the need of incorporating dynamic forecast of disasters in decision aid models. Fifth, it comments on the possibility of producing real time analysis based on available information using decision aid models. The topics mentioned in this introduction are only some potentially interesting areas for further research.

The use of information and decision aid models to support disaster management is a relevant research area. This book provides new insights on the use of information as well valuable decision aid models to support disaster preparedness and response. The book comes at a crucial moment considering the growing body of research in disaster management and humanitarian logistics in the past few years. Apart from the literature surveys included in the first part of the book, the second part presents a selection of decision aid models with uncertainty. The third part of the book includes additional applications in disaster management and emergencies.

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Chapter 2

Decision Aid Models and Systems for Humanitarian Logistics. A Survey

M.T. Ortuño[1,*], P. Cristóbal[2], J.M. Ferrer[1], F.J. Martín-Campo[1], S. Muñoz[1], G. Tirado[1], B. Vitoriano[1]

[1] *Dpto. de Estadística e Investigación Operativa, Universidad Complutense de Madrid, Spain*

[2] *Dpto. de Matemática Aplicada a los Recursos Naturales, Universidad Politécnica de Madrid, Spain*

The number and impact of disasters seems to be increasing in the last decades, and their consequences have to be managed in the best possible way. This paper introduces the main concepts used in emergency and disaster management, and presents a literature review on the decision aid models and systems applied to humanitarian logistics in this context.

2.1 Introduction

The number and impact of disasters seems to be increasing in the last decades, and their consequences have to be managed in the best possible way. Recent years have seen an explosion of literature regarding disaster and emergency management, as it is a topic of high relevance in today's world. Among this literature, there is an increasing amount of research regarding mathematical models and systems which can help in the decision aid processes developed when trying to respond to the consequences of a disaster. In this introductory section the main definitions concerning disasters, emergencies and humanitarian logistics are stated, which will allow to classify the research into the main phases of disaster management.

*Contact e-mail: tortuno@mat.ucm.es

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2.1.1 *Hazards and disasters*

A **hazard** is a threatening event or probability of occurrence of a potentially damaging phenomenon within a given time period and area. It can be both natural or human-made.

- Natural: naturally occurring physical phenomena caused either by rapid or slow onset events which can be geophysical, hydrological, climatological, meteorological or biological (earthquakes, landslides, tsunamis, volcanic activity, avalanches, floods, extreme temperatures, droughts, wildfires, cyclones, storm/wave surges, disease epidemics, animal plagues, etc.).
- Human-made or technological: events caused by humans and which occur in (or close to) human settlements, such as complex emergencies/conflicts, famine, displaced populations, industrial accidents (toxic dumps or radioactive escapes), catastrophic transport accidents, etc.

An **emergency** is a situation that poses an immediate risk to health, life, property or environment.

A **disaster** is the disruption of the normal functioning of a system or community, which causes a strong impact on people, structures and environment, and goes beyond the local capacity of response. Sometimes, to declare or not an emergency as a disaster is a political decision, because it has consequences for the involvement of third parties in the intervention or for insurance, for example.

Catastrophe is another term used in disaster management. There is also a discussion in the literature about the difference between disaster and catastrophe. Usually a catastrophe is considered an extremely large-scale disaster. As stated in Quarantelli [74], *just as "disasters" are qualitatively different from everyday community emergencies, so are "catastrophes" a qualitative jump over "disasters"*. This qualitative jump is reflected in several characteristics and results in important differences in the logistics of the intervention, as discussed in what follows.

2.1.2 *Disaster management and humanitarian logistics*

Disaster response is a complex process that involves severe time pressure, high uncertainty and many stakeholders. It also involves several autonomous agencies to collaboratively mitigate, prepare, respond, and recover from heterogeneous and dynamic sets of hazards to society.

The agents involved differ depending on the type of disaster (civil protection and local security agencies usually manage technological disasters, while natural disasters normally involve also NGOs and international agencies), the disaster consequences and the place where it strikes, due to vulnerability.

The agents involved in disaster response can be classified into three levels, as involvement in the operations depends on the consequences:

- Local level: the first response level, usually addressed by local agencies, civil society organizations and civil protection. Typically, this level of emergency is not declared as a disaster.
- National level: the army and national civil protection, governmental organizations and NGOs are usually involved when an emergency is defined as a disaster. Sometimes, international organizations with local offices also participate at this level.
- International level: foreign governments and inter-governmental organizations, international NGOs for disaster response and the United Nations Agencies. Coordination at this level is a crucial matter, usually performed by OCHA (Office for the Coordination of Humanitarian Affairs) of United Nations, and the IASC (Inter-Agency Standing Committee), primary mechanism for inter-agency coordination, including key UN and non-UN humanitarian partners. This level is reached when national capacity of response is not enough (due to the scale of the disaster and/or the vulnerability of the country) and the national government authorizes an international humanitarian operation.

The decision making processes in disaster management are thus extremely difficult, due to the multiple actors (decision-makers) which are involved, and the complexity of the tasks addressed. Among those tasks, all the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements and alleviate the suffering of vulnerable people is called **humanitarian logistics**, as defined in the Humanitarian Logistics Conference, 2004 (Fritz Institute).

Based on this definition, humanitarian logistics also appears in contexts different from disaster management; the World Food Programme (WFP) and the World Health Organization (WHO), for instance, develop many operations which can be considered humanitarian logistics without being a response to a specific disaster. However, it is in disaster management where the application of humanitarian logistics is more complex and difficult and where more differences with business logistics appear. Therefore, our review is restricted to this context. The main issues that differentiate humanitarian supply chains in the context of disaster management from business supply chains are the following:

- Unpredictable demand in terms of timing, geographic location, type and quantity of commodity.
- Short lead time and suddenness of demand for large amounts of a wide variety of products and services.
- Lack of initial resources in terms of supply, human resources, technology, capacity and funding (see Balcik and Beamon [9]).
- Presence of multiple decision makers that can be sometimes difficult to identify.

2.1.3 *Phases, tasks and decisions of the disaster management cycle*

In the decision making processes needed in humanitarian logistics for disaster management, the context and the nature of the decisions to be made change over time as we move from before to after the disaster event. Deciding about preventive actions to mitigate the effects of a possible future earthquake is not the same as deciding about the precise actions to undertake just after it strikes, or a month later. The context-related uncertainties and time pressure may vary a lot from one situation to the other, as well as the nature of the decisions and the criteria of the involved actors. This has led to distinguishing four successive phases in the management of emergencies and disasters according to the main nature of the tasks to be performed and their temporal location with respect to the disaster event:

- Mitigation: all the middle and long-term actions and decisions aimed to prevent and mitigate the consequences of a future disaster, as long as it is not (known to be) imminent. Typical tasks of this phase are the identification of risk groups and vulnerability patterns and their treatment, or the development of prediction systems and emergency plans and the allocation of resources for them.
- Preparedness: all the short-term interventions once the available prediction systems have raised an alarm of an upcoming adverse phenomenon until it finally strikes. This includes setting off the emergency systems and evacuation plans, the real-time tracking of the hazard, the analysis of the most probable scenarios, the reinforcement of critical infrastructures, etc. This phase also includes some long-term decisions such as inventory prepositioning and network design.

- Response: this phase is focused on saving lives and it is characterized by a short duration with high emergency and high uncertainty. It is usually divided into a first response phase, devoted to the rescue and urgent medical assistance of injured and affected people (depending on the disaster scenario, it may last around one week from the moment of the disaster event), and a middle-term response phase, devoted to estimate and mitigate the potentially unattended first needs of the affected population as a result of possible damage to life-line infrastructures and resources (shelter, ordinary medical assistance, water and food supply, etc.). This middle-term stage usually involves the delivery of aid from outside of the affected zone and can last for weeks or even months from the moment of the disaster, depending on its nature and magnitude as well as on the economic and development circumstances of the affected country.
- Recovery: this phase is focused on achieving efficiency and it is characterized by its long duration with low emergency and low uncertainty. It refers to all the long-term actions and decisions aimed to recuperate the normal functioning of the affected community and the reconstruction of the social fabric, including life-line resources, services and infrastructure, and the necessary improvements in order not to repeat the specific vulnerabilities shown by the affected groups and places. Sometimes, after certain disasters, a periodic flow of humanitarian aid will be needed to support particularly vulnerable people, which is outside the scope of disaster management.

Though this division in phases is clear and well-founded from a temporal and conceptual point of view, it is important to remark that the process of disaster management has to be understood as a whole, where phases are not independent of each other despite their different focus. In this way, the preparedness phase relies critically on the prediction systems set up in the mitigation phase and the urgent decision-making of the former phase would be impossible without the previous vulnerability analysis and emergency plans developed in the latter phase. Similarly, the allocation of resources for first response operations must be taken into account when designing the mitigation policy. Besides, the middle-term response stage cannot be successful if it does not enable an adequate recovery process. In this sense the delivery of external aid has to be carefully examined and carried out in order not to destroy the local economy. Furthermore, notice that the recovery and mitigation tasks partially overlap, in such a way that once an affected community has reached a new equilibrium, it has to re-evaluate the possible occurrence of future disasters and thus a new mitigation stage follows the recovery phase. Thus, the disaster management process is a non-stop cycle (see Fig. 2.1, as in Tomasini and van Wassenhove [87]), in which each phase is based on the previous ones, clearly showing the interdependence between all of them.

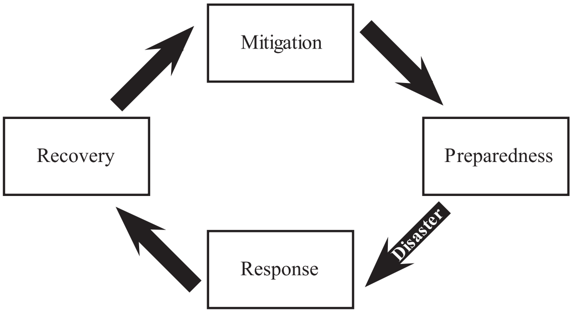

Fig. 2.1 Phases of the disaster management cycle

Some other factors appear that must be considered in all phases of the disaster management cycle. A key factor in humanitarian logistics is the management of funding and donations. Donations are usually classified into two groups: earmarked donations, given by donors to be used in specific operations, and non-earmarked donations, that have no constraints of use. The management of both kinds of donations is crucial to achieve efficiency, and thus it is important to take them into account when making decisions.

In order to help in the decision making processes arising in each of the interrelated previous phases, different mathematical models can be developed. In Altay and Green [4], the literature in Operations Research models for disaster operations management up to 2005 is reviewed. In this work we present an up-to-date review of the Operations Research literature, which is completed with a review on the decision aid systems already in use by different organizations.

The paper is organized as follows. In Section 2.2 the literature on decision aid models is reviewed, classifying the bibliography according to the type of problem, the disaster management phase and the solution technique. Section 2.3 introduces the decision aid systems most commonly used in practice, describing their main functionalities and providing related references. Finally in Section 2.4 some conclusions are drawn.

2.2 Decision Aid Models. Literature Review

This section is a humanitarian logistics literature review focused on papers presenting mathematical models. They will first be classified according to the disaster management phase considered and afterwards according to the type of problem approached. A special subsection will be devoted to donations and funding. At the end of the section a brief classification according to the solution technique used to solve the proposed models is also provided.

We will restrict the review mostly to deterministic solution techniques, because, even though uncertainty is a key factor in humanitarian logistics, the treatment of this uncertainty in the literature is presented in a different chapter of this book.

2.2.1 *Pre-disaster actions: mitigation and preparedness*

In this section, the bibliography concerning mitigation and preparedness has been classified into the following six groups, according to the main problem tackled: assessment, facility location, supply chain design, distribution planning, evacuation, and inventory planning.

Assessment

- Tovia [88] builds a simulation model for emergency response to be used by offices of emergency preparedness. It is conceived to evaluate response capabilities and assess the logistics resources required to evacuate, shelter and protect the population, in a timely fashion in the event of a hurricane.
- Zobel and Khansa [100] present a multi-criteria approach providing a quantitative measure of resilience in the presence of multiple related disaster events, in order to be able to compare several configurations and to assess their relative returns and risks for effective emergency management.
- Kung *et al.* [49] make use of multiple linear regression, multivariate analysis, back-propagation networks and simulation for designing a real-time mobile system to predict and assess the occurrence of debris flows.
- Uchida [91] develops a simulation model for clarifying how disaster warning issuance conditions affect “cry wolf syndrome” in the case of landslides caused by heavy rainfall.

Facility location

- Akkihal [3] considers a battery of mixed-integer linear programs for locating warehouses for non-consumable inventories required for the initial deployment of aid after a disaster occurrence.
- Doerner *et al.* [32] provide a multi-criteria programming model for locating public facilities as schools in areas close to the coast, taking into account risks of inundation by tsunamis. It performs a comparison between two solution approaches: a genetic algorithm and a decomposition technique.
- Eiselt and Marianov [33] propose a 0-1 linear programming model for locating or strengthening cell phone towers in order to maximize service coverage and minimize the loss of communications in case a natural disaster occurs.

Supply chain design

- Hale and Moberg [38] consider a set cover location model for establishing an efficient network of secure storage facilities that can effectively support multiple supply chain facilities.
- Van Wassenhove [93] shows the complexities of managing supply chains in humanitarian settings and outlines strategies for better preparedness.
- Nagurney *et al.* [62] state a variational inequality problem for designing a supply chain network for critical needs, minimizing the total cost and considering demand uncertainty.

Distribution planning

- Nolz *et al.* [66] provide a multi-criteria metaheuristic based on evolutionary concepts for planning water distribution tours in disaster relief, determining the physical location of water tanks and selecting roads to be used for the transportation of drinking water.
- Rottkemper *et al.* [76] propose a bi-objective mixed-integer programming model for integrated relocation and distribution planning of relief items to the affected regions in the aftermath of a disaster.

Evacuation

- Saadatseresht *et al.* [77] propose a three-step approach based on the use of multi-criteria evolutionary algorithms and on a geographical information system to determine the distribution of evacuees into safe areas in an emergency situation.
- Bretschneider and Kimms [16] present a two-stage heuristic approach for a pattern-based mixed integer dynamic network flow model to restructure the traffic routing for evacuating an urban area affected by a disaster.

Inventory planning

- Lodree and Taskin [53] introduce some variants in the classic newsvendor model in order to deal with demand uncertainty in an emergency response inventory planning problem that is relevant to manufacturing, service, not-for-profit, and government organizations that provide supplies, equipment, and manpower to support disaster relief operations.
- Qin *et al.* [73] propose an inter-temporal integrated single-period inventory model to determine the optimal order quantity of emergency resources in a flood incident. It also describes a genetic algorithm based simulation approach.

2.2.2 *Disaster response*

Most of the papers dealing with the disaster response phase are related to the distribution of humanitarian aid, in a global or a local context, the evacuation of people affected by a disaster or the location of support centers. In this section, the bibliography is classified into the following four groups, according to the main problem tackled: last mile distribution, evacuation, large scale distribution, and other problems.

Last mile distribution

- Tzeng *et al.* [90] use fuzzy multi-objective linear programming technics to approach a multi-period aid distribution problem minimizing total cost and total travel time and maximizing minimal satisfaction during the planning period.
- Balcik and Beamon [9] consider a two-phase multi-period planning model for relief distribution. In the first phase, the possible routes for vehicles within the time horizon are generated. In the second phase, the optimal routes and the amount of supplies to

be transported are selected for the coming periods by solving the underlying integer programming problem.

- Campbell *et al.* [18] introduce and analyze two alternative objective functions for the traveling salesman problem and the vehicle routing problem, considering arrival times to destinations, in order to suit the humanitarian nature of the distribution. The new problems are solved with an insertion and local search based heuristic approach.
- Gibbons and Samaddar [37] develop a simulation model for a problem of distribution of vaccines in a pandemic situation and in a context of strong randomness.
- Blecken *et al.* [15] apply both exact and heuristic techniques to deal with a warehouse provision and relief aid flow problem minimizing total cost.
- Nolz *et al.* [65] present a hybrid solution approach based on genetic algorithms, variable neighborhood search and path relinking to tackle a multi-criteria problem of water distribution to the population affected by a catastrophe.
- Vitoriano *et al.* [96] propose a multi-criteria double-flow model to address the problem of distribution of goods to the affected population of a disaster. Criteria such as cost, time of response, distribution equity, security and reliability are considered jointly using a goal programming approach. Some preliminary results are also presented in Vitoriano *et al.* [95] and Ortuño *et al.* [70].
- Berkoune *et al.* [13] develop a genetic algorithm for solving a multi-commodity and multi-depot routing problem which aims to minimize the total duration of all trips.
- Huang *et al.* [42] propose three objective functions for a routing problem concerning cost, speed and equity of the delivery. The three resulting problems are solved with different GRASP based metaheuristics and the objective function values are compared.

Evacuation

- Kongsomsaksaku *et al.* [48] provide a flood evacuation planning model in two levels: shelter location by the authority and shelter selection and evacuation routing by the evacuees. The bi-level programming problem is solved using a genetic algorithm.
- Chiu and Zheng [26] present an evacuation and support planning model on a transport network for real-time emergency response in no-notice disasters. The linear programming model is solved through the matrix formulation.
- Yi and Özdamar [99] describe an integrated location-distribution-evacuation network flow model for coordinating logistic support operations. The model determines the

number of vehicles, the number of wounded people and the amount of commodities traversing each arc via linear programming. Then, loads are distributed among vehicles by solving a system of linear equations. Yi and Kumar [98] use ant colony optimization to solve this problem, but disregarding facility location issues.

- Jotshi *et al.* [44] propose a simulation model with the support of data fusion for an emergency problem of picking up and delivering patients to hospitals.
- Ben-Tal *et al.* [12] apply robust optimization for a multi-period transportation problem consisting of dynamically assigning emergency response and evacuation traffic flow with time dependent uncertainty on the demands.

Large scale distribution

- Angelis *et al.* [6] consider an integer linear programming model to solve a multi-period weekly planning problem of aircraft routing to delivery food to Angola, in the context of the United Nations World Food Program.
- Sheu [80] presents a dynamic aid plan to be used after an earthquake for several purposes: grouping areas, estimation of affected people at each area, estimation of priorities and distribution of aid. Different mathematical techniques are applied, such as fuzzy clustering and multi-objective dynamic programming.
- Adıvar and Mert [1] propose a fuzzy linear programming model to design a plan for transporting international aid from donor countries to the country in need.
- Charles [22] states a global multilevel facility location and distribution model. This mixed integer programming model includes international suppliers, potential warehouses, affected areas and two types of means of transportation: boats and planes.

Other problems

- Beamon and Kotleba [11] introduce a multi-supplier inventory model with discrete random demands and two types of orders: normal and emergency orders. Beamon and Kotleba [10] develop and test three different inventory management strategies for the previous model that are applied in the context of the emergency situation associated to the civil war in South Sudan.
- Jin and Ekşioğlu [43] present an integer programming model for determining alternative routes after a disaster in a road network. An algorithm is proposed to update the

parameters of the simplified linear program and it is tested using a simulated disaster scenario.

2.2.3 *Disaster recovery*

In this section, the bibliography concerning the recovery stage has been classified into the following seven groups, according to the activities involved: civil infrastructure systems, power system restoration, recovery planning, economic recovery, health care and mental health recovery, urban disaster and housing recovery, and other activities.

Civil infrastructure systems: transportation networks, bridges, etc.

- Karlaftis *et al.* [47] present a methodology for optimally allocating funds for repairing an urban infrastructure transportation network following natural disasters using a three-stage genetic algorithm based approach.
- Permann [72] applies genetic algorithms to the problem of infrastructure networks modeling and analysis in order to determine the optimum assets to restore or protect from attack or other disaster.
- Mehlhorn [60] develop a method for prioritizing highway routes for reconstruction after a natural disaster.
- Natarajarathinam *et al.* [63] review the management of supply chains in times of crisis, including the recovery phase.
- Orabi *et al.* [68] present a model for damaged transportation networks to allocate limited reconstruction resources to competing recovery projects, generating optimal trade-offs between minimizing the reconstruction duration and cost. In Orabi *et al.* [69] the post–disaster recovery efforts of damaged civil infrastructure systems are optimized, minimizing both the performance loss of the damaged transportation network and the reconstruction costs.
- Matisziw *et al.* [56] present a multi-objective model to ensure that network restoration during disaster recovery is prioritized so that system performance is optimized.
- Solano [81] works on preparedness, response, and recovery plans, selecting infrastructures for protection in presence of scarce resources.
- Van Hentenryck *et al.* [92] formalize the specification of the single commodity allocation problem for disaster recovery and introduce a novel multi-stage hybrid-optimization algorithm.

- Maya and Sörensen [57] describe how to allocate scarce resources to repair a rural road network after it has been damaged by a natural or man-made disaster.
- Mehlhorn *et al.* [59] present a plan for bridges' repair to restore a highway network that allows accessibility to key facilities in the damaged area.
- Losada *et al.* [54] incorporate the facility recovery time in a model that identifies the optimal allocation of protection resources in an uncapacitated median network to hedge against worst–case facility losses.

Power system restoration

- Crowther and Haimes [30] evaluate risk management options against multiple objectives. This case study calculates an efficient frontier of solutions by integrating a simplified model of the costs of recovery to the power sector derived from open-source data with the Inoperability-Output Model.
- Ang [5] describes a model to plan the recovery of an electrical power transmission grid that has been damaged by a natural disaster or terrorist attack.
- Xu *et al.* [97] determine how to schedule inspection, damage assessment, and repair tasks so as to optimize the post-earthquake restoration of the electric power system.
- Coffrin *et al.* [28] model and solve the power system restoration planning problem for disaster recovery.
- Coffrin *et al.* [29] present a model to decide how to store power system components throughout a populated area to maximize the amount of power served after disaster restoration.

Recovery planning

- Aftanas [2] develops an objective and repeatable process for optimizing the project prioritization phase of the recovery effort.
- Buzna *et al.* [17] consider structures and organization in complex systems. The effectiveness of recovery strategies is studied for a dynamic model of failure spreading in networks.
- Nelson *et al.* [64] build a high level event and role based mobility model for simulating disaster recovery networks.

- Chen *et al.* [23] propose a quantitative measurement to recoverability assessment, and establish a model of recoverability process to minimize the recovery time and optimize the allocation of resources.
- Balasubramanian *et al.* [8] implement an integrated disaster recovery plan based upon a plurality of requirements for an application by receiving a first set of inputs identifying one or more entity types for which the plan is to be formulated.

Economic recovery: small business, private enterprises, insurance, . . .

- Ghesquiere and Mahul [36] discuss the optimal level of sovereign insurance in the case of developing countries.
- Rose [75] examines the consistency of the operational definitions of economic resilience in relation to antecedents from several disciplines, and evaluates the effectiveness of economic resilience to reduce losses from disasters on the basis of recent empirical studies.
- Saleem *et al.* [78] propose a model for pre-disaster preparation and post-disaster business continuity–rapid recovery. The model is used to design and develop a web based prototype of their business continuity information network system facilitating collaboration among local, state, federal agencies and the business community for rapid disaster recovery.
- Luckey [55] presents a literature review from 2001 to 2008, which identifies key stages for consideration when performing information technology disaster recovery planning to ensure business viability if disasters occur.

Health care and mental health recovery

- de Mel *et al.* [31] measure mental health recovery and economic recovery for small business owners affected by the 2004 Indian Ocean tsunami in Sri Lanka.
- Onyango [67] investigates humanitarian responses to complex emergencies.
- Cimellaro *et al.* [27] present a quantitative evaluation of disaster resilience which is implemented for evaluation of health care facilities subject to earthquakes.

Urban disaster and housing recovery

- Jung *et al.* [45] introduce some mathematical models for reconstruction planning in urban areas and design of redevelopment strategies that minimize future risk of flood and maximize net social benefit under spatial and equity constraints.
- Chang [20] presents a framework for assessing empirical patterns of urban disaster recovery through the use of statistical indicators.
- El-Anwar *et al.* [34] study how to quantify and maximize the sustainability of integrated housing recovery efforts after natural disasters.

Other activities

- Miles and Chang [61] present and operationalize a conceptual model of recovery to create a numerical model of recovery which is intended for decision support.
- Fiedrich and Burghardt [35] show how applications of agent technology can be used to support many processes throughout the phases of the disaster management cycle from mitigation and preparation to actual response and recovery.
- Semsch *et al.* [79] develop an approach for increasing the robustness of plans in multiagent disaster, in which interactions between agents' actions and plans may arise due to simultaneous activity of the agents in a shared environment.
- Apte [7] discusses research issues and potential actions in disaster recovery.
- Chib and Komathi [25] implement information communication technologies in recovery operations, drawing attention to vulnerability reducing potential of the initiatives.
- Kaklauskas *et al.* [46] describe the development of a knowledge model for post–disaster management using multiple criteria decision making theory.
- Chao *et al.* [21] analyze the human–computer interaction of remote disaster recovery systems.

2.2.4 *Donations and funding*

Several recent papers have approached the study of the role of donations in humanitarian logistics:

- Besiou *et al.* [14] use system dynamics simulation to present studies supporting the statement that earmarked donations decrease operational efficiency in decentralized humanitarian operations.

- Pedraza Martinez and Van Wassenhove [71] use dynamic programming to find an optimal replacement policy for the International Committee of the Red Cross, showing empirically that earmarked funding affects the implementation of replacement policies in humanitarian contexts, increasing operational cost.
- Toyasaki and Wakolbinger [89] model the strategic interaction between donors and humanitarian organizations in a deterministic setting using game theory.

The importance of donations is a fundamental difference of humanitarian logistics with respect to commercial logistics; however, they have not yet been sufficiently studied by academics and there is a wide field for future research in this context.

2.2.5 *Technique classification*

Now we categorize the bibliography based on the methodology utilized for solving the formulated problems.

- Optimization techniques
  - Mathematical programming: Aftanas [2], Akkihal [3], Ang [5], Angelis *et al.* [6], Balcik and Beamon [9], Ben-Tal *et al.* [12], Blecken *et al.* [15], Bretschneider and Kimms [16], Charles [22], Chen *et al.* [23], Chiu and Zheng [26], Coffrin *et al.* [28], Coffrin *et al.* [29], Doerner *et al.* [32], Eiselt and Marianov [33], Hale and Moberg [38], Jin and Ekşioğlu [43], Jung *et al.* [45], Losada *et al.* [54], Mehlhorn [60], Nagurney *et al.* [62], Pedraza Martinez and Van Wassenhove [71], Rottkemper *et al.* [76], Van Hentenryck *et al.* [92], Xu *et al.* [97], Yi and Özdamar [99].
  - Metaheuristics: Berkoune *et al.* [13], Blecken *et al.* [15], Campbell *et al.* [18], Coffrin *et al.* [28], Huang *et al.* [42], Jung *et al.* [45], Kongsomsaksaku *et al.* [48], Maya and Sörensen [57], Nolz *et al.* [65], Nolz *et al.* [66], Saadatseresht *et al.* [77], Van Hentenryck *et al.* [92], Yi and Kumar [98].
  - Inventory control: Beamon and Kotleba [10], Beamon and Kotleba [11], Lodree and Taskin [53], Qin *et al.* [73].
  - Constraint programming: Coffrin *et al.* [28], Van Hentenryck *et al.* [92].
- Multi-criteria decision making: Aftanas [2], Crowther and Haimes [30], El-Anwar *et al.* [34], Huang *et al.* [42], Jung *et al.* [45], Kaklauskas *et al.* [46], Matisziw *et al.* [56], Nolz *et al.* [65], Orabi *et al.* [68], Orabi *et al.* [69], Ortuño *et al.* [70], Tzeng *et al.* [90], Vitoriano *et al.* [95], Vitoriano *et al.* [96], Zobel and Khansa [100].

- Simulation: Buzna *et al.* [17], Gibbons and Samaddar [37], Jotshi *et al.* [44], Kung *et al.* [49], Miles and Chang [61], Nelson *et al.* [64], Tovia [88], Uchida [91].
- Expert systems and artificial intelligence: Chao *et al.* [21], Fiedrich and Burghardt [35], Karlaftis *et al.* [47], Permann [72], Xu *et al.* [97].
- Probability and statistics: Chang [20], Cimellaro *et al.* [27], Ghesquiere and Mahul [36], Solano [81].
- Fuzzy systems: Adıvar and Mert [1], Sheu [80], Tzeng *et al.* [90].
- Dynamic systems: Besiou *et al.* [14], Buzna *et al.* [17].
- Game theory: Semsch *et al.* [79], Toyasaki and Wakolbinger [89].

2.3 Decision Aid Systems

In the last two decades the development of decision aid systems for humanitarian logistics has grown intensely. The most used systems have focused mainly on inventory control, usually leaving aside the logistics related to the supply transportation and distribution. That is the reason why the systems described below are mainly used in the phases of Preparedness and Response, due to the importance that inventory control and fleet management have in these two phases; however, depending on the particular situation, they could also be helpful in the phases of Recovery and Mitigation.

In the following, some of the most important systems are briefly described.

SUMA and LSS. In 1992, the Pan American Health Organization, together with the Regional Office of the World Health Organization under the support of different countries (principally Holland), developed the Humanitarian Supply Management System (SUMA) [85], being one of the most complete systems able to manage the information and resources when a disaster happens. This system has been used as inventory support for other tasks in employers' organizations. The full system is composed by three modules:

- Suma Central: it is the core of the system and is normally situated in the emergency operations center. The decision makers, situated at this level, collect and define every parameter of the problem such as strategic recovery and delivery places, locations for warehouses, etc.
- Field Unit: its aim is to manage the different operations in the crucial sites such as airports, seaports and places defined in the above level. All the received supplies are separated and classified in order to better tend to the needs of the affected population.

- Stock management: it registers all information concerned with the received and delivered supplies. This module balances the available inventory in a certain warehouse.

Once the strategic parameters have been defined by Suma Central, the supplies must be managed properly. For this goal, Field Unit is used to sort and label the collected supplies in the different reception sites. The classification is divided in three types of items: “Urgent! Immediate Distribution”, “Non-Urgent Distribution”, and, “Non-Priority items”. In a secondary way, the items are separated in different groups: food, medicines, etc., and then the information is sent to Suma Central. Finally, the supplies are inventoried and delivered to other warehouses or distribution hubs, arriving at the affected population under the coordination with the operations center.

As shown above, this system requires a good tool for data transmission among the three modules, which is not always possible in a place that has been affected by a disaster. This system was used up to 2005, when its successor, called Logistics Support System (LSS) [86], was implemented, taking SUMA as a support software. Agencies as PAHO and OCHA, among others, have made the project possible. LSS makes the information exchange among NGOs, donors and affected and contributed countries easier.

Like SUMA, LSS classifies and sorts the received supplies. However, the structure of the system emphasizes the treatment of the supplies being included in a database:

- Entries: the different received supplies that have arrived in a certain local point are registered in the system as well as classified and sorted.
- Deliveries: the supplies shipments are tracked by the system taking into account the initial and destination points as well as the main features of the shipment.
- Pipeline: the expected supplies appear in this module of the system.
- Request: this part of the system manages the information about those places that need specific supplies and is useful for determining how to allocate the required supplies.
- Stock basket: once the supplies have been classified in groups, this system tracks the available stocks for better managing future requirements.
- Importing/exporting: in this part, the system is able to exchange information about the supplies with other strategic places, external systems or agencies.

SUMA has been used since 1995, when it was applied in the Hurricane Louis in Caribbean Islands, and afterwards deployed in other natural disasters such as the Hurricane Mitch that hit Central America in 1998. LSS has been used since 2005, when it was applied in the Tropical Storm Stan in El Salvador. Among many others, it was also deployed in the 2005 and 2007 earthquakes that hit Pakistan and Peru, respectively, and the 2008 volcano eruptions in Ecuador. For more details on SUMA and LSS deployments, see [85, 86]. Many agencies have taken SUMA/LSS as support for humanitarian logistics, such as UN, WHO, WFP, OCHA, UNICEF, UNHCR, PAHO, CTS, Red Cross and many NGOs like ICRC, IFRC, MSF and OXFAM, among others.

HLS and HELIOS. Humanitarian Logistics Software (HLS) [82] is a centralized web based supply chain system that was developed in 2003 by the Fritz Institute in collaboration with the International Federation of the Red Cross (IFRC) and Red Crescent. It was designed basically to track supplies and financing from donation to delivery, increasing transparency of donations, speeding up the relief chain and providing more detailed information to decision makers at headquarters and in the field. The system provides an online overview of the relief pipeline and allows a quick management of resources by using web-based supplier lists and catalogues, making it possible to make orders directly online. HLS was first used in 2004 by IFRC in several relief operations, such as the Morocco earthquake, the South Asia tsunami or the Haiti hurricane. It was also used later in operations such as the 2005 earthquake in Pakistan and the 2006 earthquake and tsunami in Indonesia, among others.

Between 2007 and 2008, HLS was replaced by a more advanced software also developed by the Fritz Institute called HELIOS [83]. It is a specific humanitarian logistics decision support tool that provides organizations with online real-time data to improve supply chain management in humanitarian relief. It consists of five modules:

- The Project Management module administrates the open projects, estimating the main needs and managing requests. This is the main module, coordinating the execution of the others when needed.
- The Request Processing module manages the information concerning issued requests, such as the issuer data, required goods, pickup and delivery locations, etc.
- The Warehouse module deals with the management of stocks and it can be activated when an issue is received or a delivery is performed.
- The Mobilization module is focused on donation management, from cash to in-kind goods and services. It is used by organizations to monitor and report on donations, highly improving the information provided to donors concerning the use of their donations.

- The Procurement module is used to administrate and purchase goods, managing the corresponding quotation requests and executing orders.

The operations to be performed are automated through a web based system in order to improve the coordination between agents, but it could also be functional offline if an internet connection is not available. In 2008, World Vision International and Oxfam GB implemented HELIOS for the first time in two locations each. Later in 2009, Oxfam extended the system to 20 different countries.

SAHANA. It is a disaster management system (see [52]) that was created by the Sri Lankan IT community after the 2004 Indian Ocean earthquake and tsumani. It was conceived as an internet based system to manage disaster relief efforts during the response and recovery phases after the disaster. In fact, the word “Sahana” means “relief” in Sinhalese, one of the national languages of Sri Lanka.

The first owner of the intellectual property of Sahana was the Lanka Software Foundation making Sahana become a global open source software project supported by volunteer contributors and several national authorities. In 2009 a non-profit organization called the Sahana Software Foundation was created to continue with the development of this project, employing experts in disaster management.

Sahana is a web based automated system mainly focused on coordination and planning of humanitarian operations. From the first implementation of 2004 the software has been further improved and at the moment it contains the following tools (see [51] for more details):

- Sahana Vesuvius: led by the US National Library of Medicine, it is focused on disaster preparedness and response needs of the medical community. It is used to assist hospitals, medical facilities and jurisdictions to tie victim records with missing people reports.
- Sahana Mayon: it is a personnel and resource management tool to manage large numbers of resources. It contains disaster scenario, facility and staff management solutions.
- Sahana Eden: it is a flexible tool with several modules that can be used in the different phases of disaster management: mitigation, preparedness, response and recovery. The core modules are the following: Organization Registry (track active organizations to provide opportunities for collaboration and coordination), Project Tracking (organize projects and identify where the greatest needs are), Human Resources (manage volunteers and people involved in the project, keeping a contact list and tracking where they

are and what skills they have), Inventory (manage inventories of items and requests of warehouses, recording and automating transactions for sending and receiving shipments), Assets (manage assets such as vehicles, radio equipment or power generators, tracking their position and condition and ensuring they are used efficiently), Assessments (collect and analyze information from assessments of different organizations through the use of custom reports, graphs and maps), Scenarios & Events (plan for several scenarios according to human resources, facilities, etc.), Mapping (integrated mapping functionality providing situational awareness and supporting standard formats from other sources and GIS, such as natural hazard risks, population or weather) and Shelter Management (track information about shelters and people arriving and departing). All these modules, together with some additional optional ones, can be configured and personalized by the users to adapt them to their particular needs.

Sahana was first deployed by the Center of National Operations (CNO) at the 2005 Sri Lanka tsunami. Since then, it has been used by several organizations to provide relief assistance, such as in the 2005 Kashmir Earthquake of Pakistan (by the National Database & Registration Authority of the Government of Pakistan), the 2006 Yogjakarta Earthquake of Indonesia (by the Indonesian Relief Source) or the 2010 Floods in Venezuela (by the Government of Venezuela). The Sahana Eden tool, recently implemented, was first used for disaster response in the 2010 Haiti Earthquake, being self-deployed by the Sahana Software Foundation, also for the first time. The system has been used in many other relief operations, see [50] for more details.

HFOSS. The project HFOSS [39] is an open source software project that participates in several other smaller projects of different kinds. In particular, in the area of disaster management HFOSS has contributed to the Sahana project, already mentioned, and developed other open source tools for humanitarian relief. One of these tools is Collabbit [41], a web software for information sharing between organizations during emergencies. It has been used, for example, by the Salvation Army Emergency Disaster Services of New York, to coordinate the 2008 Thanksgiving Day Dinner program to feed more than 10,000 people or to monitor cooling centers throughout New York for people seeking refuge from the heat in the summer. Another tool developed by HFOSS is Posit [40], an Android application to be used by rescue workers to map the disaster area with a mobile phone and communicate with a central server and with other workers. It has been used, for example, by the nonprofit organization ACDI/VOCA during food and health service operations in remote rural areas in Haiti, after the 2010 earthquake.

DMIS. The Disaster Management Information System (DMIS) [84] is a web based tool developed by The International Federation of Red Cross allowing access to real time information on disaster trends, available resources and databases, in order to support an efficient disaster preparedness and response. It is only accessible to Red Cross and Red Crescent staff, delegations and Geneva headquarters.

LOGISTIX. In 2006, Doctors without Borders developed an inventory tool for medical needs so called LogistiX [58]. It focuses on medicines inventory and it is used in the normal work of the organization. It is only accesible to Doctors without Borders, and the organization gives some courses in order to teach their volunteers how to use this tool.

It is important to remark that, apart from the systems introduced before, there are also some other systems that are not specifically designed for humanitarian logistics but are also used by NGOs for humanitarian relief. In this group it is worth noting the system so called FleetWave [24], that is a web-based enterprise information system focused on fleet management that has been used, for example, by ICRC, IFRC and WFP.

Note that these systems are mainly focused on information management, making it easier to access data regarding active organizations, human resources and beneficiaries, orders already placed or to be performed, stocks and available material, maps, etc., and improving the communication between agencies and organizations involved. This information is essential to provide decision support and it is very useful in practice, significantly improving the performance of relief operations. However, to the best of our knowledge, the existing systems have not implemented any decision model, such as the ones available in the literature and commented in the previous section, to provide automated detailed inventory or distribution plans as output.

2.4 Conclusions

Recent years have seen an explosion of literature regarding disaster and emergency management. Mathematical models have become an important tool to tackle disaster and emergency humanitarian logistics, helping in the decision aid processes appearing when trying to respond to the consequences. Even though more research is needed to incorporate the additional uncertainties faced in humanitarian logistics and the inherent difficulties due to communication and coordination problems to the models, a lot of work has been done in this direction. The review presented in this work and the chapter devoted to uncertainty in humanitarian logistics for disaster management show the extent of these efforts.

There are in the literature several studies regarding future research lines is the area. Van Wassenhove and Pedraza [94] present an extensive study on Supply Chain Management best practices that are still to be adapted to humanitarian logistics. Caunhye *et al.* [19] present a study on difficulties and future research directions that can guide the development of more accurate models, insisting on the need to develop comprehensive optimization models.

Our purpose in this work has been to link the review on models with the review on decision support systems. From this work, it can be noted that humanitarian logistics research remains highly fragmented. It is not frequent to find models that combine several operations, while in the situations faced by agents many coordinated decisions have to be taken. Moreover, in general, these models are not incorporated into Decision Support Systems which can be used in practise by the involved organizations. The systems already in use are focused on information management, but do not have optimization tools in them. It is our belief that it is necessary to shorten the gap between academics and practitioners in order to be useful to the final decision makers.

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Chapter 3

Uncertainty in Humanitarian Logistics for Disaster Management. A Review

F. Liberatore [1,*], C. Pizarro [1], C. Simón de Blas [1], M.T. Ortuño [2], and B. Vitoriano [2]

[1] *Universidad Rey Juan Carlos, Madrid, Spain*

[2] *Universidad Complutense de Madrid, Madrid, Spain*

Given their nature, disasters are generally characterized by a high level of uncertainty. In fact, both their occurrence and their consequences are not easily anticipated. Thus, NGOs and civil protection often have to take decisions and plan for their operations without having the possibility of relying on exact or complete information on the magnitude of the disaster. Over the years, a number of works and methodologies that address uncertainty in Disaster Management have been presented in the literature. In this chapter we review different forms of tackling uncertainty in Humanitarian Logistics for Disaster Management and propose a classification of the advances in this research field.

3.1 Introduction

3.1.1 *Humanitarian logistics and Disaster Management*

Different definitions can be found in literature for Humanitarian Logistics, but probably the most accurate one is the one provided in the Humanitarian Logistics Conference of 2004, by the Fritz Institute:

"Humanitarian Logistics is the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements and alleviate the suffering of vulnerable people.

It encompasses a set of activities, including preparation, planning, procurement, transportation, storage, history and customs control."

[*]Corresponding author. Contact: federico.liberatore@urjc.es

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As it can be seen, the main difference between business or military logistics and humanitarian logistics is based on the final aim of alleviating the suffering of vulnerable people. Despite of the fact that this is not an exclusive point of disaster management (each humanitarian aid operation as those performed by the World Food Program or the World Health Organization into underdeveloped areas or many of the cooperation for development activities usually have this common final aim), the usual context where humanitarian logistics has been studied is into Disaster Management. Although there are other studies in the field of humanitarian logistics (e.g., Pedraza-Martinez *et al.* (2011), present a study of field fleet management not under emergency), it is in this context where the main differences with business logistics proposed in Balcik and Beamon (2008) fit better:

- unpredictable demand in terms of timing, geographic location, type of commodity, quantity of commodity;
- short lead time and suddenness of demand for large amounts of a wide variety of products and services;
- lack of initial resources in terms of supply, human resources, technology, capacity and funding.

As it can be seen from these characteristics, the first one is related with the uncertainty. Disaster management decision makers usually have to make their decisions under risk or uncertainty coming from different sources.

3.1.2 *Uncertainty and Risk*

Uncertainty is defined by the Oxford Dictionary as *the state of being uncertain;* **Uncertain** is defined as *not able to be relied on; not known or definite.* **Risk** is defined (among other senses) as *the possibility that something unpleasant or unwelcome will happen*, and **Risk Management** as *the forecasting and evaluation of financial risks together with the identification of procedures to avoid or minimize their impact.* In our context this concept will be extended to others than financial risks.

From these definitions, it can be seen that uncertainty and risk is not the same, and it is more or less accepted in the literature that the term **Decision under Risk** refers to decision making where the unknown states or consequences are represented through probabilities, and **Decision under Uncertainty** is used when other characterizations appear to deal with the not well-known or definite information. Nevertheless, through this paper no distinction will be made in order to give a global picture of the topic.

Typologies of uncertainties are available in the literature of different disciplines. Some of the most typical ones are the following (see Moss and Schneider (2000)):

Problems with data

- Missing components or errors in the data.
- "Noise" in the data associated with biased or incomplete observations.
- Random sampling error and biases (non-representativeness) in a sample.

Problems with models

- Known processes but unknown functional relationships or errors in the structure of the model.
- Known structure but unknown or erroneous values of some important parameters.
- Known historical data and model structure, but reasons to believe parameters or model structure will change over time.
- Uncertainty regarding the predictability (e.g., chaotic or stochastic behaviour) of the system or effect.
- Uncertainty introduced by approximation techniques used to solve a set of equations that characterize the model.

Other sources of uncertainty

- Ambiguously defined concepts and terminology.
- Inappropriate spatial/temporal units.
- Inappropriateness of/lack of confidence in underlying assumptions.
- Uncertainty due to projections of human behaviour (e.g., future consumption patterns, or technological change), which is distinct from uncertainty due to "natural" sources (e.g., climate sensitivity, chaos).

In the context of disaster management, it is important to distinguish that some of the sources of uncertainty come from the unknown future, because decisions are made before the event happen. In this sense, we can distinguish two main phases:

- Pre-event phase: actions and decisions developed before the event has happened; they are focused on mitigation and preparedness.

- Post-event phase: actions and decisions developed after the event has happened; they include response and recovery activities.

The pre-event activities usually are developed assuming future scenarios, which should be characterized, and decisions can be common for all of them, or defined for each of them in case they would happen. This kind of studies includes risk management (e.g., natural risks, social/vulnerability risks), where usually a probability distribution is associated to the risk scenarios. But other possibilities as belief structures or evidential reasoning could be also considered.

The post-event decisions usually include uncertainty coming from the lack of information or some inherent ambiguity to it. Semantic uncertainty about the consequences is a common issue, among others. For instance, when classifying disaster consequences, even the frontiers between emergency, disaster or catastrophe are not crisply defined.

This Chapter is organized as follows: Section 3.2 focuses on the uncertain parameters usually considered in Humanitarian Logistics, and the main methodologies used to deal with the uncertainty are shown in Section 3.3. The specific literature review is compiled and commented in Section 3.4, and, finally, some conclusions are drawn.

3.2 Uncertainty in disaster management

Disaster management includes activities performed to be prepared in case of a disaster takes place, where the future is really unknown, so this preparedness is developed under an uncertain future. Some kind of natural hazards, as tropical storms, usually are monitored and as they approach the uncertainty about the future evolution of the event is disappearing, but not about the consequences. When the event takes place, chaos and unpredictable human behavior cause information flow transmissions breaks which result in information lacks and uncertainty in structure, range and number of casualties or damages. Furthermore, when the affected population provides information, sources may be diverse causing chaotic data without the aid of support tools and time for verification. Additionally, reporters, NGOs, and other emergency agencies usually act as the main information sources leading to disaggregated data, instead of structured information as required by aid decision management tools.

Figure 3.1 summarizes the different parameters under uncertainty considered in the literature in the context of Humanitarian Logistics. The uncertain parameters are grouped according to the associated system element.

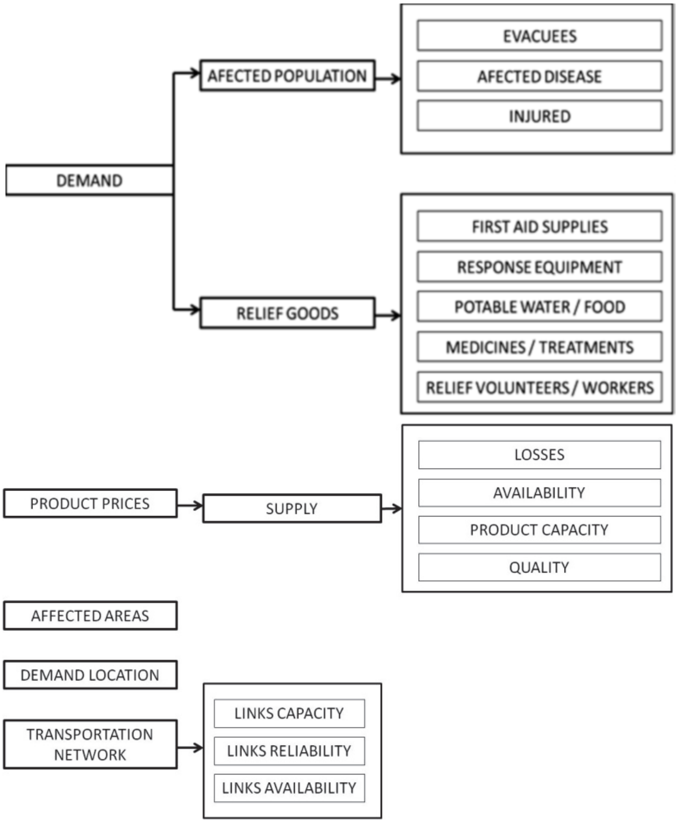

Fig. 3.1 Different parameters with uncertainty considered in the literature in the context of Humanitarian Logistics

Most of the contributions in Humanitarian Logistics research have focused on **demand** uncertainty. It can be divided in two groups: demand regarding the number of affected population and demand of required relief goods. In the former, we may find contributions dealing with the number of rescues (i.e., number of people to be evacuated), number of affected by a disease, and number of injured. In the latter, the literature considers first aid supplies, response equipments, potable water, food, medicines, disease treatments, and required relief workers for commodities handling. De la Torre (2001) states that considering uncertainty in the supply of relief goods is more important as underestimating it might result in substantial delays in the distribution.

Partial or completed **supply** losses at storage locations have also been considered. In this category uncertainties regarding products quality, availability, and production capacity in a disaster's wake are included. A similar type of uncertainty is the one concerning **affected areas and demand locations**, which includes magnitude of damages to supply stores and occurrence of the disaster. Also, some contributions considered uncertainties regarding **product prices** due to scarcity and survival rates.

Finally, **transportation network** uncertainties include links capacity (e.g., in terms of number of evacuees and vehicles), reliability, availability (e.g., roads, bridges, crossovers), and traversing time.

A conceptual map of the relations among the different elements presented is illustrated in Figure 3.2. In the map, the arrows define the cause-effect relationship identified in the real case data sets presented in the literature.

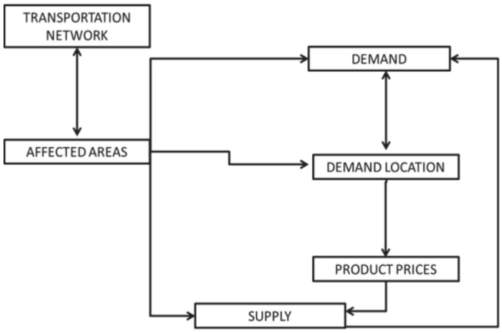

Fig. 3.2 Conceptual relationships among the uncertainty types

3.3 Methodologies Description

The main methodologies found in literature related with decision aid models with uncertainty for disaster management, can be classified into those describing uncertainty based on probabilities, and those based on other type of uncertainty characterizations such as fuzzy logic.

Once the uncertainty is characterized, suitable techniques to develop decision aid models based on this information can be found in the literature. A first description about the most used techniques when dealing with uncertainty is reported in the following.

3.3.1 *Risk Mapping and Probabilistic Values*

Risk maps originated from models of disease transmission based on spatial and temporal data. These models incorporate, to varying degrees, epidemiological, entomological, climatic and environmental information.

As stressed in Huang *et al.* (2007), a risk map of natural disasters is *an atlas of a community or geographical zone that identifies the places and the buildings that might sustain heavy damages caused by natural disasters.* The objective of a risk map is to identify the probability of the occurrence of a specific hazard, as well as the contingent vulnerabilities of exposed elements at risk, intensity and areas of impact, within a period of time. The first risk maps were defined in 1800, when insurance companies where hit by fires in major cities. Mapping was used to measure flammable exposures by placing pins on a map showing the location of insurance buildings, limiting the number of insurances in a given city or block. These *pins maps* where used until 1960's and, because their creation was too time consuming, they began to be replaced by more sophisticated computer generated maps that took into account frequency and severity distribution to estimate potential losses.

Nowadays, risk maps are developed by international research groups, such as United Nations Environment Program (UNEP), International Bank for Reconstruction and Development, The World Bank and Columbia University (in Dilley (2005)) and the Federal Emergency Management Agency (FEMA[1]). Also, risk companies provide risk maps for budget purposes (Insurance Center Associates[2]). Many countries have national regulations forcing to develop risk maps, which are obtained by governmental entities (national or local) of environment or safety. Risk maps are crucial for pre-event activities as mitigation and preparedness, being usually inputs for decision aid models.

Other probabilistic values to model uncertainty, but not exactly considered risk mapping, are also included in this section, especially those focused on the uncertainty related with the status of the infrastructure or reliability, after a disaster has happened. They are used over the network, so a map is included, but they are useful in a post-event phase more than for pre-event for risk management. Their treatment more as a quality of the elements than as a probability distribution, suggests separating it from those stochastic programming models, where probability distributions are considered themselves.

[1] http://www.fema.gov/hazard/index.shtm
[2] http://www.inscenter.com/info-center/disaster-planning/risk-profile

3.3.2 *Probability Distributions and Stochastic Programming*

Stochastic Programming is an approach for modeling optimization problems when the parameters are uncertain, but assumed to lie in some given set of possible values following a probability distribution. In such a case, one might seek a solution that is feasible for all possible parameter choices and optimizes the expected value of a given function of the decisions and the random variables.

Stochastic Programming models try to take advantage of the fact that probability distributions governing the data are known or can be estimated. These probability distributions can be estimated from data that have been collected over time, or in the absence of data from future periods, these distributions will have to be elicited from some accompanying model, which in its simplest form might derive solely from the prior beliefs of the decision maker.

The most widely applied and studied stochastic programming models are two-stage linear programs. Here the decision maker takes some action in the first stage, after which a random event occurs affecting the outcome of the first-stage decision. A recourse decision can then be made in the second stage that compensates for any bad effects that might have been experienced as a result of the first-stage decision. The optimal policy from such a model is a single first-stage policy and a collection of recourse decisions (a decision rule) defining which second-stage action should be taken in response to each random outcome.

Stochastic programming models usually are large dimensions models, implying the use of advanced mathematical programming techniques. Perhaps this is one of the reasons, in addition to its good fit to the problem characteristics, to explain the large number of academic articles devoted to this methodology in the last years into the area of disaster management.

3.3.3 *Robust Optimization*

Robust Optimization is a methodology, combined with computational tools, to process optimization problems in which the data are uncertain and only known to belong to some uncertainty set. In contrast with Stochastic Optimization which models the uncertainty through a probabilistic description, Robust Optimization models the possible set of values, but nothing is said about their probabilities. Instead of seeking to immunize the solution in some probabilistic sense to stochastic uncertainty, the decision-maker constructs a solution that is admissible in some sense (e.g., quasi-optimal) for any realization of the uncertainty in the given set. Robust optimization can be especially suitable in absence of data, or when there is no interest to give more importance to some values of the parameter than to others. Computational tractability is also a primary motivation to choose this methodology. Currently, Evolutionary Computing introducing robust optimization with multiple objectives could be seen as one of the most promising methodologies related, being the paper Dev and Gupta (2006) a seminal paper of the area, very interesting and understandable written in a very pedagogic way.

3.3.4 *Simulation Models*

A simulation model is a mathematical model of a system or process which tries to replicate in the computer a system's behaviour. The most extended use of simulation models is to represent dynamic systems, but especially when including uncertainty, static systems also are studied through simulation in order to obtain a simulated sample of the output. Techniques to obtain values of random variables are known as Monte Carlo simulation. In spite of having several shortcomings, simulation models are still widely used in modelling some humanitarian logistic problems, as the egress problem. Simulation models have also been widely used to incorporate evacuees' behavioural effects on the evacuation process.

Compared to optimization models, simulation models have a major lack. In fact, they do not provide the best strategy or decision to manage the system; they allow evaluating the performance of a strategy. Choosing a best strategy or decision implies experimenting with the model on a *What if* basis; i.e., by defining previously the decisions to be considered and using the simulation to evaluate them.

Another limitation of simulation models with uncertainty is that, in order to obtain results of system performance measures within required confidence intervals, large amounts of data and correspondingly large amounts of computation time and storage space are required. Further, it is not possible to generalize simulation results obtained from one system to another.

Simulation models, however, allow representing systems with a higher degree of accuracy, and they can be also used to complement analytical models in approximating system performance measures.

3.3.5 *Fuzzy Sets*

There are other concepts and notions of theories and models addressing imprecision, uncertainty, ambiguity and partial knowledge with respect to probability concept.

For years, fuzzy modeling has been one of the most relevant issues in qualitative analysis, given the linguistic capabilities of fuzzy logic, but now it is the base of many decision support models whose output is quantitative. In fact, fuzzy set theory, firstly introduce in Zadeh (1965), enables the use of natural language, implements relative concepts like big, old, strong, etc., and processes them on definite mathematical principles. Using fuzzy logic, it is possible to process objects that partially belong to more than one category. There is no need to generalize reality to fit it into classes; rather the degree of membership to the category is given. Note that, due to linguistic and numeric requirements, the fuzzy-modeling process has generally to deal with an important trade-off between the accuracy and the interpretability of the model. In other words, the model is expected to provide high numeric precision while incurring into a loss of linguistic descriptive power as little as possible.

3.4 Annotated Bibliography

In the last decades, Humanitarian Logistics has drawn the interest of both practitioners and academics. As a result, the scientific contributions in this field have grown exponentially over the last 20 years. On behalf of the extremely complexity of these problems due to their inherit uncertainty, the major contributions in the literature deal in a deterministic context with the aim of approximate to real problems. As Ben-Tal *et al.* (2010) stress we can find high uncertainty in disaster consequences and human behaviour in catastrophic situations. Therefore, humanitarian management is an important application area for optimization with uncertainty. As they underline, the penalty cost for an infeasible solution is loss of life or property and it is very difficult to estimate or forecast the uncertainty model parameters due to unexpected human behaviour and nature of disaster.

We contribute with an annotated bibliography on Humanitarian Logistics for Disaster Management under uncertainty. Our review focuses on papers dealing with Humanitarian Logistics management where there exists a lack of data related to demand (in terms of rescues, goods, etc.), locations (available suppliers, affected areas, etc.), supplies (hospitals, assets, food, water, etc.) or any related issue.

Tables 3.1 to 3.5 presents a summary of the main contributions to the topic, briefly described later. The first column of the tables shows the first author of the article and its publishing year. The second column describes the problem type dealt by the authors. In the next four columns we categorize the works depending on the emergency management phases addressed. Following the emergency management phases definitions provided in

Altay and Green (2006) we consider **mitigation** as the application of measures that will either prevent the onset of a disaster or reduce the impacts should one occur; **preparedness** as the set of activities that prepare the community to respond when a disaster occurs; **response** as the employment of resources and emergency procedures as guided by plans to preserve life, property, the environment, and the social, economic, and political structure of the community; and **recovery** as the set of actions taken in the long term after the immediate impact of the disaster has passed to stabilize the community and to restore some semblance of normalcy.

The seventh column presents the uncertainty inherent to the problem considered. The eighth column presents the objective or goal considered and, finally, last column describes the methodology used by the authors to deal with the uncertainty. They are organized by publication date.

Table 3.1 Review of the scientific contributions to Humanitarian Logistics employing Risk Maps and Probabilistic Values

Author	Problem type	Pre-Disaster		Post-Disaster		Uncertainty types	Objective function	Methodology
		M	P	R	RV			
Belardo *et al.* 1984	Location of oil spill response equipment		✓	✓		Event location	Multiple objective	Risk maps
Huang *et al.* 2007	Maximal Coverage model		✓			Availability ofemergency resources, service and travel times, emergency frequency.	Maximize cover of critical network elements.	Risk maps and Robust optimization
Günneç and Salman 2011	Network reliability and expected post-disaster performance		✓			Links status (available or not)	Network reliability	Risk maps and Stochastic optimization
Nolz *et al.* 2011	Last-mile distribution			✓	✓	Arcs associated risk	Multi-objective model: risk measure, coverage, total travel time.	Probabilistic values
Vitoriano *et al.* 2011	Last-mile distribution			✓	✓	Arcs reliability and security.	Multi-criteria model: time, cost, equity, priority, reliability, security.	Probabilistic values

Table 3.2 Review of the scientific contributions to Humanitarian Logistics employing Probability Distributions and Stochastic Programming

Author	Problem type	Pre-Disaster		Post-Disaster		Uncertainty types	Objective function	Methodology
		M	P	R	RV			
Fiedrich *et al.* 2000	Initialsearch-and-rescue period after strong earthquakes			✓		Affected area, causalities, transportation times	Minimize the total number of fatalities	Stochastic optimization via probabilistic constraints
Chan *et al.* 2001	Multiple-depot, multiple-vehicle, location-routing			✓		Demand	Minimize the sum of the routing, depot and vehicle fixed-costs	Stochastic optimization via probabilistic constraints
Barbarosoglu Arda 2004	Multi-commodity, multi-modal, network flow			✓		Affected areas, demand, transportation routes	Minimize total cost and expected scenario cost	Stochastic optimization via scenario analysis
Chang *et al.* 2007	Determinationof a rescue resource distribution system for urban flood disasters		✓			Rescue demand	Minimize rescue equipment expected shipping distance, local bases setup and acquisition and transportation costs.	Stochastic optimization via scenario analysis
Yazizi Ozbay 2007	Capacity requirements and desirable shelter locations	✓	✓			Link capacity changes	Minimize global travel time	Stochastic optimization via probabilistic constraints
Zhu *et al.* 2008	Resourceallocation problem to minimize the total rescue cost		✓			Resource demand	Minimize total rescue cost	Stochastic optimization via scenario analysis

Author	Problem type	Pre-Disaster		Post-Disaster		Uncertainty types	Objective function	Methodology
		M	P	R	RV			
Shen *et al.* 2009	Medicamentsand treatments pick-up and delivery in large scale bio-terrorism emergency		✓	✓		Supplies, demand and traffic conditions	Minimize unmet demand	Stochastic optimization via probabilistic constraints
Song *et al.* 2009	Evacuationplan for transit-dependent residents		✓			Demand	Minimize total evacuation time	Stochastic optimization via probabilistic constraints.
Hentenryck *et al.* 2010	Singlecommodity allocation problem				✓	Transportation routes, times, affected areas	Minimize last delivery time	Stochastic optimization via scenario analysis
Mete Zabinsky 2010	Storage and distribution problem of medical supplies		✓	✓		Locationand amount of demand, available transportation routes and transportation times	Minimize Transportation duration and unsatisfied demand	Stochastic optimization via scenario analysis
Rawls and Turnquist 2010	Location and quantities of emergency supplies to be pre-positioned		✓	✓		Demand and transportation network availability	Minimize the expected costs, commodity acquisition and stocking, supplies shipments, unmet demand and unused material.	Stochastic optimization via scenario analysis
Salmerón Apte 2010	Allocationof budget to acquire and position relief assets		✓			Location and amount of demand	Minimize the expected number of casualties	Stochastic optimization via scenario analysis

Author	Problem type	Pre-Disaster		Post-Disaster		Uncertainty types	Objective function	Methodology
		M	P	R	RV			
Günneç and Salman 2011	Networkreliability and expected post-disaster performance		✓			Links status (available or not)	Network reliability	Risk maps and Stochastic optimization via scenario analysis
Li *et al.* 2011	Sheltering network planning		✓	✓		Location and amount of demand	Minimizesheltering, resources holding, transportation and distribution costs.	Stochastic optimization via scenario analysis
Rottkemper *et al.* 2011	Inventoryrelocation problem with overlapping disasters			✓	✓	Demand	Minimize transportation, replenishment, inventory holding, and unsatisfied demand costs.	Stochastic optimization
Noyan 2012	Response(storage) facility locations and inventory levels	✓				Demand, trans. Capacities, and damage level of supplies	Minimize the expected total cost	Stochastic optimization via scenario analysis
Duran *et al.* 2011	Optimalnumber and location of pre-positioning warehouses	✓	✓			Product quality, availability, and production capacity	Minimize the average response time	Stochastic optimization problem via scenario analysis

Table 3.3 Review of the scientific contributions to Humanitarian Logistics employing Robust Optimization

Author	Problem type	Pre-Disaster		Post-Disaster		Uncertainty types	Objective function	Methodology
		M	P	R	RV			
Huang *et al.* 2007	Maximal Coverage model			✓		Availabilityof emergency resources, service and travel times, emergency frequency.	Maximize cover of critical network elements.	Risk maps and Robust optimization
Ben-Tal *et al.* 2011	Dynamicassignment emergency response and evacuation traffic flow	✓	✓			Demand (Time dependent)	MinŰmax	Robust optimization

Table 3.4 Review of the scientific contributions to Humanitarian Logistics employing Simulation Models

Author	Problem type	Pre-Disaster		Post-Disaster		Uncertainty types	Objective function	Methodology
		M	P	R	RV			
Bakuli, Smith 1996	Evacuation network		✓			Capacityrequired to provide an adequate service	Maximize evacuees, delay and circulation costs	Simulation

Table 3.5 Review of the scientific contributions to Humanitarian Logistics employing Fuzzy Sets

Author	Problem type	Pre-Disaster		Post-Disaster		Uncertainty types	Objective function	Methodology
		M	P	R	RV			
Adivar and Mert 2010	Internationaldisaster relief network optimization			✓	✓	Availability and cost of emergency resources, delivery delay time	Multi-objective model: transportation and items cost, max-min credibility.	Fuzzy optimization
Sheu *et al.* 2010	Emergencylogistics operations in large-scale natural disaster			✓		Relief demand	Relief-demand urgency under TOPSIS objective function.	Fuzzy optimization
Rodríguez *et al.* 2010	DSSto predict the effects of a disaster in terms of casualties, injures, homeless, affected, and total damage cost (in US$)	✓	✓	✓		Demand	Relief demand urgency	Fuzzy optimization

Reviews in Humanitarian Logistics may be found in Altay and Green (2006), who focuses on operation research methodologies and potential research lines, Balcik and Beamon (2010), who examines the coordination mechanisms and evaluates their adaptability to relief environments, and Caunhye *et al.* (2011), who proposes a classification of pre-disaster operations (i.e., evacuation, stock prepositioning and facility location) and a post-disaster operations (i.e., evacuation, relief distribution, and casualty transportation). More recent contributions are due to De la Torre *et al.* (2012) who present a survey of routing problems applied to Disaster Relief. The authors refer in the survey some articles including uncertainty in demand and supply, as well as in routes and vehicle fleets, always form the point of view of the distribution aid model. Finally, this book includes other review chapters referring to papers including some kind of uncertainty, or some chapters devoted to some specific methodology to model uncertainty.

In the following, an annotated bibliography on Humanitarian Logistic for Disaster Management under uncertainty is presented. The papers are shown as presented in the previous tables, by sections. Sometimes a paper appears in more than one table, so it is describes on the section corresponding to the first table where it has been included. For each work, a brief description of the main elements and contributions is reported.

3.4.1 *Risk Mapping and Probabilistic Values*

Belardo *et al.* (1984), deals with the problem of locating oil spill response equipment with a partial set covering model, including both assessments of the relative probability of occurrence and the impact after occurrence of various spill types by means of a multiple objective approach. The purpose is to attain the best overall protection with existing resources while minimizing the risk of being unprepared for politically and environmentally sensitive events.

Huang and Fan (2007), compare different modeling approaches for the problem of allocating multiple emergency service resources to protect critical transportation infrastructures. The objective of the paper is to test various risk preferences in decision making under uncertain service availability and accessibility in case of disaster. A stochastic and a robust formulation for the maximum coverage problem are proposed. The models are tested on realistic data, and a sensitivity analysis is conducted to show the robustness of the solutions found to changes in the models' parameters. An extension of this work can be found in Huang and Fan (2011).

Günneç and Salman (2011), assess the problem of evaluating the reliability and the expected post-disaster functionality of a transportation network under disaster risk. The authors propose eight probabilistic measures of connectivity and expected travel time/distance between critical elements of the network. Also, dependencies among the links are considered. The methodology is based on the generation of scenarios and a specifically tailored algorithm is proposed. The applicability of the approach is illustrated by means of a case study of the Istanbul highway system under earthquake threat. Also, the paper provides an excellent review of the most relevant contributions on network risk assessment for disaster preparedness.

Nolz *et al.* (2011), face the problem of designing a distribution system in a post-disaster context. The authors propose a multi-objective problem considering a risk, a coverage, and total distribution time objective function. In particular, risk measures represent the probability that a path might have become impassable as a result of the disaster. Different risk measures, including correlated measures, are considered to model different disaster scenarios. The rationale behind this work is that, in case of disaster, distribution systems should be designed while taking into consideration the risk associated to the possible routes (e.g., it might be desirable to avoid bridges and tunnels). The problem is solved by an iterative algorithm that generates potentially Pareto-optimal solutions. Finally, the algorithm is tested on real-world data from the province of Manabí, Ecuador, and the different risk approaches are analyzed in order to evaluate the most appropriate risk measure for delivering disaster relief supplies.

Vitoriano *et al.* (2011), proposes a model for the optimization of last-mile distribution operations. The formulation is based on a continuous aid flow model entwined with an integer vehicle flow model. The authors recognize the limits of designing emergency operations according to the classical cost minimizing measures. For this reason, they present a multi-criteria model that optimizes with respect to attributes that are more relevant to a disaster context, such as response time, equity in the distribution, reliability and security of the routes. Specifically, reliability and security are represented by associating to every arc a transit and ransack probability, respectively. These parameters represent respectively the probability that the road conditions allow a vehicle to cross the link, and that the vehicle will be ransacked during the journey. Various probability measures are calculated (e.g., global, maximum) and used as decision criteria. A preliminary version of this work can be found in Ortuño *et al.* (2011).

3.4.2 *Probability Distributions and Stochastic Programming*

Fiedrich *et al.* (2000), minimizes the number of fatalities finding the best assignment of available resources to operational areas taking into account the possibility of more successive natural disasters. Fatalities are calculated as result of primary and successive damages, delays in rescues or lack in medical treatments. These authors propose a model taking into account the possibility of secondary or even more successive natural disasters. Operational areas are defined as places with trapped persons; locations endangered by secondary disasters and immediate rehabilitation areas. Hospitals, crossroads and available depots are considered as assets for refugee. Locations and tasks are linked together in an allocation model solved by means of a dynamic optimization model. The main objective is the decrease in the time limit for search-and-rescue in the first few days conditional on the goal to minimize the total number of fatalities. Uncertainty is model by means of survival rates for trapped persons and rescues without medical treatments availability, probabilities of successive disaster events, transportation times and time completion. Due to the problem complexity, the authors implemented both Tabu Search and Simulated Annealing heuristic algorithms and compare them by means of a set of fictitious data. The conclusions derived from the analysis exhibit that approximately the first 3 days after an earthquake event are essential for the performance of the relief efforts. Afterwards the probability for rescuing trapped persons alive decreases radically.

Chan *et al.* (2001), considers a multiple-depot, multiple-vehicle, location-routing problem with stochastically processed demands and apply their methodologies to a medical-evacuation case study of the U.S. Air Force. They solve the distribution center location problem by means of the heuristic proposed by Clarke and Wright (1964) in a medical evacuation framework where a plan for allocating aircraft was devised for both the beginning of the conflict and as the conflict progresses. Uncertainty is tackle devoted to demand by means of a priori or robust optimization, defined as procedures that one performs ahead of time to anticipate future events. They consider stochastically processed demands as: the requirement for raw materials to be stored at supply depots when surplus inventory is strictly disallowed at the processing plants. A 90-day case-study is provided for future researchers as a benchmark for other solution algorithms.

Barbarosoglu and Arda (2004), following the stochastic multiple-depot, multiple-vehicle, location-routing problem, develops a two stage stochastic model for transportation planning in earth quake response. In the first stage, decisions regarding the transportation of goods from existing supplies for preposition are taken considering the objective of minimizing transportation costs and scenarios expected costs. In the second stage, data related to demand and supply is disclosed and supplies are transported to demand points minimizing total flow, shift and penalty for inventory holding and shortage costs. Uncertainty in the event impact, damage and resource requirements is considered. The problem formulation contemplates random arc capacities in order to represent the survivability of the routes and the vulnerability of the supply nodes and availability and usability of commodities. A case study with data provided by the Marmara earthquake in Turkey ($M = 7.4$) in 1999.

Chang *et al.* (2007), aims at developing a decision making tool for government agencies to plan for flood emergencies logistics when the number of rescues in uncertain. They determine the locations of rescue equipment storehouses and solve the model by using a sample average approximation (SAA) scheme. The urban areas flooded are considered uncertain, due to the difficulty of predicting where drainage overflows occur and, therefore, the estimation of rescue demand is uncertain. The authors propose a preparation planning for emergency logistics in order to make a prudent distribution of the rescue equipment. Two stochastic programming models are proposed and solved by means of a heuristic algorithm, which determines the rescue resource distribution plan for urban flood disasters, including the structure of rescue organization, the location of rescue resource storehouses, the allocation of rescue resources with respect to the capacity constraints, and their distribution. Disaster areas are classified in groups by emergency level and the objective is to minimize the expected shipping distance. In a second stage, selected local rescue bases that need to be set up after the disaster, the quantity of rescue equipment in the storehouses, and the transportation plans of rescue equipment are determined. The model is applied to Taipei City, located in Northern Taiwan, with the additional constraint of total rescue operation length being less than 36 hours.

Yazici and Ozbay (2007), centers in network reliability and treats the determination of changes in capacity requirements and shelter locations taking into account capacity link changes during evacuation procedures. They analyze their methodology with a simplified multiple-origin, multiple-destination version of the Cape May, New Jersey network. They seek for the desirable shelter locations as a result of link capacity changes during evacuation being evaluated by letting a stochastic model assign flows generating the minimum system wide travel time. The model formulation is an extension of a cell transmission—based system optimal dynamic traffic assignment with probabilistic capacity constraints. Uncertainty is considered in the unexpected change of link capacities due to the impact of events such as hurricanes and earthquakes. The authors highlight the risk in considering the predictions of the deterministic model in terms of food, medicine, and other emergency supplies shortages in shelters.

Zhu *et al.* (2008), propose a resource allocation model to minimize the total rescue cost subject to the local reserve depots' capacity constraints. The aim is to determine the location of reserve depots and the amount and type of resources to be stored. The type of uncertainty considered is the disaster magnitude and resource needs, and is modeled by means of discrete scenarios. Based on the impact of the disaster, scenarios are divided in two sets: local government and national government responsibility recovery. Three objective functions are proposed for the problem formulation, based on commodities inventory holding and transportation costs. The problem is solved by means of an LP relaxation algorithm and a case study in Shandong Province (China) is considered.

Shen *et al.* (2009), considers an inventory routing problem where both routes and delivered quantities are important for efficiency disaster management planning. The author develops a two stage model for routing vehicles to service in large scale bio-terrorism emergency with the objective of minimizing unmet demand. The main difference with other approaches is the short time limit for response. Demand in terms of required emergency supplies and number of casualties exposures and traffic conditions are considered to be uncertain. The first stage of the algorithm generates pre-planned routes in advance of any possible emergencies. This problem is formulated as a mixed integer programming model (MIP) and solved by means of a Tabu Search algorithm. In the second stage, information related to affected areas is disclosed and pre-planned routes are adjusted to the given information by means of three different recourse strategies; i.e., LP, Knapsack, and re-planning. The methodology performance is analyzed with random generated instances.

Song *et al.* (2009), deals with the problem of generating evacuation transportation plans. The model optimizes shelter locations and evacuation routes to define bus routing and passenger pick up points during hurricanes evacuations. A multi-graph street network is considered for transit evacuation taking into account one way, two ways, prohibited turns and different delay time for left-turn, right-turn and through running of transit vehicle at intersections. The locations of the civilians to be evacuated are uncertain. The problem is solved by means of a combination of genetic, artificial neural networks and hill climbing heuristic strategies.

Hentenryck *et al.* (2010), proposes a three-stage stochastic optimization model for single commodity allocation problem in disaster recovery management. The problem is focused on potable water deliver for hurricane recovery with the objective of minimizing the amount of unsatisfied demands, transportation times from the commodity allocations to demand points, and storage costs. As MIP approaches often do not scale to real world instances, the authors propose a hybrid optimization method in three stages: in the first stage, locations for commodity allocation are determined and solved by means of a MIP. Then, in the second stage transportation routes from storage locations to demand points are solved to optimality. Finally, in the third stage a neighborhood search determines the order in which transportation routes obtained in the second stage must be schedule with the aim of minimizing last delivery time.

Mete and Zabinsky (2010), follows the line of Belardo *et al.* (1984) and proposes a two stage stochastic optimization approach for the storage and distribution problem. The model is applied to medical supplies for disaster management when demands of goods are uncertain. They develop a mixed integer programming model to select the storage locations of medical supplies and required inventory levels for each type of medical supply. The objective is to minimize the transportation time weighted by the transported load. Uncertainty is modeled through scenarios that define the location of affected areas, amount of demand, network routing reliability, and transportation times. In the first stage, decisions related to warehouse location and goods inventory level are taken to minimize the expected total operating costs. In the second stage, decisions related to the delivery of goods to demand points are taken minimizing the transportation duration (transportation times weighted by the amount) and unsatisfied demand. Penalties incurred for unsatisfied demands are limited by means of constraints. The methodology is applied to an urban medical supply storage and distribution problem.

Rawls and Turnquist (2010), similarly to Mete and Zabinsky (2010), proposes a two-stage stochastic optimization approach for the location and storage of emergency supplies before a disaster and their distribution to multiple demand points after the catastrophe. The model considers uncertainty in demand for the stocked supplies as well as uncertainty regarding transportation network connectivity level after an event. In a first stage, the response (storage) facility locations and the inventory levels to be pre-positioned are determined minimizing the expected associated cost. In the second stage, the distribution problem of available supplies to demand locations is solved. Through discrete scenarios the possibility of loss (partial or completed) in supplies at storage locations, unusable links connections in the transportation network, and demand uncertainty are represented. The objective of the stochastic problem is to minimize the expected cost over all scenarios resulting from the selection of the pre-positioning locations, stock and facility sizes costs, transportation costs and unmet demand. The author proposes an adaptation of the Integer L-Shaped Method by means of Lagrangian relaxation to solve the resulting stochastic mixed integer problem. A case study in the Gulf Coast area of the US focused on hurricanes is considered. The network has 30 nodes and 55 links.

Salmeron and Apte (2010), proposes a two-stage stochastic optimization model to guide the allocation of budget to acquire and position relief assets with the aim of minimizing the expected number of casualties. The first stage decisions involve the expansion of resources (e.g.; warehouses, medical facilities with personnel, ramp spaces, shelters, and access routes). As the author considers successive disaster events, priority is given to those resources that allow for future expansions. The second stage (temporally located 3 days after the event, approx) deals with the transportation of injured population to shelters and hospitals, and the delivery of supply needs to the stay back population, with the objective of minimizing the expected unmet transfer population that would result in casualties.

Günneç and Salman (2011), see on the section for Risk Mapping and Probabilistic Values.

Li *et al.* (2011), devises a two stage stochastic model to determine shelters location, capacity, and resource level in a preparedness stage, and evacuees and resources distribution in a response stage. Shelters that meet the FEMA standards in terms of mass and quality sheltering are referred as Permanent Shelters; those that do not, are referred as Temporary Shelters. The objective function proposed gives priority to Permanent Shelters versus Temporary Shelters and minimizes sheltering costs per evacuee, resources holding costs, and the expected value of the response stage. The second stage objective function includes transportation costs of evacuees, resource distribution costs, and surplus and shortage costs for resources after an evacuation. Due to the binary variables employed in the formulation for the first stage model, the author highlights the extreme computational complexity of the model and proposes a classical L-Shaped decomposition method to solve the problem. A case study of the Gulf Coast region of United Sates is presented for sheltering network planning and operations against hurricanes.

Rottkemper *et al.* (2011), consider the inventory location problem in the context of humanitarian logistics. In the inventory location model, flows between the depots must be determined so that the total costs (i.e., the sum of transportation costs, replenishment costs, inventory holding costs, and penalties for unsatisfied demand) is minimized. In their model, the authors take into consideration *overlapping disasters*; i.e., subsequent emergencies or incidents that can occur during the response to or the recovery from a previous disaster. As a consequence, the proposed model is multi-period in nature. Also, uncertain demands are considered. The problem, formulated as a deterministic model where the unmet uncertain demand is penalized in the objective function, is extensively tested on a Burundi case-study.

Noyan (2012) considers a risk-adverse stochastic model to determine the response (storage) facility locations and the inventory levels of the relief supplies at each facility in the presence of uncertainty in the demand and in the damage level of the disaster network. Furthermore, their model allows damage at the links in the network and partial or total loss of the supplies at storage location when the disaster event occurs. Compared to Rawls and Turnquist (2010), the novelty of this approach is the incorporation of a conditional value at risk measure. As integer variables are not considered in the second stage formulations and uncertainty is characterized by a finite set of scenarios, the authors apply a Benders' decomposition algorithm with multicuts methodologies for problem solving. A comparison with the case study proposed by Rawls and Turnquist (2010) is given in order to draw attention to the solution differences with respect to risk preferences.

Duran *et al.* (2011), in a more general framework, explores a pre-positioning strategy to improve the emergency response times in collaboration with CARE and Gatech. The author proposes a model that finds the optimal number, location, and inventory level of warehouses around the world in the face of a disaster or multiple disasters. The model considers uncertainties regarding product quality, availability, and production capacity in a disaster affected areas. The proposed mixed integer programming inventory location model considers location costs to represent the possibility of using free or at cost warehouse storage locations provided by some governments. The objective is the reduction in transportation times for international aid in disaster management. Their data includes a set of 233 demand instances and a given budget that determines the maximum number of warehouses and total inventory to allocate. The objective is to find the configuration of the supply network that minimizes the weighted average response time; i.e., flying time from the supplier to arrive at an entry port of the affected area plus one day for set-up and material handling. Differently from previous contribution, this work considers the occurrence of catastrophes at different locations which results in an adverse effect regarding to the replenishment lead time.

3.4.3 *Robust Optimization*

Huang *et al.* (2007), see on the Risk Mapping and Probabilistic Values section.

Ben-Tal *et al.* (2011), follows the line introduced by Song and Zhang (2009) and deals with the problem of generating dynamic (multi-period) evacuation transportation plans which are robust to uncertainty in outgoing demand. Uncertainty is given by the difficulty of estimating the number of civilians at source nodes due to unexpected human behavior and nature of disaster. The problem is formulated as a linear program based on cell transmission models. The role of hard constraint is emphasized since the penalty cost for an infeasible solution is the loss of life or property. The authors develop a robust optimization framework where actual decision variables (flows) are determined for each period t by inserting the revealed uncertainties from previous periods in the linear decision rule ("wait and see" strategy). As the optimal solution may perform much worse in the worst case, the aim is to provide a good solution for all possible scenarios. They apply the methodology to two test instances (Chiu *et al.* (2007), and Yazici and Ozbay (2007)).

3.4.4 *Simulation Models*

Bakuli and Smith (1996), deals with the evacuation building problem in case there is uncertainty in the capacity required for an adequate service. The authors found by computational experience the extremely complexity in using digital simulation for problem solving. Therefore, the authors propose an analytical model to aid the network design process. The problem was represented by means of a queuing model and solve with a mean value analysis algorithm. The multi-objective approach of the problem was solved by maximizing the number of evacuees and determining control variables for the critical capacity sections of the network.

3.4.5 *Fuzzy Sets*

Adivar and Mert (2010), optimize a simple relief distribution system in which donor countries provide relief items which are collected at collection points and, then, shipped to points of delivery in disaster affected countries. The type of uncertainty considered is related to imprecise information concerning the quantity of items provided by the donor countries, the procurement items cost at donor country level, and the potential delay at collection point level. The model, multi-objective in nature, includes the following objective functions: minimizing the total procurement and transportation cost, and maximizing the worst credibility (i.e., the highest delivery delay). The authors deal with the uncertainty by *fuzzifying* both the uncertain parameters and the credibility. As a consequence, the problem is formulated as a multi-objective fuzzy mathematical model. In order to be solver, the model is reformulated as a parametric linear programming model. Finally, the devised methodology is tested on real data collected from NATO-EADRCC reports (publicly available).

Sheu *et al.* (2010), presents a dynamic relief-demand management model in large-scale natural disasters. Uncertainty is driven by the number of disaster affected people due to imperfect information. In fact, the relief demander is usually not the same as the information provider. Also, information sources are diverse and hard to be promptly verified. Therefore, the required information for logistics management in large scale events is desired to be aggregated in urban areas. The methodology proposed is divided in three steps: data aggregation in urban areas, area severity classification according to the expected number of fatalities, and multi-criteria decision making to rank the order of priority. The time frame considered is the 72 hours after the disaster. During this phase the most critical activities are search and rescue of entrapped civilians. The case study replicates the massive Chichi earthquake (7.3 on the Richter scale), which occurred in central Taiwan on 1999 (2455 deaths in total, more than 8000 injured, and the destruction of 38,935 homes). The results where compared with the real severity level of 13 urban areas through the consideration of 9 possible scenarios. A previous and less sophisticated version of this work can be found in Sheu (2007).

Rodriguez *et al.* (2010), design a Decision Support System (DSS) for aiding humanitarian organizations based on fuzzy logic. Such DSS, called SEDD, focuses on providing an estimation of the effects of a disaster right after a disaster strikes; i.e., when there is a lack of reliable knowledge on the real magnitude of the emergency. Given a disaster-type and the affected area, SEDD makes use of the data stored in the EM-DAT [1] database to predict the number of casualties, injured, homeless, affected, and the total damage value (in US Dollars). The little data, technological, and infrastructure requirements make SEDD particularly useful and accessible to NGOs.

In a subsequent paper, Rodriguez *et al.* (2012), the interpretability of the results provided by SEDD is improved by including three kinds of output; i.e., numerical, interval, and class predictions.

Next, in Rodriguez *et al.* (2011), the authors compare the fuzzy DSS with classical statistical analysis tools, such as multiple linear regression, linear discriminant analysis, classification trees, and support vector machines. The conclusion of this work is that SEDD outperforms the methods above in the task of simultaneously providing an accurate and interpretable inference tool for the evaluation of the consequences of disasters.

3.5 Conclusions

Uncertainty, understood as the imprecision, ambiguity, lack of information or partial knowledge, is a major topic in the literature, and especially when studying dynamic systems including uncertain future. But it is especially relevant in Disaster Management, where the high level of uncertainty inherit to most of the parameters involved in humanitarian logistics makes a difference respect to other kind of logistics.

Different approaches to deal with uncertainty in humanitarian logistics can be found in the literature. They differ in the way to model uncertainty, the way to manage it, the parameters considered to be under uncertainty. Decision aid models based on these approaches have been developed with different aims and goals, but there is still a long way to go to put these models into production, especially because many times they require deep analyses of data, strong computation efforts and/or the required training of final users.

Our survey shows that the majority of the contributions in decision models for Humanitarian Logistics make use of Stochastic Programming. Nevertheless, these studies usually are not implemented in systems or tools applied by practitioners. In the real world, much more is being applied of risk mapping for preparedness (emergency protocols developed usually by national or local civil protection entities) or to image processing to obtain maps of the affected area of a disaster (captured by satellites or planes). This information is the base for making decisions on the humanitarian logistics related to disaster management but usually is not integrated in decision making models. So, larger efforts should be done to deal into the models with this kind of uncertainty, developing systems able to manage it and training final users to understand it and capitalize on its potential.

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Chapter 4

Fuzzy inference systems for disaster response

Başar Öztayşi [1], Hülya Behret [2], Özgür Kabak [1], İrem Uçal Sarı [1], and Cengiz Kahraman [1]

[1] *Istanbul Technical University, Department of Industrial Engineering, 34367 Macka Istanbul Turkey*

[2] *Erciyes University, Department of Industrial Engineering, 38039, Kayseri, Turkey*

Disaster management is extremely important in today's world, which is defined as the organization and management of resources and responsibilities for dealing with all humanitarian aspects of emergencies, in particular preparedness, response and recovery in order to lessen the impact of disasters. Disaster response is one of the critical stages of disaster management, which necessitates spontaneous decision making when a disaster occurs. Fuzzy inference systems are very suitable for such decision making environments since the inputs and outputs of disaster events cannot be sharply defined. This chapter describes potential applications of fuzzy inference systems in disaster response.

4.1 Introduction

The term disaster is derived from the Latin roots dis- and astro, meaning "away from the stars" or, in other words, an event to be blamed on an unfortunate astrological configuration (Coppola, 2006). A disaster is defined as an overwhelming ecological disruption occurring on a scale sufficient to require outside assistance (Syed, 2009). An event, concentrated in time and space, in which a society, or a relatively self-sufficient subdivision of a society, undergoes severe danger and incurs such losses to its members and physical appurtenances that the social structure is disrupted and the fulfillment of all or some of the essential functions of the society is prevented. (Fritz, 1961). When a hazard has effect on vulnerable people it is called a disaster. Disaster can be considered as the combination of hazards, vulnerability and inability to reduce the potential negative consequences of risk (URL-1).

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According to International Federation of Red Cross and Red Crescent Societies (IFRC), though often caused by nature, disasters can have human origins (URL-1). Natural hazards are naturally-occurring physical phenomena caused either by rapid or slow onset events. IFRC classifies the natural hazards into five main categories: geophysical (earthquakes, landslides, tsunamis and volcanic activity), hydrological (avalanches and floods), climatological (extreme temperatures, drought and wildfires), meteorological (cyclones and storms/wave surges), and biological (disease epidemics and insect/animal plagues) (URL-1). Technological or man-made hazards, on the other hand, are human caused events that occur in or close to human settlements. Examples are environmental degradation, pollution and accidents (URL-1).

IFRC defines disaster management as follows:

"The organization and management of resources and responsibilities for dealing with all humanitarian aspects of emergencies, in particular preparedness, response and recovery in order to lessen the impact of disasters" (URL-1).

As shown in Fig. 4.1, comprehensive disaster management is based upon four distinct components: mitigation, preparedness, response, and recovery (Coppola, 2006). The four-phase classification is based on the Comprehensive Emergency Management concept introduced in the 1978 report of the National Governors Association Emergency Preparedness Project. Mitigation Involves reducing or eliminating the likelihood or impact on the society of a hazard, or both. Preparedness involves equipping people who may be impacted by a disaster or who may be able to help those impacted with the tools to increase their chance of survival and to minimize their financial and other losses. Response involves taking action to reduce or eliminate the impact of disasters that have occurred or are currently occurring, in order to prevent further suffering, financial loss, or a combination of both. Finally recovery involves returning victims' lives back to a normal state following the impact of disaster consequences. The recovery phase generally begins after the immediate response has ended, and can persist for months or years thereafter.

Despite all activities accomplished in mitigation and preparedness phase, disasters occur and create damage. Disaster response is defined as the total sum of actions taken by people and institutions in the face of disaster (Syed, 2009). Disaster response provides for the immediate protection of life and property, reestablishing control and minimizing the effects of a disaster (Rao, 2007). Response processes begin as soon as it becomes apparent that a hazard event is imminent and lasts until the emergency is declared to be over (Coppola, 2006). Disaster response includes the issuance of predictions and warnings, and

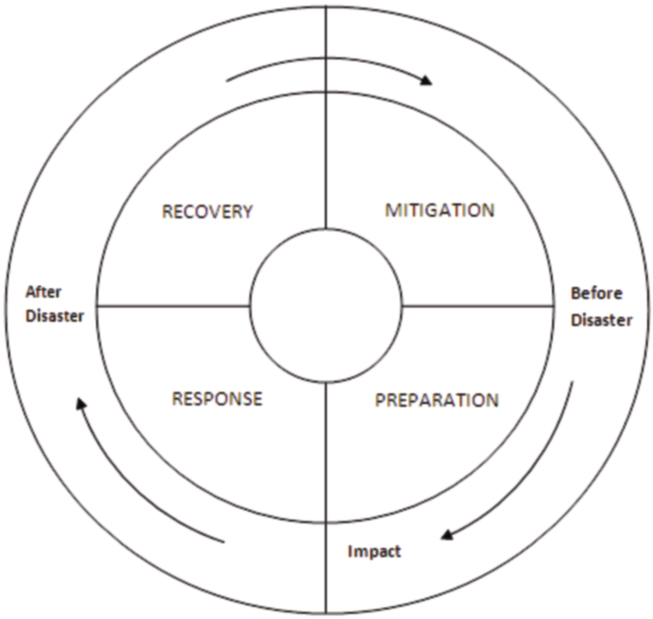

Fig. 4.1 Disaster Management Cycle (Alexander, 2002)

preparations immediately before an event occurs. Besides, disaster response contain other forms of protective actions include actions aimed at limiting injuries, loss of life, and damage to property and the environment that are taken prior to, during, and immediately after a hazard event. Response includes not only those activities that directly address these immediate needs—such as first aid, search and rescue, and shelter—but also includes systems developed to coordinate and support such efforts.

In order to conduct an effective disaster management through decreasing the impact of hazard and tackling vulnerability, it is required to deal with uncertainties. Especially in the pre-event phase, risk management should deal with the uncertainties resulting from unknown time and unknown consequence of disasters to prevent the onset of a disaster, reduce the impacts, or prepare the community to respond when a disaster occurs. In the post-event phase, complexity and uncertainty of the social, economic and political consequences of disasters should be analyzed effectively for the employment of resources and emergency procedures. Therefore uncertainty is one of the most challenging and important problems in the disaster management.

In Altay and Green (2006) more than 50% of the analyzed papers take into account uncertainty by means of operations research methodologies such as probability, simulation, queueing theory, fuzzy sets and stochastic programming. Fuzzy sets are one of the least preferred approaches in the literature for disaster management.

Fuzzy set theory, which was founded by Zadeh (1965), has emerged as a powerful way of quantitatively representing and manipulating the imprecision in decision-making problems. Fuzzy sets or fuzzy numbers can appropriately represent imprecise parameters, and can be manipulated through different operations on fuzzy sets or fuzzy numbers. Since imprecise parameters are treated as imprecise values instead of precise ones, the process will be more powerful and its results more credible. Fuzzy set theory has been studied extensively over the past 40 years (Kahraman *et al.*, 2006).

Fuzzy set theory is being recognized as an important problem modeling and solution technique. The use of fuzzy set theory as a methodology for modeling and analyzing decision systems is of particular interest to researchers due to fuzzy set theory's ability to quantitatively and qualitatively model problems which involve vagueness and imprecision (Kahraman *et al.*, 2006).

Fuzzy set theory approaches to disaster management are scarce. Among the relevant literature some noteworthy studies are as follows: Shen (2007) presents a hybrid fuzzy clustering-optimization approach to the operation of emergency logistics co-distribution responding to the urgent relief demands in the crucial rescue period. Tsai *et al.* (2008) apply fuzzy set theory for decision making in a geographic information system to the allocation of disaster shelters. Simonovic and Nirupama (2005) develop a new technique to enhance the ability to address different uncertainties in spatial water resources decision-making that provided a measurable improvement in the management of floods. Li *et al.* (2005) use fuzzy comprehensive evaluation of risk in a decision support tool for typhoon insurance pricing to support fuzziness and uncertainty. More literature survey is provided in Section 4.3.

The aim of the chapter is to describe the potential application of fuzzy inference systems (FISs) in disaster response systems. In this manner the chapter is organized as follows. In Section 4.2 the disaster recovery systems are introduced in details. Section 4.3 describes the FISs and provides a brief literature review about previous studies. Section 4.4 contains a sample FIS for spontaneous volunteer management in disaster response systems and finally further steps are discussed in conclusions.

4.2 Disaster Response System

As described in the previous section, disaster response activities are the actions taken in a short term just after or just before a disaster occurs. According to Altay and Green (2006) the typical activities involved in response phase are listed as follows:

(1) Activating the emergency operations plan
(2) Activating the emergency operations center
(3) Evacuation of threatened populations
(4) Opening of shelters and provision of mass care
(5) Emergency rescue and medical care
(6) Fire fighting
(7) Urban search and rescue
(8) Emergency infrastructure protection and recovery of lifeline services
(9) Fatality management

The aim of above-given activities is the employment of resources and emergency procedures as guided by plans to preserve life, property, the environment, and the social, economic, and political structure of the community (Altay and Green, 2006).

The disaster response system functions may be classified into two groups as pre-disaster and post disaster activities. Pre-disaster activities may be efficient if advanced warning systems exist and appraise the upcoming disaster (Coppola, 2006).

(1) Warnings: refers to arrangements to rapidly disseminate information concerning imminent disaster threats to government officials and the population (Syed, 2009).
(2) Evacuation: involves the relocation of a population from zones at risk of imminent disaster to a safer location.
(3) Logistics of resources and supplies: with the help of advanced warning of the disaster, officials can find a chance to transport supplies into the affected site before hazard conditions and consequences make such movement more difficult (Coppola, 2006).
(4) Last-minute mitigation and preparedness: Mitigation and preparedness are most effective when they are performed far in advance of a disaster. However, actions often may be taken in the few hours or days before a disaster occurs.

As disaster response begins, the first priority is saving lives. The emergency activities include search and rescue, first aid, and evacuation that are directly related to saving lives.

Besides, depending on the type of the disaster, other supporting activities may be needed. The post-disaster activities are as follows:

(1) Search and Rescue: is the process of identifying the location of disaster victims that may be trapped or isolated and bringing them to safety and medical attention.
(2) First Aid Medical Treatment: In a disaster the quantity of victims may be so great that they completely overwhelm the capacity of local clinics or hospitals to care for them all. In such situations, injured victims should be located and a first aid medical treatment must be applied to stabilize their condition, and transport them to a facility where they can receive the medical assistance necessary to save their lives (Coppola, 2006).
(3) Evacuation: Before, during, or after a disaster occurs, moving populations away from the hazard and its consequences reduce the effect of many disasters.
(4) Disaster Assessment: As soon as possible after the disaster has begun, response officials must begin collecting data, which is then formulated into information to facilitate the response. It is vital to know at any given time or at short intervals what is happening, where it is happening, what is required to address those needs, and what resources are available.
(5) Logistics and Supply: The delivery of emergency relief will require logistical facilities and capacity. A well-organized supply service is crucial for handling, storage and dispatch of relief supplies.
(6) Safety and Security: In the response period of a disaster, the social order of the affected area is disrupted. Local officials focus mostly on managing the hazard's consequences. However, safety and security needs of the survivors are superior to normal and must be fulfilled.
(7) Health and Sanitation: In times of disaster, risk of injuries and illnesses is higher than normal situations. However, health facilities may be full or damaged so facilities for emergency healthcare operations must be prepared to accommodate the health needs of the affected population. One of the most important issues is achieving proper sanitation.
(8) Donation Management: In disasters, individuals governments, private and religious groups, and businesses are likely to donate disaster victims However, without an effective mechanism to accept, catalogue, store, and distribute those donations it is impossible to transmit these donation to the victims.

Emergency operations management is a vital component of disaster response. Emergency operations management of disaster response and recovery activities is best facilitated from a centralized location that is normally established away from the disaster scene. Decision making is highly important for disaster response because the mentioned activities must be accomplished with a limited resource and agencies that quickly descend upon the impacted areas. For this reason disaster decision support systems have been the subject of many studies in the literature (Lu and Yang, 2011; Arora *et al.*, 2010; Rodríguez *et al.*, 2010; Yoon *et al.*, 2008; Zografos *et al.*, 2002; Wallace and Balogh 1985). Inference can be defined as the act or process of deriving logical conclusions from premises known or assumed to be true. In the disaster management area the inference system can be used as a disaster response expert system. According to inference rules and special knowledge, the inference system can analyze a situation and give feasible response to decision makers (Jianshe, 1994).

In disaster response system, the decision makers deal with highly divergent conditions and demands. Unique to each disaster, the participants, victims' and community needs differ and as a consequence the timing and order of events, actions and processes diverge. Because of this dissimilarity in demands and actions, it is not easy to construct a single model to describe the relationship of demand to capacity (Confort *et al.*, 2004). Since the disaster situation usually cannot be described precisely, and the information is often incomplete decision makers do not have enough information to perform decision analysis. To deal quantitatively with such an imprecision or uncertainty, the fuzzy set theory is adapted to the studies about disaster management (Jianshe, 1994; Cret *et al.*, 1993; Shiri and Kisi, 2010).

4.3 Fuzzy Inference Systems

Fuzzy inference systems (FISs) are rule based systems with concepts and operations associated with fuzzy set theory and fuzzy logic (Ross, 2004; Mendel, 2001). FISs start from highly formalized insights about the structure of categories found in real life and then articulate fuzzy "IF-THEN" rules as a kind of expert knowledge. Fuzzy systems combine fuzzy sets with fuzzy rules to produce overall complex nonlinear behaviors (Sen, 2010).

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. By this way, fuzzy inference allows constructing structures that can be used to produce responses (outputs) to certain stimulations (inputs), based on stored knowledge on how the responses and stimulations are related. In FISs, the knowledge is stored in the form of a rule base. In some cases, this knowledge is obtained by extracting information thoroughly from experts, which is usually known as fuzzy expert systems (Hall and Kandel, 1991). In other cases, data driven approaches are used in which membership functions and rules are developed using a training data set where the parameters for the membership functions and rules are consequently optimized to reduce training error (Keshwani *et al.*, 2008).

There are two systems for fuzzy inference, which are usually denoted as: Takagi–Sugeno-Kang type (or just called Sugeno type) FIS and Mamdani type FIS. Sugeno type FIS was first proposed by Takagi and Sugeno in 1985 and by Sugeno and Kang in 1988. A sugeno type FIS has fuzzy inputs and a crisp output (linear combination of the inputs). Sugeno type FIS is computationally effective and works well with optimization and adaptive techniques (such as ANFIS), which makes it very attractive in control problems, particularly for dynamic nonlinear systems. Mamdani type FIS is first proposed by Mamdani in 1974 and Mamdani and Assilian in 1975. A Mandani FIS has fuzzy inputs and a fuzzy output. The Mamdani type FIS is manually constructed on the basis of expert knowledge and the final model is neither trained nor optimized. Mamdani type FIS uses a set of linguistic rules obtained from experienced human operators (Mamdani and Assilian, 1975). The main feature of such type of FIS is that both the antecedents and the consequents of the rules are expressed as linguistic constraints (Zadeh, 1997). Mamdani type FIS can provide a highly intuitive knowledge base that is easy to understand and maintain. Therefore, this type of FIS is more widely used, mainly in decision making applications. Both models are similar and consider fuzzy inputs but Mamdani returns fuzzy outputs while Takagi–Sugeno returns crisp outputs (Mamdani, 1974; Takagi and Sugeno, 1985). Since Mamdani approach is not exclusively dependent on a data set, with sufficient expertise on the system involved, a generalized model for effective future predictions can be obtained (Keshwani *et al.*, 2008). As completely linguistic form of rules in Mamdani models has advantages in the representation of expert knowledge and in the linguistic interpretation of dependencies. It allows us to describe the expertise in more intuitive, more human-like manner. This study would apply the Mamdani type inference to predict the parameters.

Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. Because of its multidisciplinary nature, FISs are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply fuzzy systems.

Fuzzy inference process comprises of five parts: fuzzification of the input variables, application of the fuzzy operator (AND or OR) in the antecedent, implication from the antecedent to the consequent, aggregation of the consequents across the rules, and defuzzification.

A typical FIS can be described in four steps which are; fuzzification, fuzzy rules, fuzzy inference and defuzzification (Figure 4.2).

Step 1: (*Fuzzification*) Fuzzification process involves the definition of the membership functions of input/output variables by linguistic variables. In this study, triangular membership functions are used for the representation of linguistic expressions of input/output variables because of simplicity.

Step 2: (*Fuzzy rules*) A FIS with i-input variables has $r = p^i$ rules, where p is the number of linguistic terms per input variable. As the dimension and complexity of a system increase, the size of the rule base increases exponentially.

The rules for the present study are structured as:

$$\text{IF } I_1 \text{ is } \tilde{A}_1^j \text{ AND } I_2 \text{ is } \tilde{A}_2^j \text{ AND } \ldots I_n \text{ is } \tilde{A}_n^j \text{ THEN } y \text{ is } \tilde{B}^j \text{ for } j = 1,2,\ldots,r \tag{4.1}$$

where I_i $(i = 1,2,\ldots,n)$ are input variables and y is the output variable, $\tilde{A}_1^j$, $\tilde{A}_2^j$, $\ldots$, $\tilde{A}_n^j$ and $\tilde{B}^j$ are the linguistic terms used for the membership function of the corresponding input and output variables for the j^{th} rule, respectively.

Step 3: (*Fuzzy inference*) Fuzzy inference is an inference procedure to derive a conclusion based on a set of if–then rules. In this study, Mamdani method is applied for fuzzy inference. The Mamdani inference method is manually constructed on the basis of expert knowledge and the final model is neither trained nor optimized. The method considers fuzzy inputs and returns fuzzy outputs (Mamdani, 1974). Since Mamdani approach is not exclusively dependent on a data set, with sufficient expertise on the system involved, a generalized model for effective future predictions can be obtained (Keshwani *et al.*, 2008). The mechanism of Mamdani inference method is as follows: (1) If there is more than one input in the rule, fuzzy set operations should be applied to achieve a single membership value; (2) then implication method (min) is applied to reach each rule's conclusion; (3) the outputs obtained for each rule are combined into a single fuzzy set, using a fuzzy aggregation operator (max).

For the case where input variables I_i $(i = 1,2,\ldots,n)$ are crisp variables and the fuzzy rules are described by Equation (4.1), so for a set of disjunctive rules, where $j = 1,2,\ldots,r$, the output using Mamdani inference method is formulated as follows (Ross, 2004);

$$\mu^{j}_{\tilde{B}}(y) = \max_{j} \left\lfloor \min \left\lfloor \mu^{j}_{\tilde{A}_1}(I_1), \mu^{j}_{\tilde{A}_2}(I_2), \ldots, \mu^{j}_{\tilde{A}_n}(I_n) \right\rfloor \right\rfloor \tag{4.2}$$

Step 4: (*Defuzzification*) Through fuzzy inference, the result can be converted into a definite value. In this study the center of area defuzzification method is used in order to get the advantage of its continuity and disambiguity. Center of area (also called centroid method or center of gravity method) is the most prevalent and physically appealing of all the available defuzzification methods (Ross, 2004). It is given by the algebraic expression as follows:

$$c* = \frac{\int \mu_{\tilde{C}} \cdot c \cdot dc}{\int \mu_{\tilde{C}} dc}, \qquad c \in \tilde{C} \tag{4.3}$$

where $\tilde{C}$ is a fuzzy set having the membership function $\mu_{\tilde{C}}$.

The graphical illustration of the used FIS is represented in Figure 4.2.

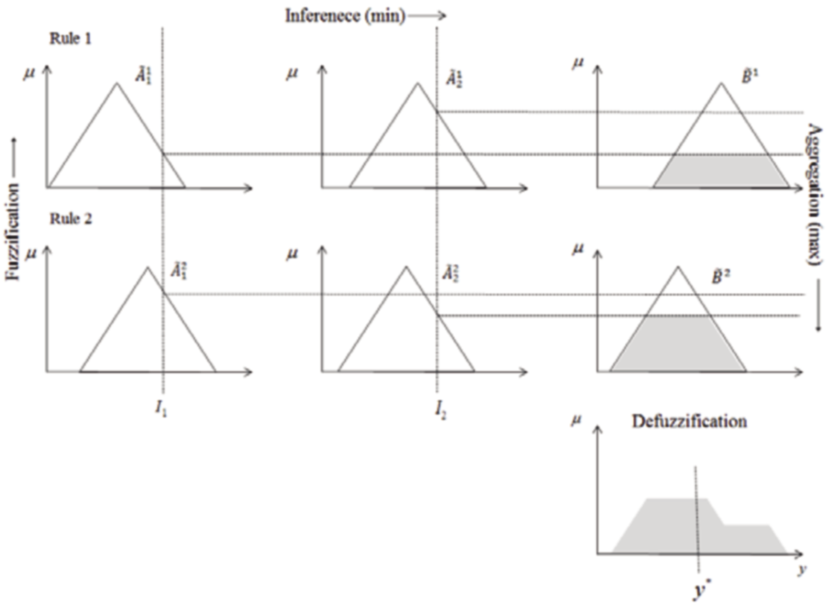

Fig. 4.2 Graphical Mamdani (max-min) inference method

4.4 Literature Review

Disasters are unpredictable and have highly destructive effects that cause a great uncertainty in disaster management. Fuzzy set theory is used to deal with the uncertainty in disaster management areas such as forecasting earthquake damages, flood damages and landslide susceptibility analysis, safety monitoring of hillsides, developing fire protection policies... etc.

Cret *et al.* (1993) use the fuzzy set theory and fuzzy decision analysis to estimate earthquake damage. They proposed a system to formalize knowledge acquired from experience and assess earthquake damage from ground conditions and ground motion characteristics. Fuzzy damage indices are generated from the results of the proposed system. Fuzzy decision analysis is used to transform this imprecise information into distinct decision on whether to cut or maintain the gas supply in a given area of the network.

Huang and Leung (1999) propose a hybrid fuzzy neural network to determine the relationship between isoseismic area and earthquake magnitude.

Şen (2011) proposes a method to classify the buildings in terms of their weaknesses for a possible earthquake. The most important building factors that would affect the impacts of earthquake on the buildings and their relationships with the five hazard categories are determined by fuzzy numbers. The relationships are presented through a supervised hazard center classification method.

Chang and Chang (2006) use the adaptive network-based FIS to build a prediction model for reservoir management. A reservoir in Taiwan which came across a large number of typhoon and heavy rainfall events in past years was used as a case study to illustrate the applicability and capability of the adaptive network-based FIS.

Shiri and Kisi (2010) investigate the application of hybrid wavelet-neuro-fuzzy model to model daily, monthly and yearly stream flows which are important as it determines the reservoir inflow as well as the flooding events.

Akter and Simonovic (2005) propose a methodology to capture the views of multiple stakeholders which are associated with flood management decision making problems by using fuzzy set theory and fuzzy logic. By using fuzzy expected value three different possible forms of individual stakeholders' input are analyzed to obtain the aggregated input.

Simonovic and Akter (2006) use fuzzy expected value input with the multi-criteria decision-making tool named Fuzzy Compromise Programming. The methodology has been applied to floodplain management in the Red River Basin, Canada that faces periodical flooding.

Chang *et al.* (2008) propose the counter propagation fuzzy-neural network for extracting flood control knowledge in the form of fuzzy if–then rules to simulate a human-like operating strategy in a city flood control system through storm events. The Yu-Cheng pumping station, Taipei City, is used as a case study.

Topuz *et al.* (2011) propose an approach that integrates environmental and human health risk assessment for industries using hazardous materials in order to support environmental decision makers with quantitative and directive results. Analytic hierarchy process and fuzzy logic are used as tools to handle problems caused by complexity of environment and uncertain data.

Cheng and Ko (2002) describe the development of a decision support system for safety monitoring of hillsides by using fuzzy set theory.

Saboya Jr. *et al.* (2006) use fuzzy logic to evaluate the susceptibility of occurrence of landslides in the areas where landslides are susceptible to occur. The methodology is applied to identify the susceptibility of landslides in a chaotic occupied urban area of Rio de Janeiro, Brazil, where some occurrences have been reported.

Dokas *et al.* (2009) integrate fuzzy expert systems, fault tree analysis and worldwide web technologies and applied in the development of the landfill operation management advisor which is a novel early warning and emergency response system for solid waste landfill operations.

Sezer *et al.* (2011) establish the results of an adaptive neuro-FIS model using remote sensing data and geographical information system for landslide susceptibility analysis in a part of the Klang Valley areas in Malaysia.

Oh and Pradhan (2011) present landslide susceptibility mapping using an adeptive neuro FIS using a geographic information system environment.

Chang and Chien (2006) use a fuzzy–neural hybrid system to simulate typhoon waves. A membership function based on the fuzzy theory is expressed by a union Gaussian function to illustrate the rapid wave decaying.

Iliadis and Spartalis (2005) propose a two level method to develop a rational and sensible protection policy from natural disasters. On the first level the annual forest fire risk for each area of Greece is estimated by using fuzzy trapezoidal membership function. On the second level a narrow expected closed interval for the burned area are forecasted by using a fuzzy expected interval model.

Iliadis (2005) proposes a decision support system which applies an inference mechanism based on various aspects of fuzzy sets and fuzzy machine learning techniques to develop a rational and sensible forest fire prevention and protection policy.

Liu *et al.* (2010) present a geographical information system and information diffusion based methodology for risk analysis of grassland fire disaster to livestock production in the grassland area of the northern China.

Huang and Inoue (2007) discuss three soft risk maps of a flood, a drought and an earthquake which are aimed at the visualization of risk levels of natural disasters defined by fuzzy probabilities.

In the above literature review, it is found that the papers using fuzzy set theory in disaster management focus on estimating the magnitude of the disasters such as fires, earthquakes and floods. Therefore we can conclude that, to the best of our knowledge, there is limited number of fuzzy set theory based studies on disaster management, particularly on disaster response. Hence we aim at modeling a FIS for spontaneous volunteer management, which is one of the important activities in disaster response.

4.5 A Fuzzy Inference System for Spontaneous Volunteer Management

Spontaneous volunteer management is one of the important parts of disaster response process. Potential spontaneous volunteers are individuals or groups of people who seek or are invited to contribute their assistance during and/or after an event and who are unaffiliated with any part of the existing official emergency management response and recovery system and may or may not have relevant training, skills or experience (URL-2). The spontaneous, unaffiliated volunteers, who are often our neighbors, friends, and ordinary citizens, frequently arrive at a disaster scene to give help. But because they are not connected with any part of the existing emergency management response system, group, or organization, their offers of help are regularly underutilized and can even be challenging to most professional responders (Gallant, 2008). Uncoordinated or uncontrolled spontaneous volunteers can interfere with disaster relief operations and cause a secondary disaster. To avoid such a situation volunteer management centers should be established away from the disaster scene and classification of volunteers should be managed in these centers in order to efficiently utilize volunteers.

At this stage, the classification decision is highly important for disaster response because of the limitation on the amount of water, food and waste disposal in the disaster area.

Table 4.1 Input variables of FIS

Input	Fuzzy variables	Fuzzy numbers
Age (A)	young middle age old	(18,18,45) (35,45,55) (45,65,65)
Compatibility of the physical characteristics (PC) Leading and management skills (LM) Human relations skills (HR) Computer knowledge (CK) First aid knowledge (FA) Driving experience (DE)	low medium high	(0,0,4) (2,5,8) (6,10,10)

Moreover, the time limitation is also an important factor which will force decision makers to make decisions in a limited time. Applicants for volunteer may have various motivation and skills. The aim of the volunteer management centers will be effectively assigning the volunteers to the pre-disaster or post-disaster activities by checking their knowledge and skills.

In this section, we offer a FIS developed by using MATLAB Fuzzy Logic ToolboxTM for spontaneous volunteer management. The first step of the FIS is the fuzzification process which involves the definition of the membership functions of input/output variables by linguistic variables. The input variables of the inference system will be the skills and qualifications of volunteers for the classification process. Since the aim of the volunteer management centers are effectively assigning the volunteers to the pre-disaster or post-disaster activities by checking their knowledge and skills, the output variables of the system will be these activities. For the input/output variables, triangular membership functions are used to represent the linguistic values.

For the volunteer classification process, the inputs of the FIS are determined as age, compatibility of the physical characteristics, leading and management skills, computer knowledge, first aid knowledge and driving experience. The input variables and the related linguistic variables and fuzzy numbers are represented in Table 4.1. Furthermore, we collected pre/post disaster activities into five groups as search and rescue, health and sanitation, safety and security, logistics and supply and communication to be the outputs of the proposed FIS. The compatibility of the volunteers to working in these activities is determined by linguistic variables represented by triangular fuzzy numbers (Table 4.2).

After the definition of the membership functions of input/output variables by linguistic variables, the fuzzy rules are structured. Fuzzy rules consist of IF-THEN rules and produce

Table 4.2 Output variables of FIS

Output	Fuzzy variables	Fuzzy numbers
Search and rescue (S&R)		
Health and sanitation (H&S)	very compatible	(0,0,0.4)
Safety and security (S&S)	compatible	(0.1,0.5,0.9)
Logistics and supply (L&S)	incompatible	(0.6,1,1)
Communication (COM)		

output values for the given input values to construct a classification framework for spontaneous volunteer management. In this study we totally structured 15 rules and these rules can be increased for a more detailed analysis. Three examples of structured rules are given below:

IF "A" is young and "PC" is high and "LM" is high and "HR" is high and "FA" is high, THEN S&R is very compatible,

IF "PC" is medium and "LM" is medium and "DE" is medium, THEN S&S is compatible,

IF "CK" is low, THEN COM is incompatible,

Subsequent to the construction of fuzzy rules, the fuzzy inference process is performed to derive a conclusion based on a set of IF-THEN rules. In this study, Mamdani method is used for fuzzy inference (Eq. (4.2), Figure 4.2). The input parameters for each volunteer are evaluated and the compatibilities of the volunteer to pre-determined activities are determined by FIS developed by using MATLAB Fuzzy Logic ToolboxTM. The proposed FIS is represented in Figure 4.3.

Let we have a volunteer with the following properties:

Age: 25
Compatibility of the physical characteristics: 8
Leading and management skills: 5
Human relations skills: 3
Computer knowledge: 9
First aid knowledge: 2
Driving experience: 6

When we operate FIS for the above input parameters we observe that this volunteer is very compatible to communication activity with 0.863 membership degree and he is also compatible to search and rescue, safety and security or logistics and supply activities with

Fig. 4.3 FIS for spontaneous volunteer management

0.5 membership and this volunteer is incompatible for health and sanitation with 0.153 membership degree (Fig. 4.4).

The output of the FIS shows that a volunteer with the above properties is a very suitable candidate for communication activity. However, if there is no more person required for communication activity than this volunteer, he/she can be assigned to search and rescue, safety and security or logistics and supply activities.

4.6 Conclusion

In this chapter we study disaster management as it is one of the most important phenomena in today's world. We particularly focused on the disaster response, which is one of the critical stages of disaster management. We used a FIS to deal with uncertainties inherent in a disaster response activity. As a result, this chapter describes potential applications of FISs in a disaster response system.

In the literature review it is found that the papers using fuzzy set theory in disaster management focus on estimating the magnitude of the disasters such as fires, earthquakes and floods. However, to the best of our knowledge there is limited number of works on disaster response using fuzzy set theory. Therefore our study can be considered as an initial

Fig. 4.4 Matlab output of fuzzy rules for spontaneous volunteer management

attempt to use fuzzy set theory in disaster response that provides a FIS for spontaneous volunteer management, which is one of the most critical activities of disaster response.

The proposed FIS is composed of fuzzy rules where the input and output parameters are both represented by fuzzy numbers. In the proposed FIS, we used Mamdani type inference in which the knowledge is obtained by extracting information thoroughly from experts. The system gives quick and flexible solutions to the problem defined in spontaneous volunteer management. For further research, we suggest using other type of inference systems based on data driven approaches including adaptive learning mechanisms such as Sugeno type inference system.

FIS can also be used for other activities of disaster response systems such as donation management, evacuation systems, emergency operations management, and also in other fields of disaster management.

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Chapter 5

Security Based Operation in Container Line Supply Chain: A Literature Review

Dawei Tang [1,*], Dong-Ling Xu [2], Jian-Bo Yang [2], and Yu-wang Chen [2]

[1] *Safety and Environment Assurance Center, Unilever Colworth, Colworth Science Park, Sharnbrook, Bedfordshire, UK, MK44 1LQ*
[2] *Manchester Business School, the University of Manchester, Manchester, UK, M15 6PB*

[*] *dawei.tang.wh@gmail.com*

Container Line Supply Chain (CLSC) plays a dominant role in world cargo transportation, but also subjects to various threats during its operation due to its inherent features. The threats can not only cause disruptions for CLSC operation, they may also lead to various disasters globally. To help to manage the potential disasters, in this chapter, current research on security for CLSC operation is reviewed. Specifically, the research is divided into three categories: (1)research from a general level, including standards, regulations, codes, etc. issued by international, national and industrial organizations, aiming at improving CLSC security, (2) research on specific security issues in CLSC, e.g., threats faced by CLSC, features of CLSC, criteria for security assessment of CLSC, etc., and (3) research on different risk analysis tools and their applications in CLSC security related areas. Further, the limitations of current research are also analyzed and potential directions for future research in this field are suggested.

5.1 Introduction

One of the most prominent features of modern business is that more and more companies, instead of operating on their own, are operating cooperatively within a supply chain. Supply chain, since its introduction into business operation, has played and will continue to play an important role in modern business. However, the level of risks involved in supply chain is also increasing due to some features of contemporary business, for example, trend of globalization and outsourcing (Chopra and Meindl, 2004; OECD, 2004), increasing product and service complexity (GAO, 2005), more rapid consumer demand changes (Sørby, 2003), shorter product lives (Sørby, 2003), and so on.

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As one of the major categories of supply chain, Container Line Supply Chain (CLSC), which transports cargo in containers, shares many common characteristics and risks with general supply chains. At the same time, it also has its unique features.

Since their introduction in the 1950s, containers have become increasingly important in world cargo transportation as it enables smooth and seamless transfer of cargo among various modes of transportation, and thus makes cargo movement much more efficient (Levinson, 2006; Wydajewski and White, 2002). It is estimated that approximately 95 percent of the world's trade moves by containers (OECD, 2003) and approximately 250 million containers are shipped annually around the world (DHS, 2007). These two figures clearly indicate that CLSC is a dominant means to ship cargo around the globe (Fransoo and Lee, 2011; OECD, 2005).

Despite the dominant role of CLSC in world cargo transportation, CLSC is also subject to many threats due to the following reasons:

- CLSC is complex. A typical container transaction involves as many as 30 different physical documents and at least 25 different organizations (Cooperman, 2004), including raw material vendors, semi-finished and finished product manufactures, exporters, shippers, freight forwarders, importers, consignees, and so on (Yang, 2011). Further, documents and organizations involved in CLSCs may spread all over the world. In addition, among many organizations involved, there is no single organization governing the international movement of containers (Bakir, 2007) and there is no single organization that has full responsibility for the CLSC security (OECD, 2003).
- CLSC is vulnerable. During the transportation process of a container, many different kinds of threats, including cargo theft, smuggling, stowaway, terrorist activity, piracy and even labor protest, can have a serious impact on CLSC. In addition, any breach in security in one part of CLSC may compromise the security of the entire chain (Bakir, 2007; Ø. Berleetal *et al.*, 2011; Khan and Burnes, 2007; Sarathy, 2006).
- CLSC operates with insufficient preventative measures. Despite the complexity and vulnerability of CLSC mentioned above, corresponding preventative measures against various threats are not sufficient. For example, nowadays, only about 2 percent of the imported containers are physically inspected in most countries (Closs and McGarrell, 2004), and the bill of lading, which states the contents of containers, is rarely verified through inspections of containers after packing or during transportation (OECD, 2003).

It can be easily concluded from the above discussion that there is a relatively high probability for the occurrence of disruptions and even failures of CLSC. On the other hand, the consequences of the disruptions or failures, which may include immediate consequences, cascading consequences and long-term consequences, may be severe. They may cause great human causalities, considerable financial loss, serious environmental pollutions, and even global disasters. For example, if a port is seriously damaged by the explosion of an atomic weapon, it may cause 100 billion dollars in port lock-out losses and 5.80 billion dollars in port recovery losses (Yang, 2011). It can be seen from the above that CLSC is operating in a highly risky environment.

Facing the fact that CLSC is a dominant but high risky means to transport world cargo, scholars and researchers have started paying increasing attention on studying security issues of CLSC in recent years, especially after the terrorist attack on September 11th, 2001. In this chapter, a brief review of current research on security issues in CLSC is provided to investigate what has been achieved in this field, to discuss the limitations of current research and to suggest potential directions for future research. Through the discussion in the chapter, the ultimate aim is to provide assistance for decision making relevant to management of potential disasters caused by CLSC security incidents.

The chapter is organized as follows. In Section 5.2, the concepts of risk, security and other related terms which will be used throughout this chapter are clarified. Section 5.3 is dedicated to reviewing current research on security issues in CLSC, including research on security issues in CLSC from a general level, research on different specific issues about security in CLSC and research on the applications of different risk analysis tools in CLSC security related areas. In Section 5.4, the limitations of current research are discussed on the basis of the above review, followed by the discussion of potential directions for future research. The chapter is concluded in Section 5.5.

5.2 Basic Definitions

Prior to reviewing current research on security issues in CLSC, some concepts need to be defined to clarify the boundary and provide a basis of the discussion in this chapter.

Specifically, as the chapter mainly focuses on CLSC security, the concepts of security should be defined. In addition, for some other terms which are closely related to security, such as risk, threat, hazard and especially safety, their concepts should also be defined for the clarification of the scope of security.

Currently, for different purposes, there are different definitions of risk, safety, security, hazard, threat and other related terms from different points of view (Firesmith, 2003; Jonsson, 1998; Lau, 1998; Sørby, 2003; Willis and Ortiz, 2004). According to the content of the research in this chapter and the opinions of different Port Facility Security Officers (PFSO) from interviews, the definitions which are used in this chapter are based on those proposed in (Firesmith, 2003):

- Safety: the degree to which accidental harm is prevented, detected, and reacted to;
- Security: the degree to which malicious harm is prevented, detected, and reacted to;
- Hazard: a situation that increases the likelihood of formation of one or more related accidental harms;
- Threat: a situation that increases the likelihood of formation of one or more related malicious harms;
- Risk: a term which is used to describe the likelihood of occurrence and the consequences of a hazard or a threat. Accordingly, risk can be categorized as hazard based risk and threat based risk. The 'risk' discussed in this chapter mainly refers to threat based risk.

From the above definitions, we can see that threat, threat based risk and security are the terms regarding malicious harm, while hazard, hazard based risk and safety are the terms regarding accidental harm. In addition, the relation among threat, threat based risk and security can be analyzed as follows: threat represents a certain state of a situation; threat based risk considers both likelihood of the threat and potential consequence caused by the threat; in addition to the likelihood and the potential consequence, security also considers the features of the party which is under the threat. Similar conclusion can be drawn for the relation among hazard, hazard based risk and safety.

5.3 Current research on security issues in CLSC

5.3.1 *Research on security issues in CLSC from a general level*

One of the most typical documents in this category is the ISPS Code (IMO, 2002a), which was issued by IMO in 2002. This code is released in response to the "perceived threats to ships and port facilities in the wake of the 9/11 attacks in the United States" (PECC, 2004). It is a "comprehensive set of measures to enhance the security of ships and port facilities" (IMO, 2002a), which covers the specifications of general responsibilities of contracting governments and ship companies; the general responsibilities of security officers in ship companies, individual ships and ports; the descriptions of different security levels of both ships and port facilities; the general requirements on development, training and drilling of ship and port facility security plans; the verification and certification for ships, and so on.

As nearly all CLSCs are operating internationally, customs, with their unique authorities and expertise, play a central role in ensuring CLSC's security (WCO, 2007). Correspondently, in 2007, WCO issued a SAFE Framework of Standards (WCO, 2007) to secure and also facilitate the movement of global trade. This framework is mainly based on two aspects: Customs-to-Customs network arrangements and Customs-to-Business partnerships. The former has 11 standards while the latter has 6 standards. In the standards, the responsibilities of different organizations along a whole chain of cargo custody, from stuffing site to unloading site, which were always ambiguous in the past, are clearly stated.

Another set of important documents relevant to CLSC security is the ISO 28000 series (ISO, 2007a; ISO, 2007b; ISO, 2007c; ISO, 2007d), which are the standards on security management systems for supply chains (LRQA, 2009; Piersall, 2007). Among the series, ISO 28000 (ISO, 2007a) is a general specification which introduces the elements for security management systems, including security management policy, security risk assessment and planning, implementation and operation for security management, checking and corrective actions, management review and continual improvement. ISO 28004 (ISO, 2007d) is a detailed explanation on ISO 28000, which explains each part of ISO 28000 in 4 dimensions, i.e., intent, typical inputs, process and typical output of each part.

Besides the documents issued by international organizations, some regional initiatives are also developed. For example, in Europe, the ISPS Code is incorporated into the EC Regulation 725/2004 (EC, 2004; TRANSEC, 2011); EC Regulation 884/2005 sets the procedures for conducting EC inspections in the field of maritime security (EC, 2005a); and EC Directive 65/2005 aims at enhancing security throughout ports (EC, 2005b; TRANSEC, 2011). In addition, Authorized Economic Operator (AEO) is introduced by EC to CLSC operators in Europe in 2005 (EC, 2005b) to encourage organizations involved in CLSCs to enhance security in their operation.

All the documents mentioned above focus on sea transportation of cargo. However, in CLSC, a container's voyage contains not only sea transportation but also inland transportation, the security issues of which need to be considered as well. As such, the International Shippers and Freight Forwarders Security Code (ISFFS Code) was proposed in 2003 by International Trade Procedures Working Group (ITPWG) of United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) (ITPWG, 2003). This code mainly develops a set of requirements to ensure the security of cargo transported by road, rail or inland waterways, including requirements on stuffers and packers; requirements on warehouses, storage areas and terminals; requirements on forwarders and transporters; requirements on information processors, and so on. For each category, the requirements are further categorized according to pre-defined security levels.

Apart from the efforts of international/regional organizations, U.S. government also issued initiatives concerning CLSC security under the threats of terrorists. Among the initiatives, the Container Security Initiative (CSI) (CBP, 2002a) and the Customs-Trade Partnership against Terrorism (C-TPAT) (CBP, 2002b) are two of the most important ones. Both the initiatives were issued around 2002 by Customs and Border Protection (CBP), a component of Department of Homeland Security (DHS). Both of them are developed in response to "security vulnerabilities created by ocean container trade and the concern that terrorists could exploit these vulnerabilities to transport or detonate Weapons of Mass Destruction (WMD) in the United States" (GAO, 2003). The emphasis of CSI is the requirement to examine highly risky cargo at foreign ports before they are loaded on a vessel heading to the United States (Robert and Kelly, 2007). It is a government to government initiative. On the other hand, the emphasis of C-TPAT is the requirement to improve global supply chain security by private sectors along the whole supply chain (GAO, 2003). To be more specific, it is a voluntary program between private sectors and customs, which contains 22 key elements. It is a government to business initiative. In addition to CSI and C-TPAT, another major program to improve U.S. marine security is the 24-hour Advance Cargo Manifest Declaration Rule, which requires that containers must be manifested at least 24 hours before they are loaded to any US-bound vessel. The information submitted facilitates the targeting and pre-screening of suspected containers. Similar to the 24-hour rule, a 96-hour rule, which relates to ships rather than cargo, is also proposed by DHS. The rule requires that all ships calling at U.S. ports should provide a notice of arrival 96 hours in advance to the U.S. government, which makes it possible for the U.S. government to target particular ships for which it has security concerns (Pinto, *et al.*, 2008).

The effective area of CSI, C-TPAT and ISPS Code along CLSC can be shown in the Figure 5.1 as follows (OECD, 2003):

More recently, DHS issued a "Strategy to Enhance International Supply Chain Security" (DHS, 2007) in response to the Security and Accountability For Every Port Act (SAFE

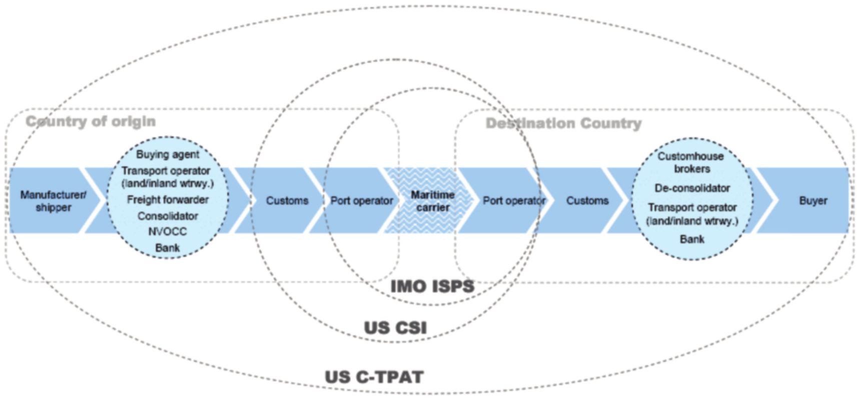

Fig. 5.1 Effective area of CSI, C-TPAT and ISPS Code

Port Act) (US Congress, 2006), which is a public law aiming to improve maritime and cargo security through enhanced layered defenses. The strategy issued by DHS intends to establish an overarching framework for the secure flow of cargo through supply chains. The strategy identifies critical nodes along an international supply chain, delineates the roles and responsibilities of different organizations involved, and most importantly, explains necessary responsive activities and factors that need to be considered during the recovery process after a disruption. These response and recovery issues are seldom mentioned in other similar documents.

In addition to the documents issued by governmental and international/regional organizations, some industrial organizations also developed certain initiatives for CLSC security. For example, Transported Asset Protection Association (TAPA) developed a set of requirements and standards to assess the security of organizations involved in CLSCs, such as Freight Security Requirement (FSR) which specifies the minimum acceptable standards for security throughout the supply chain and the methods to be used in maintaining those standards (TAPA, 2011), and Trucking Security Requirement (TSR) which specifies the minimum acceptable standards for security throughout the supply chain utilizing trucking and associated operations and the methods to be used in maintaining those standards (TAPA, 2008). TSR may be used in conjunction with FSR.

Further, some academic papers also discuss security related issues in CLSC from a general level. For example, current legislations on port safety and security are reviewed and current security situations faced by ports and EU inter-model transportation are discussed (Psaraftis, 2005). Security measures taken by the U.S. government and international organizations are reviewed and the development of a global agreement to ensure security of CLSC is also suggested to link security and other maritime trade-related issues together (Stasinopoulos, 2003). Key shore-based and near shore activities associated with maritime operations, which are currently not covered by ISPS Code, are identified, relationships among the activities are investigated, and key criteria for a good marine security management system are studied (Paulsson, 2003). The impacts of CSI on maritime supply chains, especially financial impacts are analyzed in general by Banomyong (2005). In addition, Helmick discusses what had been done and what should be done in the field of port and marine security (Helmick, 2008), indicating that further refinement and standardization of risk based decision methodologies and applications are clearly needed, including comprehensive threat assessment, consideration of vulnerability variables through the whole global supply chain, quantification of relative risks and uniform risk assessment methodologies, etc.

In a word, this stream of research focuses on a general level, aiming at developing and discussing strategies, policies, principles, specifications, requirements, etc. to enhance CLSC security. It is the basis and general guidelines of all the research on security issues in CLSC. However, this stream of research is too general for the development of analytical CLSC security analysis models and the generation of detailed and specific measurements to ensure CLSC security.

5.3.2 *Research on specific issues of security in CLSC*

5.3.2.1 *Research on features of CLSC and threats faced by CLSC*

Considering the features of CLSC and threats faced by CLSC, OECD issued several reports. In the report issued in 2005 (OECD, 2005), which concentrates on container transport security across inland and marine transport mode under the potential threat of containers being used by terrorists as a delivery vehicle for chemical, biological, radiological or nuclear (CBRN) weapons, the features of a container transport chain are analyzed in detail. Based on the analysis, the nature of CBRN threat is also revealed. In the report issued in 2003 (OECD, 2003), threats faced by maritime transport are analyzed based on the following categories: cargo, vessels, people, finance/logistics support and trade disruption. Research in the above areas can provide general knowledge on how CLSC is operating and how vulnerable CLSC is to different threats. The knowledge provides a background for CLSC security analysis.

5.3.2.2 *Research on security assessment criteria of CLSC and components of security plans in CLSC*

In some literature, general criteria for CLSC security assessment are analyzed and the essential components of security plans are discussed.

In ISPS Code (IMO, 2002a), the topics of security assessment and security plans for both ships and port facilities are two of the most important contents. In the ISPS Code, data required by security assessment and components required to develop a security plan are specified in detail.

In the SAFE Framework of Standards (WCO, 2007), elements considered by AEOs and Customs can be broadly divided into several categories, including cargo security, conveyance security, premises security, personnel security, trading partner security and crisis management & incident recovery. These categories indicate high-level criteria when CLSC security needs to be assessed.

In ISO 28001 (ISO, 2007b), the best practices for implementing supply chain security assessments and security plans are discussed, including process and criteria for security assessment and essential components for a security plan in a general level.

Another literature about assessment criteria is a report issued by RAND Cooperation in 2004, which is one of the first of a series of studies on the topic of supply chain security (Willis and Ortiz, 2004). In the report, five capabilities, regarding the efficiency and security of global container supply chain, are proposed, and the capabilities can be considered as general criteria for CLSC security assessment.

The criteria discussed in the above literature are proposed according to different emphases on security issues in CLSC from different points of view. A comprehensive understanding of the criteria can help to construct a set of high-level attributes for CLSC security assessment. Research on essential components of a security plan reveals aspects to be considered to respond to different security incidents, which is also important for security assessment since responding capability is one of the elements which needs to be considered when CLSC security is analyzed.

5.3.2.3 *Research on countermeasures of CLSC facing different threats*

The countermeasures of CLSC against different threats can be roughly divided into 3 categories: managerial measures, operative measures and technical measures.

Managerial countermeasures refer to policies, regulations, requirements or general methodologies used to respond to threats faced by CLSC. For example: in ISO 28001 (ISO, 2007b), a general methodology for developing countermeasures is proposed; in ISO 28003 (ISO, 2007c), regulations for audit or certification agencies of supply chain security management systems are discussed; in the WCO Safe Framework of Standards (WCO, 2007), requirements on the information of imported and exported cargo are provided, which needs to be submitted to customs; regulations about how to provide critical data of maritime security incidents to first responders are also developed (Wydajewski and White, 2002).

Operative countermeasures refer to actions taken by different operators in CLSC to make it more secure. In C-TPAT (CBP, 2002b), 22 key elements are proposed. The operative countermeasures mentioned in the elements include employee background checks, inspection of empty containers, and so on. The operative countermeasures proposed by Bakir (2007) include access control, security awareness training, standardization of paperwork security and maintaining the security of warehouse perimeters. Other operative countermeasures include continuously reviewing and updating security procedures (Closs and McGarrell, 2004), developing contingency plans (Tang, 2006), securing container integrity (OECD, 2005), and so on.

Technical countermeasures refer to technologies which can be used to enhance CLSC security. The countermeasures include the application of newly developed information technologies (Noda, 2004) and data mining technologies (Lee and Wolfe, 2003), the implementation of Non-Intrusive Inspection (NII) technologies like X-ray or Gamma-ray scanning (Hessami, 2004), the introduction of so-called 'smart containers' (Kim, *et al.*, 2008; Robert and Kelly, 2007), Radio Frequency Identification (RFID) technique (Yoon. et al, 2007), tracking technique (David, 2005 ; Tsamboulas, 2010), high capable seals (McCormack, *et al.*, 2010; Tirschwell, 2005 ; Tsamboulas, 2010) and so on.

Note that the above 3 categories of countermeasures are not independent of each other, e.g., managerial countermeasures are implemented through operative countermeasures, while technical countermeasures provide support to both managerial countermeasures and operative countermeasures.

All the 3 categories of countermeasures mentioned above can provide ideas on how to improve CLSC security and which factors should be considered when CLSC security is analyzed.

5.3.2.4 *Research on cost and performance estimation for implementation of security related measures*

The report issued by OECD in 2003 (OECD, 2003) proposes a method to estimate costs for implementation of different initiatives to enhance maritime security. Specifically, it mainly estimates the implementation costs of ISPS Code through the estimation of costs to implement each part of the Code.

Performance estimation can be found from a series of reports issued by United States Government Accountability Office (GAO). One of the roles of GAO is to assess the performance of CSI and C-TPAT during their implementation. Based on the assessment, recommendations can be generated to help CBP improve the performance of CSI and C-TPAT. In 2003, shortly after CSI and C-TPAT were implemented, GAO issued the first report to assess their performance (GAO, 2003). One of the problems revealed by GAO in the report is that there lacks a set of criteria to measure the performance and achievements of the two initiatives. In 2005, another report (GAO, 2005) was issued by GAO to follow up the recommendations proposed in the previous report. In this latter report, it was stated that progress had been made in developing performance criteria for assessing the initiatives' performance, but the criteria mainly focused on the performance of information sharing and collaboration among CSI and host country personnel, and they could not be used to measure the effectiveness of CSI targeting and inspection activities. Following this assessment result, CBP refined overall CSI performance criteria, but the criteria for core CSI functions are still absent, as indicated in a report issued by GAO in 2008 (GAO, 2008).

In CLSC security analysis, one of the most important tasks is to allocate resources, e.g., budgets, human resources, hardware facilities, etc. to improve the security of organizations involved in CLSC. As resources are always limited, it is necessary to utilize resources in an efficient and effective way. Accordingly, the consumption of resources for different alternatives to improve security should be estimated. As budgets are the most common resources for security improvement, the estimation of costs incurred by implementing different security improvement alternatives is very important. In addition, different measures for security improvement have different impact on security, so performance estimation is also essential for security analysis as the impact of different measures on the performance of relevant factors related to CLSC security should be estimated. The literature reviewed in this part can provide a rough and initial idea on how cost and performance can be estimated.

5.3.2.5 *Summary*

The research reviewed in this section aims at exploring different aspects of CLSC and is more specific than what is discussed in Section 3.1. Several preliminary ideas, which can be applied and further developed in the research on security analysis in CLSC, are discussed in this section. However, nearly all these ideas are proposed in a subjective and descriptive way and there lacks an analytical and structured model for CLSC security analysis, which can help to generate practical and specific suggestions on how CLSC security can be ensured and maintained.

5.3.3 *Research on risk analysis methods with their application in the areas relevant to CLSC security analysis*

When risk and security analysis methods are discussed, the most fundamental question is how to model the concept of risk and security. In other words, what are the basic components of risk and security? Usually, risk is described by two components, i.e., the likelihood of occurrence of an undesirable event and the severity of its consequences (Aagedal *et al.*, 2002; Bahr, 1997; Butler, 2002; IMO, 2002b; Li and Cullinane, 2003). Although security shares some common characteristics with risk, there are still subtle differences between these two concepts, as discussed in Section 2, and thus components used to analyze and model risk and security may not be exactly the same. However, components appropriate for security modeling are not widely discussed in previous research.

Based on the components of risk, different methods for risk analysis are proposed, but few of them are specifically applied to risk analysis under the context of CLSC. Thus, the methods reviewed in the following are mainly about risk analysis in general supply chains or risk analysis in individual marine operations.

The research on risk analysis in general supply chains began only recently (Khan and Burnes, 2007; Rao and Goldsby, 2009), and most research is conducted in a descriptive and qualitative way. For instance, the relation between product design and supply chain risk was discussed (Khan *et al.*, 2008); a conceptual framework for supply chain risk management was developed (Manuj and Mentzer, 2008); a general framework for natural disaster response of a supply chain was proposed based on interviews with logistics managers (Perry, 2007); while Christopher and Lee (2004) discussed the impact of visibility on supply chain risk; and Giaglis *et al.* (2004) proposed an architecture for minimization of logistics risk by routing vehicles in real time using mobile technologies. On the other hand, for limited quantitative research related to risk issues in general supply chains, some discussions lie in the analysis of inventory risk, demand risk, supply risk and transportation risk for individual organizations in supply chains (Tomlin, 2006; Towill, 2005; Wilson, 2007), while other discussions focus on modeling relationships among supply chain risk and supply chain efficiency and profitability (Agarwal and Seshadri, 2000; Wang and Webster, 2007). In summary, for risk analysis in general supply chains, there is not enough analytical research conducted, and among the limited research conducted quantitatively, information needed for risk analysis models is measured numerically. In addition, in existing quantitative research, very limited attention has been paid to the analytical risk assessment of the whole supply chain.

Among the methods for risk analysis related to marine operations, Formal Safety Assessment (FSA) is widely applied, which is introduced by IMO as "a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO's options for reducing these risks" (IMO, 2002b). According to FSA, safety assessment is conducted through the following 5 steps: hazard identification, risk analysis, Risk Control Options (RCO) development, Cost Benefit Assessment (CBA) and recommendations for decision making. In addition to the introduction by IMO, there are also some academic papers discussing the topic of FSA. For example, FSA is applied to analyze risk in individual containerships (Wang and Foinikis, 2001), cruise ships (Lois, *et al.*, 2004) and general ships (Wang, 2001); it is also introduced with several practical applications in the UK, Germany and some Scandinavian countries (Soares and Teixeira, 2001); in addition, a review process, i.e., FSA qualification, is introduced to support the consolidation of confidence in FSA results (Rosqvist and Tuominen, 2004) and a critical review of FSA with detailed introduction and analysis for each step of FSA is also proposed (Kontovas and Psaraftis, 2009). Although FSA has been adopted by IMO since 2002, and it has been applied in various situations by researchers, it also has its limitations. For example, FSA only provides a general framework and process for safety analysis, and there is limited practical guidance on how to conduct different steps in the process; when FSA is applied in different situations, risk is usually represented by an index number (Kontovas and Psaraftis, 2009; Lois, *et al.*, 2004; Rosqvist and Tuominen, 2004; Wang and Foinikis, 2001), which may lead to information loss (Kontovas and Psaraftis, 2009); in addition, the uncertainty, which is prevalent in risk and safety analysis in maritime operation, are seldom discussed in the applications of FSA; further, all the applications of FSA focus on individual maritime operators instead of a whole supply chain.

Another category of methods for risk analysis related to marine operation is based on probabilities. For example, Event Tree Analysis (ETA) are applied for vulnerability assessment of a maritime transportation system (Ø. Berleetal *et al.*, 2011); both Fault Tree Analysis (FTA) and ETA are introduced to risk assessment in shipping and ports (Bichou, 2008); in addition, Fault Trees and Event Trees are used to model a general risk management framework for a maritime supply chain (Yang, 2011), and ETA and FTA are also introduced under the framework of FSA (Kontovas and Psaraftis, 2009). In addition to FTA and ETA, Bayesian Network (BN) is another tool used for risk analysis in the areas relevant to CLSC. Specifically, BN is used under the framework of FSA by Kontovas and Psaraftis (2009), it is also used to assess safeguards to secure supply chains (Pai, *et al.*, 2003) and to assess risk of container supply chain (Yang, 2006). Although ETA, FTA and BN have the capability to handle uncertainty involved in security analysis in CLSC, they can only handle the uncertainty caused by randomness. However, due to the complexity of CLSC operation, not all uncertainty involved in CLSC security analysis are caused by randomness, and uncertainty can also be caused by fuzzy information or ignorance in subjective judgments. In addition, the precise probabilities required by ETA, FTA and BN are usually very difficult to generate under the context of CLSC security analysis, as there is usually insufficient historic data available to generate probabilities in an objective way (Bichou, 2008). Even available information is usually not sufficient for experts to specify probabilities according to their subjective knowledge.

To avoid specification of precise probabilities, Fuzzy Logic is applied for risk analysis in port operations (Ung, 2007), offshore engineering (Ren, *et al.*, 2009) and container supply chains (Yang, 2006). However, the rationality of fuzzy arithmetic is always arguable, and the way to aggregate information based on fuzzy logic leads to information loss.

Moreover, some methods in Artificial Intelligence are applied for risk analysis for marine operations and one of the examples is the application of Artificial Neural Network (ANN) for risk assessment in port operations (Ung, 2007). Although ANN is a well developed method, it is a ‘black box’ method which cannot explicitly show its inference process.

Apart from the above methods, the Evidential Reasoning (ER) approach, which is based on Dempster-Shafer theory (Shafer, 1976), was developed in early 1990’s (Yang and Singh, 1994) and improved in 2000’s (Yang and Xu, 2002). The ER approach has been applied to analyze risks in offshore engineering systems (Liu, *et al.* 2005; Ren, *et al.*, 2005; Sii, *et al.*, 2005) and to assess risk of container supply chains (Yang, 2006). Compared with the methods reviewed above, the ER approach has the following two major advantages: 1) it has a solid mathematical basis (Shafer, 1976); and 2) with the introduction of the concept of belief distribution, information with different features and different kinds of uncertainty can be accommodated and handled by the ER approach under a unified framework, and there is no information loss during the reasoning process. Based on the ER approach, RIMER was proposed (Yang, *et al.*, 2006). Under the framework of RIMER, belief distributions are used to model individual factors threatening CLSC security, and Belief Rule Bases (BRB), which incorporates belief distributions into conventional rule bases, are applied to model the relations among the factors. Apart from the advantages of the ER approach as mentioned above, RIMER is capable and flexible in representing knowledge contained in inference models, and unlike ANN which is a 'black box' method, the inference process of RIMER is transparent.

From the above discussion, it can be seen that compared with other methods as reviewed above, RIMER can be considered as a potential basic tool for CLSC security analysis.

5.4 Summary and limitations of current research and potential directions for future research for CLSC security

From the above discussions, we can find several features of current research relevant to CLSC security analysis:

- There is preliminary research on CLSC security. However, the research is either in a very general level, e.g., regulations, codes, initiatives issued by different organizations, or only subjective and descriptive in discussing specific security issues of CLSC, and the analytical discussions on CLSC security are not enough (Rao and Goldsby, 2009; Tsamboulas, 2010; Yang, 2011), which makes practical and specific guidance on how to improve CLSC security absent;
- There are a number of methods available for analytical risk analysis, and some of them are applied in the areas close to CLSC security analysis. However, most of the methods have limitations when they are directly applied for security analysis in CLSC;
- The research on analytical CLSC security analysis is seldom conducted

In addition, the characteristics of CLSC relevant to security analysis can be summarized as follows according to the literature reviewed in this chapter:

- CLSC is dominant in world cargo transportation, the operation of CLSC is very complex, and CLSC is vulnerable to various threats during its operation;

- Organizations involved in a CLSC are not operating independently, there are interactions among organizations;
- Due to the complexity of CLSC, the factors which can influence CLSC security may spread all over the world, and it is unlikely that all the factors can share the same nature;
- Due to the complexity of CLSC, uncertainty is inevitable and prevalent in CLSC operation (Bichou, 2008; Rao and Goldsby, 2009). In addition, the sources of uncertainty are various;
- Although CLSC security has started attracting attention of different organizations and various researchers recently, historical data regarding CLSC security incidents are very limited (Bichou, 2008; Kontovas and Psaraftis, 2009);

Based on the above features of current research and the above characteristics related to CLSC security analysis, the potential directions for future research for CLSC security and the corresponding requirements are suggested as follows:

- Developing structured frameworks to identify, model and measure different factors as well as analytical relationships among the factors for CLSC security analysis. The framework should be developed under the context of the whole supply chain instead of individual organizations within supply chains. In other words, the relations and interactions among different organizations in a CLSC should be considered in the framework. In addition, the framework should be able to accommodate factors and knowledge involved in the security analysis process with different features and different kinds of uncertainty;
- Developing new methods or enhancing the capability of existing methods to rationally assess the security level of a certain CLSC with different kinds of uncertainty involved in assessment processes taken into consideration. The generation of parameters needed for the methods should not be heavily dependent on historical data; experts' judgments should play a key role in the specification of the parameters; the bias of judgments should be minimized and the consistency of the judgments should be maintained;
- Developing new methods to improve CLSC security in a cost-effective way based on CLSC security assessment result. The outcome generated by the methods should be able to provide practical and specific suggestions on how to maintain and improve CLSC security;
- Applying the frameworks and methods to analyze the security of specific CLSCs.

5.5 Conclusion

In this chapter, the concept of risk, safety, security and other related terms are discussed first and current research on security issues in CLSC is reviewed. In general, the current research can be divided into 3 categories, i.e., research on security issues in CLSC from a general level, research on specific issues about security in CLSC and research on the application of risk analysis tools in CLSC and related areas. From this review, it can be concluded that the research on CLSC security is still at its early stage, and is mainly descriptive and subjective. There is a clear need to develop analytical and/or quantitative methods to analyze CLSC security, which should be developed in the context of a whole supply chain with capability to accommodate different forms of information with different kinds of uncertainty. The specification of parameters in such methods should be based on experts' knowledge and outcomes generated should provide practical and specific suggestions on how CLSC security can be maintained and improved and how potential disasters which may be caused by CLSC security incidents can be managed.

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Chapter 6

A Linguistic-Valued Information Processing Method for Fuzzy Risk Analysis

Li Zou [1], Zheng Pei [2], Da Ruan [3], and Yang Xu [4]

[1] *School of Computer & Information Technology, Liaoning Normal University, Dalian 116029, China*
[2] *School of Mathematics & Computer Engineering, Xihua University, Chengdu 610039, China*
[3] *SCK • CEN & Ghent University, Boeretang 200, 2400 Mol, Belgium*
[4] *Intelligent Control Development Center, Southwest Jiaotong University, Chengdu 610031, China*

E-mail: zoulicn@163.com, pqyz@263.net, xuyang@home.swjtu.edu.cn

Risk analysis is a crucial issue to be handled in disaster management. Fuzzy risk analysis, i.e., risk analysis model using fuzzy set theory aims to assess the risk of hazard event under incomplete or imprecise environment. In practice, the evaluations of risk is always expressed by linguistic values in natural language. In this chapter, we present two approaches for fuzzy risk analysis with linguistic evaluation values. The first approach is based on the unbalanced linguistic weighted geometric operator, which can be used to deal with aggregation of unbalanced linguistic risk evaluation values with numerical weights or linguistic weights. The advantage of the approach is that the evaluation result is linguistic value which is no need of approximation processing and easier to communicate to decision and policy-makers. The other approach is based on linguistic truth-values lattice implication algebra from the logical algebraic point of view. We discuss the operations and special properties of the lattice implication algebra with evaluation-10 linguistic evaluation values. The reasoning and aggregation process directly act on the linguistic evaluation values in the risk analysis process. This approach can better express and handle both comparable and incomparable linguistic information in risk analysis domains. The proposed approaches aim at provide a support for risk analysis in different application context including disaster management under uncertain environment.

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6.1 Introduction

From the system point of view, risk analysis means to combine the individual responses to one statement on the system's performance for the purpose of decision-making. It deals with the occurrence of individual failure events (e.g., changes in components or in relations among components as distinct points in space and time) and their possible consequences on the system level [1]. In the procedure of risk analysis, the estimation of the likelihood (e.g., frequencies) and the consequences of hazard occurrence are included. The estimation of the likelihood of hazard occurrence depends greatly on the reliability of the system's components, the interaction of the components taking the system as a whole and human-system interactions. Risk evaluation needs a systematic research of accidental scenarios, including failure rates for the component (e.g., safety barriers) as well as for operator behavior (human factor) within an evolving environment [3].

In practice, information of risk analysis stems from historical data of complex systems or knowledge of decision makers, experts and regulators. Accordingly, there exist qualitative and quantitative methods in risk analysis to identify the risk drivers, assess their likelihood of occurrence and their potential consequences, and find ways to monitor and then mitigate the risks [2]. The differences between qualitative and quantitative methods for risk analysis are focused on the evaluation of the likelihood of accident sequences. In the quantitative methods, probability and Bayesian networks are the main tools for risk analysis due to their ability to model probabilistic data with dependencies between events, compute the distribution probabilities in a set of variables according to the observation of some variables and the prior knowledge of the others, and quantify low probability events [3, 23, 24].

Qualitative methods to risk analysis are largely based on expert judgement under the assumed boundary conditions, in which statements and implications are considered in performing a risk analysis, and the result is expressed by a linguistic value, e.g., safe or unsafe. Due to uncertainty and complexity, information about the probabilities of various risk items is vaguely known. This makes researchers to consider risk analysis based on fuzzy logic, i.e., fuzzy risk analysis. In recent years, many methods to fuzzy risk analysis based on fuzzy numbers have been discussed, e.g., based on fuzzy arithmetic operations [35], the similarity measure of fuzzy numbers [5, 7], interval fuzzy numbers, the alpha level sets, and the ranking of fuzzy numbers [4, 8–13] and fuzzy partition tree [37]. In all of these fuzzy risk analysis, many shapes (membership functions) associated to fuzzy numbers are used to represent fuzziness of the evaluating value of the risk of each subcomponent [34], e.g., triangular fuzzy numbers, trapezoidal fuzzy numbers and interval fuzzy numbers. Then fuzzy arithmetic operations, the similarity measure of fuzzy numbers and the ranking of fuzzy numbers could help us to evaluate the result of the risk analysis system.

To the best of our knowledge, there are the following three drawbacks when we use membership functions associated to fuzzy numbers to represent fuzziness in risk analysis:

(1) Fuzzy arithmetic operations, the similarity measure of fuzzy numbers and the ranking of fuzzy numbers depend on membership functions associated to fuzzy numbers, e.g., triangular fuzzy numbers, trapezoidal fuzzy numbers and interval fuzzy numbers. Different shapes of fuzzy numbers lead to different results. Thus, in practice, which one is the best for a given risk analysis is a problem;
(2) In risk analysis, linguistic values or fuzzy numbers rather than membership functions are used to represent fuzziness of the evaluation value. The result of risk analysis does not depend on their membership functions;
(3) In many cases, processing membership functions associated to linguistic values increase the computational complexity, and membership functions no longer keep the same form after fuzzy arithmetic operations. As the results do not exactly match any of the initial linguistic values, an approximation process must be developed to express the results in the initial expression domain which induces the consequent loss of information and hence the lack of precision.

From the practical point of view, a main characteristic of fuzzy risk analysis is that they always use natural languages and the result of fuzzy risk analysis is always expressed by natural language. Risk analysis based on Computing with Words (CWW) provides an alternative method to process these natural languages. CWW, which was proposed by Zadeh, is a methodology for reasoning, computing and decision-making with information described in a natural language [14, 21, 43, 47]. Basically, CWW is a system of computation two important capabilities [30]: a) the capability to preciseate the meaning of words and propositions drawn from natural language; b) the capability to reason and compute with precisiated words and propositions. In CWW, linguistic values rather than membership functions or numerical values play an important or key role, i.e., linguistic values are computational variables. This avoids the loss of information in the results of risk analysis, which in this way are also easier to communicate with decision- and policy-makers.

Informally, risk analysis based on CWW belongs to qualitative methods. In [15], fuzzy number indexes of linguistic evaluation values was used to deal with fuzzy risk analysis problems, in which the linguistic evaluation values were represented by their fuzzy number indexes, and the final evaluation value was obtained by linguistic information fusion based on fuzzy number indexes of linguistic values [17, 20]. In [16], we considered unbalanced linguistic information in fuzzy risk analysis, and proposed a new method for fuzzy risk analysis with unbalanced linguistic evaluation values.

There exists incomparable linguistic evaluation values in fuzzy risk analysis. Xu, Pei *et al.* characterized the set of linguistic values by a lattice-valued algebraic structure and investigated the corresponding logic systems with linguistic truth-value based on lattice implication algebra (*LIA*) [38, 39]. From the lattice-valued logic system point of view [40, 41], linguistic truth-values by the lattice implication algebra can express both comparable and incomparable elements [44, 45]. Zou *et al.* [46] proposed a framework of linguistic truth-valued propositional logic and developed the reasoning method of linguistic truth-valued logic system.

6.2 Preliminaries

In this section, we first outline the notion of fuzzy risk analysis, the 2-tuple fuzzy linguistic representation model, unbalanced linguistic term sets and linguistic truth-valued lattice implication algebra.

6.2.1 *Fuzzy risk analysis*

The aim of fuzzy risk analysis is to evaluate the probability of failure of every component consisted of many sub-components, in which estimations of severity of loss and probability of failure of sub-components are included. Formally, risk analysis can be described as follows: assume that there are r components $P_1, P_2, \ldots$ and P_r made by r manufactories $M_1, M_2, \ldots$ and M_r, respectively. Each component P_i consists of s sub-components p_{i1}, $p_{i2}, \ldots$ and p_{is}. Each sub-component p_{ij} ($1 \leqslant i \leqslant r$, $1 \leqslant j \leqslant s$) is evaluated by means of its severity of loss L_{ij} and its probability of failure F_{ij}. Each probability of failure F_i of component P_i is calculated through both the correspondent severity of loss L_{ij} and the probability of failure F_{ij} ($1 \leqslant j \leqslant s$). Then the larger the value of F_i is, the higher the probability of failure of component P_i is made by manufactory M_i ($1 \leqslant i \leqslant r$). The structure of fuzzy risk analysis can be shown in Fig. 6.1 [8].

According to the evaluation of the likelihood of accident sequences, qualitative and quantitative approaches to risk analysis have been discussed. In the quantitative approaches to risk analysis, every severity of loss L_{ij} and probability of failure F_{ij} of sub-components

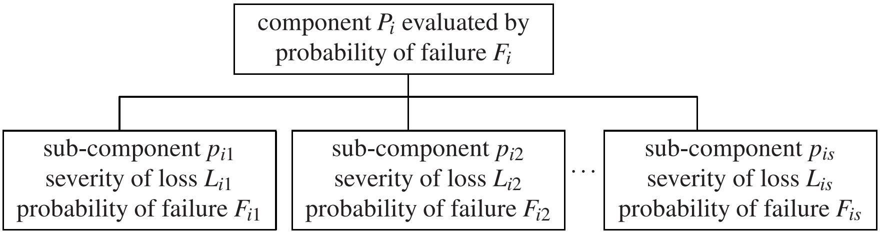

Fig. 6.1 The structure of fuzzy risk analysis

p_{ij} ($1 \leqslant i \leqslant r$, $1 \leqslant j \leqslant s$) are described by probabilities. Then Bayesian networks are used for obtaining final evaluation results. As a general modeling approach, Bayesian networks offers a compact presentation of the interactions in a stochastic system by visualizing system variables and their dependencies. Formally, a Bayesian network consists of two main parts: a qualitative part and a quantitative part. The qualitative part is a directed acyclic graph mirrored the nodes of the system variables and the conditional dependence between variables are represented by the edges of the graph. Conditional probability functions are included in the quantitative part according to the relations between the nodes of the graph. According to Figure 6.1, the probability of failure F_i of component P_i can be calculated by the conditional probability distribution $P(F_i \mid Pa(L_{i1}, F_{i1}), Pa(L_{i2}, F_{i2}), \ldots, Pa(L_{is}, F_{is}))$, where $Pa(L_{ij}, F_{ij})$ ($1 \leqslant j \leqslant s$) is joint distribution function of sub-component p_{ij}.

Due to the complexity of systems and lack of data, risk assessments often rely on experts' opinion. The experts' opinion has its inherent vagueness, which is expressed by linguistic evaluation values, such as *very low, fairly low, pretty low, medium, almost high, more or less high, very high and absolutely high, etc*. According to the concept of linguistic variable proposed by Zadeh [42], membership functions can be used to represent linguistic evaluation values and handle risk analysis. Generally, risk analysis based on fuzzy numbers is presented as follows:

(1) Aggregate all evaluation values $\{(L_{ij}, F_{ij}) \mid 1 \leqslant j \leqslant s\}$ of component P_i by fuzzy number aggregation operators, e.g., fuzzy weighted mean method and the generalized fuzzy number arithmetic operator, where L_{ij} and F_{ij} are represented by corresponding fuzzy numbers (membership functions), i.e., $F_i = \frac{\sum_{j=1}^{s} F_{ij} \otimes L_{ij}}{\sum_{j=1}^{s} L_{ij}}$, in which $\otimes$ is a generalized fuzzy numbers multiplication and F_i is a fuzzy number;

(2) Rank fuzzy numbers $\{F_i \mid 1 \leqslant i \leqslant r\}$ by the ranking values of the fuzzy numbers. The larger the value of F_i is, the higher the risk of the manufactory M_i is;

(3) Approximate fuzzy number $\max\{F_i \mid 1 \leqslant i \leqslant r\}$ to linguistic values, the final evaluation result is a linguistic evaluation value corresponding to such a fuzzy number.

In [15, 16], alternative methods have been presented, i.e., CWW is used to handle risk analysis and compared with methods for risk analysis based on fuzzy numbers. Evaluation values are linguistic evaluation values instead of fuzzy numbers (their membership functions) and the final evaluations are directly represented by linguistic evaluation values without approximation from a fuzzy number to a linguistic evaluation value. Generally, risk analysis based on CWW is presented as follows:

(1) Aggregate all linguistic evaluation values $\{(L_{ij}, F_{ij}) \mid 1 \leqslant j \leqslant s\}$ of component P_i by linguistic aggregation operators, i.e., $F_i = f(\{(L_{ij}, F_{ij}) \mid 1 \leqslant j \leqslant s\})$, in which, f is a linguistic aggregation operator;
(2) Rank linguistic evaluation values $\{F_i \mid 1 \leqslant i \leqslant r\}$ by the ranking method of linguistic values. The larger the value of P_i is, the higher the risk of the manufactory M_i is.

6.2.2 *The 2-tuple fuzzy linguistic representation model*

The 2-tuple linguistic representation model was introduced by Herrera [25]. Let $S = \{s_0, \ldots, s_g\}$ be the initial finite linguistic value set. Formally, the 2-tuple linguistic representation model is formed by (s_i, α), in which $s_i \in S$ ($i \in \{0, 1, \ldots, g\}$) and $\alpha \in [-0.5, 0.5)$, i.e., linguistic information is encoded in the space $S \times [-0.5, 0.5)$. Based on the representation (s_i, α), we can easily obtain the following symbolic translation of linguistic values from $\beta \in [0, g]$ to $S \times [-0.5, 0.5)$, i.e., $\Delta : [0, g] \to S \times [-0.5, 0.5)$, $\beta \mapsto (s_i, \alpha)$, in which $i = round(\beta)$ ($round(\cdot)$ is the usual round operation) and $\alpha = \beta - i \in [-0.5, 0.5)$. Intuitively, $\Delta(\beta) = (s_i, \alpha)$ expresses that s_i is the closest linguistic value to β, and α is the value of the symbolic translation. Additionally, there is a Δ^{-1} function such that from a 2-tuple it returns its equivalent numerical value $\beta \in [0, g]$, i.e., $\Delta^{-1} : S \times [-0.5, 0.5) \to [0, g]$, $\Delta^{-1}(s_i, \alpha) = i + \alpha = \beta$.

In fact, it defines a set of transformation functions between linguistic values and 2-tuples linguistic representations as well as numeric values and 2-tuples linguistic representations. Evidently, an order relation on $S \times [-0.5, 0.5)$ can be deduced by Δ^{-1}, i.e., for any $(s_i, \alpha_i), (s_j, \alpha_j) \in S \times [-0.5, 0.5)$, $(s_i, \alpha_i) \leqslant (s_j, \alpha_j)$ if and only if $\Delta^{-1}(s_i, \alpha_i) \leqslant \Delta^{-1}(s_j, \alpha_j)$.

6.2.3 *Representation of unbalanced linguistic terms*

Unbalanced linguistic terms proposed in [26] are used to deal with scales for assessing preferences where the experts need to assess a number of terms in a side of reference domain higher than in the other one. Generally, an unbalanced linguistic term set S has a minimum label, a maximum label and a central label. And the remaining labels are non-uniformly and non-symmetrically distributed around the central one on both left and right lateral sets, i.e., we can represent S on the form $S = S_l \cup S_c \cup S_r$, in which S_l contains all left lateral labels but the central label, S_c just contains the central label and S_r contains all right lateral labels higher than the central label.

Example 6.1 ([27]). $S = \{$none (N), low (L), medium (M), almost high (AH), high (H), quite high (QH), very high (VH), almost total (AT), total (T)$\}$ is an unbalanced linguistic term set, in which $S_l = \{N, L\}$, $S_c = \{M\}$ and $S_r = \{AH, H, QH, VH, AT, T\}$.

Fig. 6.2 Scale with more values on the right of the midterm.

To obtain 2-tuple fuzzy linguistic representations of unbalanced linguistic terms, we need the concept of linguistic hierarchies $LH = \bigcup_t l(t, n(t))$ [29], which takes into account a set of levels where each level is a linguistic term set with different granularity from the remaining levels of the hierarchy, where $l(t, n(t))$ is a linguistic hierarchy with t being a number that indicates the level of the hierarchy and $n(t)$ the granularity of the linguistic term set of t. The linguistic term set $S^{n(t+1)}$ of the level $t+1$ is obtained from its predecessor $S^{n(t)}$ as $l(t, n(t)) \to l(t+1, 2 \times n(t) - 1)$. Transformation function of LH is defined as follows [28]: for any t and t', $TF^t_{t'} : l(t, n(t)) \longrightarrow l(t', n(t'))$ such that

$$TF^t_{t'}(s_i^{n(t)}, \alpha^{n(t)}) = \triangle_{t'}\left(\frac{\triangle_t^{-1}(s_i^{n(t)}, \alpha^{n(t)}) \times (n(t') - 1)}{n(t) - 1}\right). \tag{6.1}$$

Example 6.2. Let

$$\begin{aligned} LH &= l(1,3) \cup l(2,5) \cup l(3,9) \cup l(4,17) \\ &= \left\{s_0^3, s_1^3, s_2^3\right\} \cup \left\{s_0^5, s_1^5, \ldots, s_4^5\right\} \cup \left\{s_0^9, s_1^9, \ldots, s_8^9\right\} \cup \left\{s_0^{17}, s_1^{17}, \ldots, s_{16}^{17}\right\} \end{aligned}$$

be a linguistic hierarchy. $(s_5^9, 0.3)$ is a 2-tuple fuzzy linguistic representation of level 3, it's 2-tuple fuzzy linguistic representation in level 2 is

$$\begin{aligned} TF_2^3(s_5^9, 0.3) &= \triangle_2\left(\frac{\triangle_3^{-1}(s_5^9, 0.3)\times(5-1)}{9-1}\right) \\ &= \triangle_2\left(\frac{5.3\times 4}{8}\right) = \triangle_2(2.65) \\ &= (s_3^5, -0.35). \end{aligned}$$

By using linguistic hierarchies $LH = \bigcup_t l(t, n(t))$, we can obtain the 2-tuple fuzzy linguistic representation of each term of unbalanced linguistic term set in LH by using the algorithm presented in [26].

Example 6.3. Continuing Example 6.1. For unbalanced linguistic term set $S = \{N, L, M, AH, H, QH, VH, AT, T\}$, 1) Due to $n(2) = 5$ and $\frac{n(2)-1}{2} = |S_l| = |\{N, L\}| = 2$, the representation of S_l is obtained from level 2 of LH as follows:

$$\{L \leftarrow s_1^5, N \leftarrow s_0^5\};$$

2) Due to $n(3) = 9$, $n(4) = 17$ and $\frac{n(3)-1}{2} = 4 < |S_r| = |\{AH, H, QH, VH, AT, T\}| = 6 < \frac{n(4)-1}{2} = 8$, we use level 3 and level 4 to represent $S_r = \{AH, H, QH, VH, AT, T\}$, according to lab$_3$ and lab$_4$ of [26], $\{AH, H\}$ and $\{QH, VH, AT, T\}$ are represented in level 3 and level 4, respectively,

$$\{AH \leftarrow s_5^9, H \leftarrow s_6^9\}, \{QH \leftarrow s_{13}^{17}, VH \leftarrow s_{14}^{17}, AT \leftarrow s_{15}^{17}, T \leftarrow s_{16}^{17}\};$$

3) According to density and bridging representation gaps [26], the upside and the downside of the central label M are represented in level 2 and 3 of LH by means of $\overline{s_2^5}$ and $\underline{s_4^9}$, respectively. The upside and the downside of the label H are represented in level 3 and 4 of LH by means of $\overline{s_6^9}$ and $\underline{s_{12}^{17}}$, respectively;
4) the final 2-tuple fuzzy linguistic representations of S in LH are $S_l : \{N \leftarrow s_0^5, L \leftarrow s_1^5\}$, $S_c : \{M \leftarrow \overline{s_2^5} \cup \underline{s_4^9}\}$, $S_r : \{AH \leftarrow s_5^9, H \leftarrow \overline{s_6^9} \cup \underline{s_{12}^{17}}, QH \leftarrow s_{13}^{17}, VH \leftarrow s_{14}^{17}, AT \leftarrow s_{15}^{17}, T \leftarrow s_{16}^{17}\}$.

Let S be an unbalanced linguistic term set. Formally, for any 2-tuple fuzzy linguistic representation (s_i, α_i) ($s_i \in S$ and $\alpha_i \in [-0.5, 0.5)$), (s_i, α) can be converted by the following unbalanced linguistic transformation functions in LH and vice versa, i.e.,

$$\begin{aligned} \mathscr{LH} &: S \times [-0.5, 0.5) \longrightarrow LH \times [-0.5, 0.5), \\ &(s_i, \alpha_i) \longmapsto (s_{I(i)}^{G(i)}, \alpha_i) \text{ such that } s_{I(i)}^{G(i)} \in LH; \\ \mathscr{LH}^{-1} &: LH \times [-0.5, 0.5) \longrightarrow S \times [-0.5, 0.5), \\ &(s_k^{n(t)}, \alpha_k) \longmapsto (s_i, \lambda), \end{aligned}$$

in which $s_k^{n(t)} \in S^{n(t)} \subset LH$. (s_i, λ) is decided by cases as follows:

(1) If there exists $s_i \in S$ such that $s_i \leftarrow s_k^{n(t)}$, then we consider two possible situations depending on how s_i is represented in LH:

(a) if s_i is represented with only one label in LH, e.g., $L \leftarrow s_1^5$ in Example 6.3, then $(s_i, \lambda) = (s_i, \alpha_k)$;

(b) if s_i is represented with two labels in LH from levels, e.g., $H \leftarrow \overline{s_6^9} \cup \underline{s_{12}^{17}}$ in Example 6.3, then (s_i, λ) depends on the localization of $s_i \in S$, and $\lambda = \alpha_k$ or $\frac{\triangle_t^{-1}(s_k^{n(t)}, \alpha_k) \times (n(t+1)-1)}{n(t)-1} - round(\frac{\triangle_t^{-1}(s_k^{n(t)}, \alpha_k) \times (n(t+1)-1)}{n(t)-1})$.

(2) If there exists no $s_i \in S$ such that $s_i \leftarrow s_k^{n(t)}$, then $\mathscr{L}\mathscr{H}^{-1}((s_k^{n(t)}, \alpha_k)) = \mathscr{L}\mathscr{H}^{-1}(TF_{t'}^t(s_k^{n(t)}, \alpha_k))$, in which t' is a level of LH such that $TF_{t'}^t(s_k^{n(t)}, \alpha_k) = (s_{k'}^{n(t')}, \alpha_{k'})$ and $\exists s_j \in S$, $s_j \leftarrow s_{k'}^{n(t')}$.

Example 6.4. Continuing Example 6.3. We have

$$\mathscr{L}\mathscr{H}(H, 0.3) = (s_6^9, 0.3),$$
$$\mathscr{L}\mathscr{H}^{-1}(s_{13}^{17}, -0.2) = (QH, -0.2),$$
$$\mathscr{L}\mathscr{H}^{-1}(s_{12}^{17}, -0.2) = \mathscr{L}\mathscr{H}^{-1}(TF_3^4(s_{12}^{17}, -0.2)) = \mathscr{L}\mathscr{H}^{-1}(s_6^9, -0.1) = (H, -0.1),$$
$$\mathscr{L}\mathscr{H}^{-1}(s_{12}^{17}, 0.4) = \mathscr{L}\mathscr{H}^{-1}(TF_3^4(s_{12}^{17}, 0.4)) = \mathscr{L}\mathscr{H}^{-1}(s_6^9, 0.2) = (H, 0.4).$$

6.2.4 *Linguistic truth-valued lattice implication algebra*

Inspired by hedge algebra [31, 32], we construct lattice implication algebra of linguistic truth values in which both comparable and incomparable linguistic truth values can be expressed.

Definition 6.1 ([38]). Let $(L, \vee, \wedge, ', O, I)$ be a bounded lattice with universal boundaries O (the least element) and I (the greatest element) respectively, and "$'$" be an order-reversing involution. For any $x, y, z \in L$, if a mapping $\rightarrow: L \times L \rightarrow L$ satisfies:

(I_1) $x \rightarrow (y \rightarrow z) = y \rightarrow (x \rightarrow z)$,

(I_2) $x \rightarrow x = I$,

(I_3) $x \rightarrow y = y' \rightarrow x'$,

(I_4) if $x \rightarrow y = y \rightarrow x = I$, then $x = y$,

(I_5) $(x \rightarrow y) \rightarrow y = (y \rightarrow x) \rightarrow x$,

(I_6) $(x \vee y) \rightarrow z = (x \rightarrow z) \wedge (y \rightarrow z)$,

(I_7) $(x \wedge y) \rightarrow z = (x \rightarrow z) \vee (y \rightarrow z)$,

then $(L, \vee, \wedge, ', \rightarrow, O, I)$ is a lattice implication algebra.

Table 6.1 Negation of H

h	*absolutely*	*very*	*exactly*	*somewhat*	*slightly*
h'	*slightly*	*somewhat*	*exactly*	*very*	*absolutely*

Table 6.2 Disjunction of H

$\vee$	*absolutely*	*very*	*exactly*	*somewhat*	*slightly*
absolutely	*absolutely*	*absolutely*	*absolutely*	*absolutely*	*absolutely*
very	*absolutely*	*very*	*very*	*very*	*very*
exactly	*absolutely*	*very*	*exactly*	*exactly*	*exactly*
somewhat	*absolutely*	*very*	*exactly*	*somewhat*	*somewhat*
slightly	*absolutely*	*very*	*exactly*	*somewhat*	*slightly*

Table 6.3 Conjunction of H

$\wedge$	*absolutely*	*very*	*exactly*	*somewhat*	*slightly*
absolutely	*absolutely*	*very*	*exactly*	*somewhat*	*slightly*
very	*very*	*very*	*exactly*	*somewhat*	*slightly*
exactly	*exactly*	*exactly*	*exactly*	*somewhat*	*slightly*
somewhat	*somewhat*	*somewhat*	*somewhat*	*somewhat*	*slightly*
slightly	*slightly*	*slightly*	*slightly*	*slightly*	*slightly*

Example 6.5. We choose the five common linguistic hedges to construct the linguistic values, i.e., $absolutely, very, exactly, somewhat, slightly$ (denoted by $H = \{absolutely, very, exactly, somewhat, slightly\}$), and the partially ordered relation on H as $slightly < somewhat < exactly < very < absolutely$. According to the properties of LIA, we can define the negation, disjunction, conjunction and implication of the linguistic hedges in Tables 6.1–6.12.

Definition 6.2. Let $H = \{$ absolutely, very, exactly, somewhat, slightly $\}$ and $C = \{c_i \mid c_1 = c_2',\ c_2 = c_1',\ i = 1,2\}$. We define $L_{10} = (V, \vee, \wedge, ', O, I)$ as follows, its operations "$\vee$" and "$\wedge$" are shown in the Hasse diagram of L_{10} in Fig. 6.3, $(h_i, c_1)' = (h_i, c_2)$, $(h_i, c_2)' = (h_i, c_1)$

Table 6.4 Implication of H

$\to$	*absolutely*	*very*	*exactly*	*somewhat*	*slightly*
absolutely	*absolutely*	*very*	*exactly*	*somewhat*	*slightly*
very	*absolutely*	*absolutely*	*very*	*exactly*	*somewhat*
exactly	*absolutely*	*absolutely*	*absolutely*	*exactly*	*exactly*
somewhat	*absolutely*	*absolutely*	*absolutely*	*absolutely*	*very*
slightly	*absolutely*	*absolutely*	*absolutely*	*absolutely*	*absolutely*

and its operation "$\to$" is defined as follows:

$$\begin{cases} (h_i,c_1)\to(h_j,c_2)=\left(h_{\max\{0,i+j-4\}},c_2\right)\\ (h_i,c_2)\to(h_j,c_1)=\left(h_{\min\{4,i+j\}},c_1\right)\\ (h_i,c_1)\to(h_j,c_1)=\left(h_{\min\{4,4-i+j\}},c_1\right)\\ (h_i,c_2)\to(h_j,c_2)=\left(h_{\min\{4,4-j+i\}},c_1\right)\end{cases}$$

Then $L_{10}=(V,\vee,\wedge,',O,I)$ is an LIA.

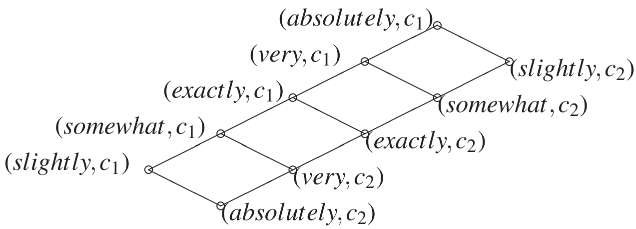

Fig. 6.3 Hasse Diagram of L_{10}.

In Definition 6.2, C is called the basic evaluation word set if it satisfies $C=\{c_i \mid c_1=c_2',\ c_2=c_1',\ i=1,2\}$. Let V be a linguistic truth-value set. Every linguistic evaluation value $v\in V$ is composed of a linguistic hedge operator h and a basic word c, i.e., $V=H\times C$ where the linguistic hedge operator set H is a totally ordered and finite set.

Note that there exist incomparable linguistic truth values (denoted by "$\|$") in L_{10}, e.g.,(exactly, c_1)$\|(somewhat,c_2)$.

Proposition 6.1. *For any* $(h_i,c_j)\in L_{10}$,

(1) $(absolutely,c_2)\to(h_i,c_j)=(absolutely,c_1)$,
(2) $(absolutely,c_1)\to(h_i,c_j)=(h_i,c_j)$,
(3) $(h_i,c_j)\to(absolutely,c_2)=(h_i,c_j)'$,

(4) $(h_i, c_j) \to (absolutely, c_1) = (h_i, c_j)$.

From the logical point of view, we obtain if the antecedent is false, the conclusion is always true regardless what the consequent is.

If two linguistic hedges of linguistic values are equal or complement, we have the following results.

Proposition 6.2. *For any $h_i, h_j \in H$,*

(1) *If $h_i = h'_j$, then $(h_i, c_1) \to (h_j, c_2) = (h_0, c_2)$;*
(2) *If $h_i = h'_j$, then $(h_i, c_2) \to (h_j, c_1) = (h_n, c_1)$;*
(3) *If $h_i = h_j$, then $(h_i, c_1) \to (h_j, c_1) = (h_n, c_1)$;*
(4) *If $h_i = h_j$, then $(h_i, c_2) \to (h_j, c_2) = (h_n, c_1)$.*

As a special case, we have:

(1) $(absolutely, c_1) \to (absolutely, c_1) = (absolutely, c_1)$;
(2) $(absolutely, c_1) \to (absolutely, c_2) = (absolutely, c_2)$;
(3) $(absolutely, c_2) \to (absolutely, c_1) = (absolutely, c_1)$;
(4) $(absolutely, c_2) \to (absolutely, c_2) = (absolutely, c_1)$.

If $(absolutely, c_1)$ is "T" and $(absolutely, c_2)$ is "F", we can obtain the classical logic implication. Hence linguistic truth-valued logic is an extension of classical logic and fuzzy logic.

6.3 Risk Analysis Based on Linguistic Aggregation

6.3.1 *The unbalanced linguistic weighted geometric operator*

To aggregate unbalanced linguistic values, we propose the unbalanced linguistic weighted geometric operator in this section.

Definition 6.3 ([22]). An weighted geometric operator of dimension n is a mapping $g : (R^+)^n \to R^+$ that has associated with it a weighting vector $W = (w_1, w_2, \ldots, w_n)$, with $w_i \in [0,1]$ and $\sum_{i=1}^n w_i = 1$, such that $g(a_1, a_2, \ldots, a_n) = \prod_{j=1}^n a_i^{w_i}$.

Definition 6.4 ([22]). Assume that the set of unbalanced linguistic values $V = \{s_i \mid i = 1, 2, \ldots, n\}$ be aggregated, in which $s_i \in S = \{s_0, s_1, \ldots, s_m\}$ $(m \geqslant n)$ is an unbalanced linguistic value. A weighting vector is $W = (w_1, w_2, \ldots, w_n)$ with $w_i \in [0,1]$ and $\sum_{i=1}^n w_i = 1$.

Then the unbalanced linguistic weighted geometric operator (the $ULWG$ operator) is defined as $f_{ULWG}(\{(w_i,s_i) \mid i=1,\ldots,n\}) = f_{ULWG}(\{(w_i, TF_{t_0}^{t_i}(\mathscr{LH}(s_i))) \mid i=1,2,\ldots,n\}) = \mathscr{LH}^{-1}(\triangle_{t_0}(\prod_{i=1}^{n}(\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(s_i))))^{w_i})) = \mathscr{LH}^{-1}(s_k^{n(t_0)}, \alpha_k)$, where t_i is the level of $\mathscr{LH}(s_i)$ in LH, t_0 is a level of LH fixed by users, $s_k^{n(t_0)} \in S^{n(t_0)} \subset LH$ and $\alpha_k \in [-0.5, 0.5)$ such that

$$k + \alpha_k = \prod_{i=1}^{n}(\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(s_i))))^{w_i}. \tag{6.2}$$

Remark 6.1. In Definition 6.4, $TF_{t_0}^{t_i}(\mathscr{LH}(s_i))$ means that unbalanced linguistic values are represented at level t_0 of LH and t_0 is decided by users. In fact, by using $TF_{t_0}^{t_i}(\cdot)$ and $\mathscr{LH}(\cdot)$, S is converted in $S^{n(t_0)}$ of LH. By using $\mathscr{LH}^{-1}$ $(s_k^{n(t_0)}, \alpha_k)$, $f_{ULWG}(V)$ is converted to the 2-tuple fuzzy linguistic representation of unbalanced linguistic value.

Example 6.6. Let $S = \{N, L, M, AH, H, QH, VH, AT, T\}$ be a set of unbalanced linguistic values. Suppose that $\{(0.25, AH), (0.35, QH), (0.4, H)\}$ will be aggregated. Here we select $t_0 = 3$ and density$_{S_r}$ =extreme [26], hence, $TF_3^{t_i}(\mathscr{LH}(AH)) = TF_3^3(s_5^9) = s_5^9$, $TF_3^{t_i}(\mathscr{LH}(QH)) = TF_3^4(s_{13}^{17}) = (s_6^9, 0.5), TF_3^{t_i}(\mathscr{LH}(H)) = TF_3^3(s_6^9) = s_6^9$, according to Eq. (6.2), we have $k + \alpha_k = 5^{0.25} \times 6.5^{0.35} \times 6^{0.4} \doteq 5.93$, $f_{ULWG}(\{(0.25, AH), (0.35, QH), (0.4, H)\}) \doteq \mathscr{LH}^{-1}(s_6^9, -0.07) = (H, -0.07)$.

In many cases, weight w_i is a linguistic weight rather that number in $[0,1]$, e.g., in fuzzy risk analysis, every severity of loss L_{ij} of sub-component p_{ij} ($1 \leqslant i \leqslant r$, $1 \leqslant j \leqslant s$) acts as the weight in aggregation, i.e., w_i is a linguistic value in Eq. (6.2). We use the following method to obtain numbers in $[0,1]$ from unbalanced linguistic values: 1) For any unbalanced linguistic values $\{l_1,\ldots,l_k\}$ and $LH = \bigcup_t l(t, n(t))$, we have $\{TF_{t_0}^{t_1}(\mathscr{LH}(l_1)),\ldots,TF_{t_0}^{t_k}(\mathscr{LH}(l_k))\}$, where t_i is the level of $\mathscr{LH}(l_i)$ ($i \in \{1,\ldots,k\}$) in LH and t_0 is a level of LH fixed by users; 2) The function $f : \{l_1,\ldots,l_k\} \to [0,1]$ is defined by

$$f(l_i) = \frac{\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(l_i)))}{\sum_{j=1}^{k}\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(l_j)))}. \tag{6.3}$$

Evidently, for any $l_i \in \{l_1,\ldots,l_k\}$, $f(l_i) \in [0,1]$ and $\sum_{i=1}^{k}\frac{\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(l_i)))}{\sum_{j=1}^{k}\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(l_j)))} = 1$.

Definition 6.5 ([22]). Assume that the set of unbalanced linguistic values $V = \{(l_i, s_i) \mid i = 1,\ldots,n\}$ is aggregated, and every l_i is a linguistic weight corresponding to s_i. Then the $ULWG$ operator with linguistic weights (the $ULWGLW$ operator) is defined as

$f_{ULWGLW}(\{(l_i,s_i) \mid i=1,\dots,n\}) = f_{ULWG}(\{(f(l_i),TF_{t_0}^{t_i}(\mathscr{LH}(s_i))) \mid i=1,2,\dots,n\}) = \mathscr{LH}^{-1}(\triangle_{t_0}(\prod_{i=1}^{n}(\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(s_i))))^{f(l_i)})) = \mathscr{LH}^{-1}(s_k^{n(t_0)},\alpha_k)$, where t_i is the level of $\mathscr{LH}(s_i)$ in LH, t_0 is a level of LH fixed by users, $s_k^{n(t_0)} \in S^{n(t_0)} \subset LH$ and $\alpha_k \in [-0.5,0.5)$ such that

$$k+\alpha_k = \prod_{i=1}^{n}(\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(s_i))))^{f(l_i)}. \tag{6.4}$$

in which every $f(l_i)$ is decided by Eq. (6.3).

Proposition 6.3 ([22]). *Let unbalanced linguistic values $V=\{(w_i,s_i) \mid i=1,\dots,n\}$ be aggregated, where $w_i \in [0,1]$ and $\sum_{i=1}^{n} w_i = 1$. If for any $i \in \{1,\dots,n\}$, $w_i = 1$, then $f_{ULWG}(\{(w_1,s_1),\dots,(w_n,s_n)\}) = s_i$.*

As special cases, we have

1) Denote $s_j = \max\{s_1,\dots,s_n\}$, if $w_j = 1$ then $f_{ULWG}((w_1,s_1),\dots,(w_n,s_n)) = s_j$;
2) Denote $s_k = \min\{s_1,\dots,s_n\}$, if $w_k = 1$ then $f_{ULWG}((w_1,s_1),\dots,(w_n,s_n)) = s_k$;
3) If $w_j = w_k = 0$ then f_{ULWG} reduces to the linguistic Olympic operator, i.e., the smallest and largest linguistic values are deleted from linguistic evaluation values.

Proposition 6.4 ([22]). *Let unbalanced linguistic values $V=\{(w_i,s_i) \mid i=1,\dots,n\}$ be aggregated, where $w_i \in [0,1]$ and $\sum_{i=1}^{n} w_i = 1$. The $ULWG$ operator satisfies:*

1) $\min\{s_1,\dots,s_n\} \leqslant f_{ULWG}(\{(w_1,s_1),\dots,(w_n,s_n)\}) \leqslant \max\{s_1,\dots,s_n\}$;
2) *f_{ULWG} is idempotent, i.e., $f_{ULWG}(\{(w_1,s_1),\dots,(w_n,s_n)\}) = s_1$ when $s_1 = \cdots = s_n$;*
3) *f_{ULWG} is monotone in relation to the input values s_i, i.e., for any $s_i' \geqslant s_i$, $f_{ULWG}((w_1,s_1),\dots,(w_i,s_i'),\dots,(w_n,s_n)) \geqslant f_{ULWG}((w_1,s_1),\dots,(w_i,s_i),\dots,(w_n,s_n))$;*
4) *f_{ULWG} is commutative;*
5) *f_{ULWG} reduces to the linguistic geometric mean if $w_i = \frac{1}{n}$ for all $i=1,\dots,n$, i.e., $f_{ULWG}(\{(w_1,s_1),\dots,(w_n,s_n)\}) = (s_k,\alpha_k)$ and $k+\alpha_k = \sqrt[n]{\prod_{i=1}^{n} \triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{LH}(s_i)))}$.*

6.3.2 *Illustrative example based on the $ULWG$ operator*

In this subsection, we apply the $ULWG$ operator to deal with fuzzy risk analysis problems. We firstly use an example to illustrate the fuzzy risk analysis process of our method, where linguistic evaluation values are unbalanced linguistic evaluation values. In the example, assume that the following unbalanced linguistic evaluation values are considered:

(1) Unbalanced linguistic evaluation values for severity of loss: $L = \{$none (N), low (L), medium (M), almost high (AH), high (H), quite high (QH), very high (VH), almost total (AT), total (T)$\}$;

(2) Unbalanced linguistic evaluation values for probability of failure: $F = \{$none (N), small (S), medium (M), almost big (AB), big(B), quite big (QB), very big (VB), almost total (AT), total (T)$\}$. The proposed fuzzy risk analysis algorithm is now presented as follows: 1) Unbalanced linguistic evaluation values for severity of loss and probability of failure are represented in the level t_0 of $LH = \bigcup_t l(t, n(t))$, where t_0 is fixed by decision makers; 2) According to transformation function (6.1), the transformed unbalanced linguistic evaluation values are 2-tuple fuzzy linguistic representations;

(3) Aggregate all linguistic evaluation values $\{(L_{ij}, F_{ij}) \mid 1 \leqslant j \leqslant s\}$ of component P_i by the $ULWG$ operator with linguistic weights, i.e.,

$$\begin{aligned}
F_i &= f_{ULWGLW}(\{(L_{ij}, F_{ij}) \mid 1 \leqslant j \leqslant s\}) \\
&= f_{ULWG}(\{(f(L_{ij}), TF_{t_0}^{t_i}(\mathscr{L}\mathscr{H}(F_{ij}))) \mid 1 \leqslant j \leqslant s\}) \\
&= \mathscr{L}\mathscr{H}^{-1}\left(\triangle_{t_0}\left(\prod_{i=1}^{n}(\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{L}\mathscr{H}(F_{ij}))))^{f(L_{ij})}\right)\right) \\
&= \mathscr{L}\mathscr{H}^{-1}(s_k^{n(t_0)}, \alpha_k),
\end{aligned}$$

$$k + \alpha_k = \prod_{i=1}^{n}(\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{L}\mathscr{H}(F_{ij}))))^{f(L_{ij})},$$

$$f(L_{ij}) = \frac{\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{L}\mathscr{H}(L_{ij})))}{\sum_{j=1}^{k}\triangle_{t_0}^{-1}(TF_{t_0}^{t_i}(\mathscr{L}\mathscr{H}(L_{ij})))};$$

(4) Rank linguistic evaluation values $\{F_i \mid 1 \leqslant i \leqslant r\}$ by the ranking method of linguistic values, i.e., $F_{i_1} \geqslant F_{i_2}$ if and only if $\triangle_{t_0}^{-1}(s_{k_1}^{n(t_0)}, \alpha_{k_1}) \geqslant \triangle_{t_0}^{-1}(s_{k_2}^{n(t_0)}, \alpha_{k_2})$. The larger the linguistic evaluation value F_i of P_i is, the higher the risk of the manufactory M_i is.

Example 6.7. Assume that there are three manufactories M_1, M_2 and M_3 producing the components P_1, P_2 and P_3, respectively, where P_1, P_2 and P_3 are the same product made by different manufactories. Each component P_i consists of three sub-components P_{i1}, P_{i2} and P_{i3}, where $1 \leqslant i \leqslant 3$. Assume that there are two evaluation items L_{ij} and F_{ij} to derive the probability of failure F_i of component P_i made by manufactory M_i, where L_{ij} denotes the severity of loss of the sub-component P_{ij}, F_{ij} denotes the probability of failure of the sub-component P_{ij}, $1 \leqslant i \leqslant 3$ and $1 \leqslant j \leqslant 3$. The linguistic evaluation values of every sub-component P_{ij} are shown in Table 6.5.

Table 6.5 Linguistic evaluation values of the sub-components made by manufactories

manufactory	sub-components	the severity of loss	the probability of failure
M_1	P_{11}	L	AT
	P_{12}	QH	S
	P_{13}	AH	M
M_2	P_{21}	M	QB
	P_{22}	H	M
	P_{23}	N	T
M_3	P_{31}	L	VB
	P_{32}	M	B
	P_{33}	AT	S

In the example, the linguistic hierarchies be $LH = l(1,3) \cup l(2,5) \cup l(3,9) \cup l(4,17)$ for the severity of loss and the probability of failure of sub-components, the levels t_0 of the severity of loss and the probability of failure are fixed by 2 and 3, respectively. Transformations of linguistic evaluation values are shown in Table 6.6. We can obtain every F_i of component P_i according to Eq. (6.3), Eq. (6.4) and Table 6.6, respectively.

Table 6.6 Transformations of linguistic evaluation values

manufactory	sub-components	L_{ij}	$TF_2^{t_i}(\mathscr{LH}(L_{ij}))$	F_{ij}	$TF_3^{t_i}(\mathscr{LH}(F_{ij}))$
M_1	P_{11}	L	$(s_1^5, 0)$	AT	$(s_8^9, -0.5)$
	P_{12}	QH	$(s_3^5, 0.25)$	S	$(s_2^9, 0)$
	P_{13}	AH	$(s_3^5, -0.5)$	M	$(s_4^9, 0)$
M_2	P_{21}	M	$(s_2^5, 0)$	QB	$(s_7^9, -0.5)$
	P_{22}	H	$(s_3^5, 0)$	M	$(s_4^9, 0)$
	P_{23}	N	$(s_0^5, 0)$	T	$(s_8^9, 0)$
M_3	P_{31}	L	$(s_1^5, 0)$	VB	$(s_7^9, 0)$
	P_{32}	M	$(s_2^5, 0)$	B	$(s_6^9, 0)$
	P_{33}	AT	$(s_4^5, -0.25)$	S	$(s_2^9, 0)$

For component P_1 with sub-components P_{11}, P_{12} and P_{13}, we have

$$f(L) = \frac{\triangle_2^{-1}(s_1^5,0)}{\triangle_2^{-1}(s_1^5,0)+\triangle_2^{-1}(s_3^5,0.25)+\triangle_2^{-1}(s_3^5,-0.5)} \doteq 0.15,$$

$$f(QH) = \frac{\triangle_2^{-1}(s_3^5,0.25)}{\triangle_2^{-1}(s_1^5,0)+\triangle_2^{-1}(s_3^5,0.25)+\triangle_2^{-1}(s_3^5,-0.5)} \doteq 0.48,$$

$$f(AH) = \frac{\triangle_2^{-1}(s_3^5,-0.5)}{\triangle_2^{-1}(s_1^5,0)+\triangle_2^{-1}(s_3^5,0.25)+\triangle_2^{-1}(s_3^5,-0.5)} \doteq 0.37,$$

$$\begin{aligned}
F_1 &= f_{ULWGLW}(\{(L,AT),(QH,S),(AH,M)\}) \\
&= f_{ULWG}(\{(f(L),(s_8^9,-0.5)),(f(QH),(s_2^9,0)),(f(AH),(s_4^9,0))\}) \\
&= \mathscr{L}\mathscr{H}^{-1}(\triangle_3((\triangle_3^{-1}(s_8^9,-0.5))^{f(L)} \times (\triangle_3^{-1}(s_2^9,0))^{f(QH)} \times (\triangle_3^{-1}(s_4^9,0))^{f(AH)})) \\
&= \mathscr{L}\mathscr{H}^{-1}(\triangle_3(7.5^{0.15} \times 2^{0.48} \times 4^{0.37})) \\
&\doteq \mathscr{L}\mathscr{H}^{-1}(\triangle_3(3.13)) = (M,-0.43).
\end{aligned}$$

Table 6.7 The probability of failure of the component made by manufactory

manufactory	the component	the probability of failure
M_1	P_1	$F_1 = (M,-0.43)$
M_2	P_2	$F_2 = (AH,-0.15)$
M_3	P_3	$F_3 = (M,-0.325)$

According to Table 6.7, the probability of failure F_2 of the component P_2 made by manufactory M_2 is $(AH,-0.15)$, i.e., almost big with the value of the symbolic translation -0.15, it is the largest linguistic evaluation value among the linguistic evaluation values of F_1, F_2 and F_3. Hence the risk of the manufactory M_2 is the highest.

Example 6.8 ([6]). Assume that the balanced linguistic values are $\{$ Absolutely -low, Very-low, Low, Fairly-low, Medium, Fairly-high, High, Very-high, Absolutely-high $\}$. Their corresponding interval valued fuzzy numbers are shown in Table 6.8. The linguistic evaluation values of every sub-component P_{ij} are shown in Table 6.9. In Table 6.9, w_{ij} denotes the degree of confidence of the decision-maker's opinion with respect to sub-components P_{ij}. The method proposed in [6] is presented as follows:

(1) Aggregate the linguistic evaluation values of sub-components P_{ij} of each component P_i made by manufactory M_i based on the fuzzy weighted mean method and the interval-valued fuzzy numbers arithmetic operators proposed in [6] to get the probability of

failure F_i, e.g., for F_1, according to Table 6.8 and Table 6.9, we have

$$F_1 = \frac{(low \otimes fairly\ low) \oplus (fairly\ high \otimes medium) \oplus (very\ low \otimes fairly\ high)}{low \oplus fairly\ high \oplus very\ low}$$
$$= \frac{(A_3 \otimes A_4) \oplus (A_6 \otimes A_5) \oplus (A_2 \otimes A_6)}{A_3 \oplus A_6 \oplus A_2} = \frac{(A_3^* \otimes A_4^*) \oplus (A_6^* \otimes A_5^*) \oplus (A_2^* \otimes A_6^*)}{A_3^* \oplus A_6^* \oplus A_2^*}$$
$$= [(0.240, 0.328, 0.656, 0.905; 0.288), (0.195, 0.306, 0.678, 0.949; 0.763)],$$

where $A_2^*, A_3^*, A_4^*, A_5^*$ and A_6^* are type-1 fuzzy numbers of A_2, A_3, A_4, A_5 and A_6, respectively, e.g., $A_2^* = \left(\frac{0.0075+0}{2}, \frac{0.0075+0}{2}, \frac{0.015+0.02}{2}, \frac{0.0525+0.07}{2}; \frac{0.5+1}{2}\right) = (0.00375,$ $0.00375,\ 0.0175,\ 0.06125;\ 0.75)$, $A_2^* \otimes A_6^* = (0.00375 \times 0.615,\ 0.00375 \times 0.65125,$ $0.0175 \times 0.77875,\ 0.06125 \times 0.825;\ \min(0.75, 0.75))$, $A_2^* \oplus A_6^* = (0.00375 \oplus 0.615,$ $0.00375 \oplus 0.65125, 0.0175 \oplus 0.77875, 0.06125 \oplus 0.825; \min(0.75, 0.75))$;

(2) Calculate the degree of similarity between the upper fuzzy numbers of the interval-valued fuzzy numbers F_i and every linguistic value shown in Table 6.8, respectively, e.g., for F_1 and A_1, we have

$$S_X^U(F_1^U, A_1^U) = S_X^U((0.195, 0.306, 0.678, 0.949; 0.763), (0, 0, 0, 0; 1))$$
$$= 1 - \frac{|0.195 - 0| + |0.306 - 0| + |0.678 - 0| + |0.949 - 0|}{4} = 0.468;$$

(3) Calculate the spread between the upper fuzzy numbers of the interval valued fuzzy numbers F_i and every linguistic value shown in Table 6.8, respectively, e.g., for F_1 and A_1, we have

$$STD^U(F_1^U, A_1^U) = |STD_{F_1^U} - STD_{A_1^U}| = 0.347,$$
$$x_1 = \frac{0.195 + 0.306 + 0.678 + 0.949}{4} = 0.532,$$
$$STD_{F_1^U} = \sqrt{\frac{(0.195 - x_1)^2 + (0.306 - x_1)^2 + (0.678 - x_1)^2 + (0.949 - x_1)^2}{4 - 1}};$$

(4) Calculate the degree of similarity on the X-axis between the interval-valued fuzzy numbers F_i and every linguistic value shown in Table 6.8, respectively, e.g., for F_1 and A_1, we have $S_X(F_1, A_1) = 1 - (|(0.195 - 0.24) - (0 - 0)| + |(0.306 - 0.328) - (0 - 0)| + |(0.678 - 0.656) - (0 - 0)| + |(0.949 - 0.905) - (0 - 0)|)/4 = 0.96675$;

(5) Calculate the degree of similarity on the Y-axis between the interval-valued fuzzy numbers F_i and every linguistic value shown in Table 6.8, respectively, e.g., for F_1 and A_1, we have $S_Y(F_1, A_1) = 1 - |y_{F_1} - y_{A_1}| = 0.915$, where y_{F_1} and y_{A_1} are associated to areas of F_1^U, F_1^L, A_1^U and A_1^L, respectively;

(6) Calculate the degree of similarity between the interval-valued fuzzy numbers F_i and every linguistic value shown in Table 6.8, respectively, which is decided by the above mentioned degrees of similarity and the spread, e.g., for F_1 and A_1, we have

$$S(F_1,A_1)=\frac{S_X^U(F_1^U,A_1^U)\times(1-|0.763-1|)}{1+STD^U(F_1^U,A_1^U)}\times S_X(F_1,A_1)\times S_Y(F_1,A_1)=0.234.$$

By using the method, the probability of failure of P_1 made by manufactory M_1 is "Medium", the probability of failure of P_2 is "fairly-high" and the probability of failure of P_3 is "fairly-high". Hence, the risk of manufactories M_2 and M_3 is the highest, see [6] for more detail.

Table 6.8 Linguistic values and their corresponding interval-valued fuzzy numbers

Linguistic values	Interval-valued fuzzy numbers
Absolutely-low (s_0^9)	$A_1=[(0,0,0,0;1),(0,0,0,0;1)]$
Very-low (s_1^9)	$A_2=[(0.0075,0.0075,0.015,0.0525;0.5),(0,0,0.02,0.07;1)]$
Low (s_2^9)	$A_3=[(0.0875,0.12,0.16,0.1825;0.5),(0.04,0.1,0.18,0.23;1)]$
Fairly-low (s_3^9)	$A_4=[(0.2325,0.255,0.325,0.3575;0.5),(0.17,0.22,0.36,0.42;1)]$
Medium (s_4^9)	$A_5=[(0.4025,0.4525,0.5375,0.5675;0.5),(0.32,0.41,0.58,0.65;1)]$
Fairly-high (s_5^9)	$A_6=[(0.65,0.6725,0.7575,0.79;0.5),(0.58,0.63,0.8,0.86;1)]$
High (s_6^9)	$A_7=[(0.7825,0.815,0.885,0.9075;0.5),(0.72,0.78,0.92,0.97;1)]$
Very-high (s_7^9)	$A_8=[(0.9475,0.985,0.9925,0.9925;0.5),(0.93,0.98,1,1;1)]$
Absolutely-high (s_8^9)	$A_1=[(1,1,1,1;1),(1,1,1,1;1)]$

Table 6.9 Linguistic evaluation values of the sub-components made by manufactories

manufactory	sub-components	the severity of loss	the probability of failure
	P_{11}	low	fairly-low ($w_{11}=0.9$)
M_1	P_{12}	fairly-high	medium ($w_{12}=0.7$)
	P_{13}	very-low	fairly-high ($w_{13}=0.8$)
	P_{21}	low	very-high ($w_{21}=0.85$)
M_2	P_{22}	fairly-high	fairly-high ($w_{22}=0.9$)
	P_{23}	very-low	medium ($w_{23}=0.9$)
	P_{31}	low	fairly-low ($w_{31}=0.95$)
M_3	P_{32}	fairly-high	high ($w_{32}=0.8$)
	P_{33}	very-low	fairly-high ($w_{33}=1.0$)

In the following, we use our method to get the probability of failure F_i made by manufactory M_i $(i = 1,2,3)$. In this example, because linguistic evaluation values are balanced, transformation function $TF^t_{t'} : l(t,n(t)) \longrightarrow l(t',n(t'))$ are unnecessary, or transformation function $TF^t_{t'}$ is such that $t = t' = 3$.

According to (6.3), (6.4) and Table 6.9, we have

$$\begin{aligned}
F_1 &= f_{ULWG}(\{(low, fairly\ low), (fairly\ high, medium), (very\ low, fairly\ high)\}) \\
&= f_{ULWG}(\{(s^9_2, s^9_3), (s^9_5, s^9_4), (s^9_1, s^9_5)\}) \\
&= \mathscr{L}\mathscr{H}^{-1}(\triangle_3((\triangle_3^{-1}(s^9_3, 0))^{f(s^9_2)} \times (\triangle_3^{-1}(s^9_4, 0))^{f(s^9_5)} \times (\triangle_3^{-1}(s^9_5, 0))^{f(s^9_1)})),
\end{aligned}$$

in which $f(s^9_2) = \frac{\triangle_3^{-1}(s^9_2)}{\triangle_3^{-1}(s^9_2)+\triangle_3^{-1}(s^9_5)+\triangle_3^{-1}(s^9_1)} = \frac{2}{2+5+1} = 0.25$, $f(s^9_5) = \frac{5}{2+5+1} = 0.625$ and $f(s^9_1) = \frac{1}{2+5+1} = 0.125$. Hence $F_1 = \mathscr{L}\mathscr{H}^{-1}(\triangle_{t_0}(3^{0.25} \times 4^{0.625} \times 5^{0.125})) \doteq \mathscr{L}\mathscr{H}^{-1}(\triangle_{t_0}(3.83) = \mathscr{L}\mathscr{H}^{-1}(s^9_4, -0.17) = (Medium, -0.17)$.

Similarly, F_2 and F_3 can be obtained as

$$\begin{aligned}
F_2 &= f_{ULWG}(\{(s^9_2, s^9_7), (s^9_5, s^9_5), (s^9_1, s^9_4)\}) \\
&= \mathscr{L}\mathscr{H}^{-1}((\triangle_3^{-1}(s^9_7, 0))^{f(s^9_2)} \times (\triangle_3^{-1}(s^9_5, 0))^{f(s^9_5)} \times (\triangle_3^{-1}(s^9_4, 0))^{f(s^9_1)}) \\
&\doteq \mathscr{L}\mathscr{H}^{-1}(s^9_5, 0.3) = (Fairly-high, 0.3),
\end{aligned}$$

$$\begin{aligned}
F_3 &= f_{ULWG}(\{(s^9_2, s^9_3), (s^9_5, s^9_6), (s^9_1, s^9_5)\}) \\
&= \mathscr{L}\mathscr{H}^{-1}((\triangle_3^{-1}(s^9_3, 0))^{f(s^9_2)} \times (\triangle_3^{-1}(s^9_6, 0))^{f(s^9_5)} \times (\triangle_3^{-1}(s^9_5, 0))^{f(s^9_1)}) \\
&\doteq \mathscr{L}\mathscr{H}^{-1}(s^9_5, -0.07) = (Fairly-high, -0.07).
\end{aligned}$$

Accordingly, the probability of failure of P_1 made by manufactory M_1 is “(Medium,-0.17)”, the probability of failure of P_2 is “(Fairly-high,0.3)" and the probability of failure of P_3 is “(Fairly-high,-0.07)”. Hence the risk of the manufactory M_2 is the highest.

Compared our method with the method proposed in [6], because interval valued fuzzy numbers are used to represent evaluation values, computation of the method is complex and the result of the method is the lack of precision, i.e., P_2 and P_3 have the same probability of failure “fairly-high”. This is loss of information due to the degree of similarity between the interval-valued fuzzy numbers. However, the result of our method is that the probability of failure of P_2 is “(Fairly-high, 0.3)” more than “(Fairly-high, -0.07)” of P_3. There is no loss of information due to 2-tuple fuzzy linguistic representation and no complex computation due to linguistic aggregation operator.

Table 6.10 The evaluations of expert 1

Risk types	Expert 1
SR	$((exactly, small), (exactly, low))$
CR	$((exactly, small), (exactly, low))$
QR	$((absolutely, small), (absolutely, low))$
PR	$((very, small), (very, low))$
RR	$((exactly, big), (exactly, high))$

Table 6.11 The evaluations of expert 2

Risk types	Expert 2
SR	$((very, small), (very, low))$
CR	$((very, small), (very, low))$
QR	$((slightly, small), (slightly, low))$
PR	$((exactly, small), (exactly, low))$
RR	$((very, small), (very, low))$

Table 6.12 The evaluations of expert 3

Risk types	Expert 3
SR	$((slightly,\ small),\ (slightly,\ low))$
CR	$((slightly,\ small),\ (slightly,\ low))$
QR	$((somewhat,\ small),\ (somewhat,\ low))$
PR	$((slightly,\ big),\ (slightly,\ low))$
RR	$((exactly,\ small),\ (exactly,\ low))$

6.4 Risk Analysis Based on L_{10}

In a project management, risk management is important. For the best benefit from the project invest, the manager must do the risk analysis. In the project risk analysis, severity of loss is expressed by the linguistic evaluation values, e.g., *very low, fairly low, pretty low, medium, almost high, more or less high, very high, and absolutely high*. Furthermore, the probability of failure is also used in fuzzy risk analysis.

Assume that there are r components $P_1, P_2, \ldots$ and P_r made by r manufactories $M_1, M_2, \ldots$ and M_r, respectively. Each component P_i consists of s sub-components

$p_{i1}, p_{i2}, \dots$ and p_{is}. Each sub-components p_{ij} ($1 \leqslant i \leqslant r$, $1 \leqslant j \leqslant s$) is evaluated by the severity of loss L_{ij} and a probability of failure F_{ij}, in which L_{ij} and F_{ij} come from the linguistic evaluation values, respectively. Now we will give a software project risk analysis model based on L_{10}, in which the basic evaluation word sets are selected by $\{c_1 = \text{high}, c_2 = \text{low}\}$ and $\{p_1 = \text{big}, p_2 = \text{small}\}$, respectively. The linguistic hedge set is $H = \{$ absolutely, very, exactly, somewhat, slightly $\}$ which is accepted by all experts.

(1) The linguistic evaluation values for severity of loss: $L = \{$ absolutely low, very low, exactly low, somewhat low, slightly low, slightly high, somewhat high, exactly high, very high, absolutely high $\}$, which can be constructed by L_{10} of severity of loss;
(2) The linguistic evaluation values for probability of failure: $F = \{$ absolutely small, very small, exactly small, somewhat small, slightly small, slightly big, somewhat big, exactly big, very big, absolutely big $\}$, which can be constructed by L_{10} of probability of failure.

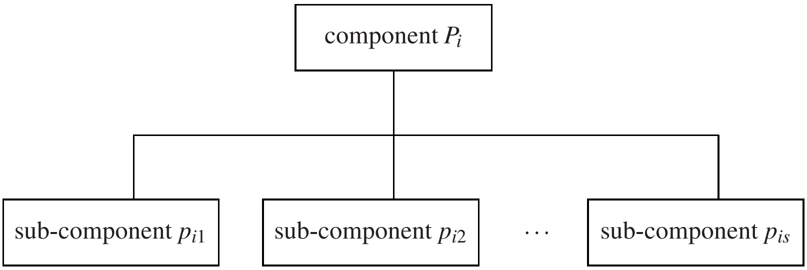

Fig. 6.4 The structure of fuzzy risk analysis

The structure of fuzzy risk analysis is shown in Fig. 6.4, in which P_i is evaluated by L_i (severity of loss) and F_i (probability of failure), and every sub-component p_{ij} ($j = 1, 2, \dots, s$) is evaluated by L_{ij} and F_{ij}. Formally, we can rewrite the result of fuzzy risk analysis as linguistic evaluation of L_i and linguistic evaluation of F_i. From the algebraic point of view, the result of fuzzy risk analysis (linguistic evaluation of L_i, linguistic evaluation of F_i) is embedded in $L \times F = \{((h_i, c_j), (h_k, p_l)) \mid (h_i, c_j) \in L,\ (h_k, p_l) \in F\}$, because L and F are all lattice implication algebras L_{10}, and $L \times F$ is a $L_{10} \times L_{10}$ lattice implication algebra. On the other hand, there exist associable relationships among sub-components of fuzzy risk analysis, e.g., sub-component p_{i1} affects sub-component p_{i2}, i.e., $p_{i1} \to p_{i2}$. Naturally, the corresponding results of p_{i1} and p_{i2} are translated by

Table 6.13 The aggregation results

Risk types	Experts
SR	$((very,\ small),\ (very,\ low))$
CR	$((very,\ small),\ (very,\ low))$
QR	$((absolutely,\ small),\ (absolutely,\ low))$
PR	$((very,\ small),\ (very,\ low))$
RR	$((very,\ small),\ (very,\ low))$

$((h_i^{p_{i1}}, c_j^{p_{i1}}), (h_k^{p_{i1}}, p_l^{p_{i1}})) \to ((h_i^{p_{i2}}, c_j^{p_{i2}}), (h_k^{p_{i2}}, p_l^{p_{i2}}))$ in $L \times F$. Hence, we obtain the result of fuzzy risk analysis by the following three steps:

(1) Integrate experts' results of each sub-component P_i. From the algebraic point of view, every binary operator can be used as an aggregation to integrate experts' results, e.g., $\vee$ or $\wedge$;

(2) Consider associable relationships among sub-components of fuzzy risk analysis. In the lattice implication algebra, every associable relationship is translated by implication formula;

(3) Integrate all results of steps 1 and 2. In the lattice implication algebra, we select $\vee$ or $\wedge$ to aggregate all results.

Example 6.9. In a repair information analysis system, there exist some risk because customers cannot explain their requirement exactly or some new technology is applied. This project risk may be schedule risk (SR), cost risk (CR), quality risk (QR), personnel risk (PR) and requirement risk (RR), in which personnel risk affects schedule risk, requirement risk affects quality risk. To analysis the project risk, the manager asked three experts (requirement analysis expert, quality analysis expert and project management expert) to assess these five kinds of risk, respectively. The evaluation results of experts are shown in Table 6.10. For example, requirement analysis expert gives the severity of loss which is "exactly small" and the probability of failure which is "exactly low" for schedule risk.

According to the steps of fuzzy risk analysis, we aggregate the evaluation results of experts, e.g., for SR, we use operator $\vee$ and obtain $((exactly,\ small),\ (exactly,\ low)) \vee ((very,\ small),\ (very,\ low)) \vee ((slightly,\ small),\ (slightly,\ low)) = ((exactly,\ small) \vee (very,\ small) \vee (slightly,\ small),\ (exactly,\ low) \vee (very,\ low) \vee (slightly,\ low)) = ((very,\ small),\ (very,\ low))$, others are shown in Table 6.13.

Table 6.14 The transformed results

Risk types	Experts
PR $\to$ SR	$((absolutely, big), (absolutely, high))$
CR	$((very, small), (very, low))$
RR $\to$ QR	$((very, big), (very, high))$

We consider associable relationships "personnel risk affects schedule risk" and "requirement risk affects quality risk", i.e., $((very, small), (very, low)) \to ((very, small), (very, low)) = ((very, small) \to (very, small), (very, low) \to (very, low)) = ((absolutely, big), (absolutely, high))$ and $((very, small), (very, low)) \to ((absolutely, small), (absolutely, low)) = ((very, small) \to (absolutely, small), (very, low) \to (absolutely, low)) = ((very, big), (very, high))$. Formally, the fuzzy risk analysis is transformed by Table 6.14.

Based on Table 6.14, we finally obtain the result of the fuzzy risk analysis as $((absolutely, big), (absolutely, high)) \wedge ((very, small), (very, low)) \wedge ((very, big), (very, high)) = ((absolutely, big) \wedge (very, small) \wedge (very, big), (absolutely, high) \wedge (very, low) \wedge (very, high)) = ((very, small), (very, low))$.

6.5 Conclusion

In practice, a main characteristic of fuzzy risk analysis is the use of linguistic values to represent the risk value instead of numerical values, the result of fuzzy risk analysis is also expressed by linguistic values in natural language. Inspired by the weighted geometric operator as a typical aggregation operator and lattice implication algebra as a logical algebra for the reasoning purpose, we have presented two methods for fuzzy risk analysis with linguistic evaluation values. In the first method, the unbalanced linguistic weighted geometric operator has been used to deal with aggregation of unbalanced linguistic evaluation values with numerical weights as well as linguistic weights. By the linguistic aggregation operator, we can directly represent the final linguistic evaluation values and without loss of information. In the second method, we have chosen five common linguistic hedges in risk analysis and the basic words including two antonyms. The evaluation linguistic values have been composed of linguistic hedges and basic words. Using the lattice implication algebra approach to the nature structure of domains of linguistic values is feasible to handle both comparable and incomparable evaluation linguistic values of fuzzy risk analysis. Some examples were also provided to illustrate the proposed approaches. These approaches will provide some methodology support for fuzzy risk analysis.

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Chapter 7

A Belief Rule-Based Generic Risk Assessment Framework

Jun Liu [1], Shuwei Chen [1], Luis Martinez [2], and Hui Wang [1]

[1] *School of Computing and Mathematics, University of Ulster, Northern Ireland, UK*
[2] *Department of Computer Science, University of Jaen, Spain*

E-mail: j.liu@ulster.ac.uk

The present work aims to propose a generic risk assessment framework for modeling, analyzing and synthesizing risk-related information with various uncertainties. Such information may be of very different nature: it can be quantitative or qualitative, and uncertain, incomplete, imprecise, conflicting, for which the traditional quantitative approach (e.g., statistical approach) does not give an adequate answer. IF-THEN rules place the key role in this framework which is then combined with Dempster-Shafer theory of evidence and decision theory in order to form a generic IF-THEN belief rule based risk assessment framework with the aim to address different types of information. The general risk assessment specification for the risk assessment of a hazard event is reviewed firstly. The belief-rule-based risk assessment framework is then illustrated and outlined including rule-base representation, inference procedure, rule-base generation and multi-source synthesis aspects. This is then followed by the illustrative analysis of hierarchical structure nature of the real world risk assessment model. How can the above discussed risk assessment framework be incorporated to form a multi-layer risk assessment model is finally specified. In the proposed generic framework, various types of information from different sources can be transformed and used in the inference process. It provides a flexible and effective way to represent and a rigorous procedure to deal with hybrid uncertain assessment information to arrive at rational conclusions.

7.1 Introduction

Risk management (e.g. disaster management), which encompasses monitoring, predicting, preventing, preparing for, responding to, mitigating and recovering from unexpected hazards (e.g., disasters), aims to deal with any potential and actual hazard (e.g., disaster) by effective and efficient organization, communication, interaction and utilization of counter

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hazard (e.g., disaster) resources [1]. It is the process of assessing hazard risks and taking steps to either eliminate or to reduce them (as far as is reasonably practicable) by introducing control measures.

Risk assessment is one of the key elements of risk management. Expressions such as "risk assessment", "risk evaluation" and "risk analysis" are used in a somewhat interchangeable way to describe a variety of techniques and processes involved in the overall management of risk [2]. Despite this lack of clarity, Frosdick [2] and other researchers consistently use the term "risk assessment" as a catch-all to include all those activities that are needed before appropriate risk reduction methods can be decided upon.

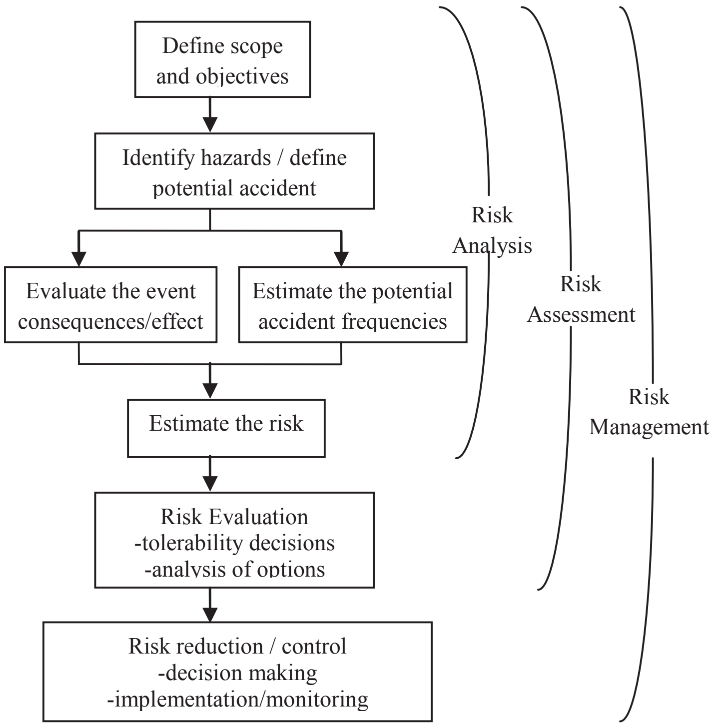

Fig. 7.1 A simplified relationship between risk analysis, risk assessment and risk management

Fig. 7.1 shows the different processes in risk management procedure and presents a simplified relationship between risk analysis, risk assessment and risk management. This definition of the risk management process has been adopted from the International Electrotechnical Commission (IEC). There are other relationships between the definitions of risk analysis, risk assessment and risk management, where risk assessment is part of the risk analysis. In this paper, we focus only on risk assessment issue.

Risk assessment (especially in disaster management) is a very complicated subject where risk is determined by numerous factors, including human error. The general area of risk assessment is vast, with many methods and tools available to use for assessing risk of various environments [3]. Many risk assessment techniques currently used in the disaster management are comparatively mature tools. However, there are still some limitations for these techniques to be widely and effectively applied to provide useful solutions to risk-based decision making. This is due to the following problems among others:

- Under prevailing circumstances, only limited or no previous experience exists on a hazard, for which the statistical accuracy is poor, in particular for a risk scenario where undesired events are extremely rare.
- It is extremely difficult to quantify the effects and consequences of hazards as they involve too many factors with a high level of uncertainty, even in those cases where the physical processes are clearly understood.
- It is extremely difficult to generate a mathematical model to represent and describe the risk behavior/discipline of disaster hazards as risk is a multiple-level and multiple-variable optimization problem.
- A large number of assumptions, judgments and opinions are involved subjectively in a risk quantification process. Therefore, it may require considerable skill for a risk analyst to interpret the results produced.

Very importantly, handling uncertainty is one of the crucial issues in the risk assessment in complex systems with diverse environments. Uncertainty in risk assessment can be considered essentially of two different types: randomness due to inherent variability in the system (i.e., in the population of outcomes of its stochastic process of behavior) and imprecision due to lack of knowledge and information on the system. The former type of uncertainty is often referred to as objective, aleatory, stochastic whereas the latter is often referred to as subjective, epistemic, state-of-knowledge [4, 5]. In most risk assessment, we have to rely on such imperfect information through appropriate risk management.

In certain circumstances, probability theory can be a powerful tool. Traditional study of risk analysis is conducted using probabilistic tools and techniques. However, it is not difficult to see that aspects related to imprecision or vagueness clearly have a non-probabilistic character since they are related to imprecision of meanings. Very often the type of uncertainty encountered in hazard does not fit the axiomatic basis of probability theory, simply because uncertainty in these hazards is usually caused by the inherent fuzziness of the parameter estimate rather than randomness. Traditional approaches, e.g., quantitative risk assessment (QRA) including probabilistic safety/risk analysis (such as Fault Tree Analysis (FTA) and Failure Mode, Effects and Criticality Analysis (FMECA)) have been widely used, but often fail short in their ability to permit the incorporation of subjective and/or vague terms as they rely heavily on supporting statistical information that may not be available [7].

Extensive research has been devoted to the analysis and management of the risks under uncertainty. Some detailed overviews of uncertainty aspects in risk and safety management can be found in [8–15]. Chowdhury *et al.* (2009) provided a detailed review of uncertainty analysis in risk management studies associated with disinfection by-products (DBPs) in drinking water and human health risk [9]. Markowski (2010) discussed and presented the sources and types of uncertainties encountered in process safety analysis and also methods to deal with them [13]. From the literature, many different formal techniques have been developed over the past two decades for dealing with uncertain information for risk assessment in decision making, where Bayesian probability theory [16, 17], Dempster-Shafer theory of evidence [18, 19], and fuzzy logic [20–22] are three of the most common methods of representing and reasoning with uncertain knowledge. Liu *et al.* (2011) provided a detailed review of risk assessment based on computing with words [23].

Novel risk analysis methods are therefore required to identify major hazards and assess the associated risks in an acceptable way in various environments where mature tools cannot be effectively or efficiently applied. The subject of our work would be to establish a general framework that provides the basis and tool for risk analysis in different application area, especially to deal with information that may be unquantifiable due to its nature, and imprecise, too complex, ill-defined, incomplete etc., for which the traditional quantitative approach (e.g., statistical approach) does not give an adequate answer.

The rest of this paper is organized as follows: Risk specification parameters for a hazard event assessment are briefly overviewed in Section 7.2. The generic belief rule based hazard risk assessment framework is then justified and outlined in Section 7.3. In order to handle more complex situation, the hierarchical structure of risk nature in complex hazard situation are illustrated using some realistic examples and the multi-layer belief rule-based risk assessment framework is introduced in Section 7.4. Conclusions are drawn in Section 7.5.

7.2 Hazard Associated Risk Specification Parameters

As can be seen from Fig. 7.1, risk assessment is a key element of risk management; it can be further separated depending on how detailed are the analysis and the labour resources available in at least three levels:

- qualitative methods
- semi-quantitative methods
- quantitative methods

During risk analysis, all three levels can be used in sequence. Qualitative methods are used to determine which scenarios are relevant to continue with the quantitative risk analysis. Initially, risk assessments were qualitative because of their subjectivity. The search for greater objectivity, led to the development of quantified risk analysis techniques. Quantitative risk analysis methods fall under the broad category of probabilistic risk assessment (PRA). Risk is generally characterized by the severity (or magnitude) of an adverse consequence that can result from an action and the likelihood of occurrence of the given adverse consequence. In PRA, consequences are expressed numerically and their likelihoods of occurrence are expressed as probabilities or frequencies. Accordingly, risk is defined as the product of likelihood and severity. Determination of needed basic event probabilities is the most difficult task in applying this technique. Many references explain all aspects of PRA in great detail [24–26].

Risk is sometimes characterized not only by likelihood and severity, but also with some additional parameters depending on the different applications. The definitions of those parameters also vary according to different application contexts. For example, FMEA approach is a widely used engineering technique for defining, identifying and eliminating known and/or potential failures, problems, errors and so on from system, design, process, and/or service before they reach the customer [27]. The traditional FMEA determines the risk priorities of failure modes through the risk priority number (RPN), which is the product of the occurrence (O), severity (S) and detection (D) of a failure. That is:

$$\mathrm{RPN} = \mathrm{O} \times \mathrm{S} \times \mathrm{D},$$

where O and S are the frequency and seriousness (effects) of the failure respectively, and D is the ability to detect the failure before it reaches the customer. The failure modes with higher RPNs are assumed to be more important and will be given higher priorities for correction.

Table 7.1 Qualitative and quantitative parameters

Risk parameter	**Qualitative descriptions**	**Quantitative descriptions**
Consequence (C)	Minor injury	No deaths per event
	Marginal: one death or permanent injury	$[10^{-2}, 10^{-1}]$ probable deaths per event
	Critical: several deaths	$[10^{-1}, 1]$ probable deaths per event
	Catastrophic: many deaths	> 1 probable deaths per event
Exposure (F)	Rare	$< 10\%$ of time
	Frequent	$\geqslant 10\%$ of time
Avoidance (P)	Possible	90% probability of avoiding hazard
	Not likely	$\leqslant 90\%$ probability of avoiding hazard
Demand rate (W)	Very low	< 1 in 30 years $\approx < 0.03$ per year
	Low	1 in $[3, 30]$ years $\approx [0.03, 0.3]$ per year
	Relatively high	1 in $[0.3, 3]$ years $\approx [0.3, 3]$ per year

Wang *et al.* [27] used three fundamental parameters to assess the safety level of an engineering system on a subjective basis: failure rate (FR), consequence severity (CS) and failure consequence probability (FCP). FR describes failure frequencies in a certain period, which directly represents the number of failures anticipated during the design life span of a particular system or an item. CS describes the magnitude of possible consequences, which is ranked according to the severity of failure effects. FCP defines the probability that consequences happen given the occurrence of the event.

In addition, four risk parameters, considered to be sufficiently generic to deal with a wide range of applications, have been combined to risk assessment as well. These parameters are: consequence (C), frequency and exposure time (F), possibility of avoiding hazard (P), and probability of the unwanted occurrence (W). All parameter aspects imply a quantitative or qualitative valuation of undesired events or harmful events effects. Table 7.1 shows an example of a risk graph as used in the UKOOA guidelines and quantitative definitions of risk parameters [28, 29]. Baybutt (2007) has developed an improved risk assessment with the following four parameters: initiating cause frequency, enabling events/conditions, safeguards failure probability and consequences of the hazardous event [30].

In summary, how to represent and determine those risk relevant factors, and then model the relationships between risk factors and risk level are the key issues to provide the risk estimation of a hazard. For example, to assess the safety associated with an event, it is required to synthesize the associated occurrence likelihood, consequence severity and failure probability. The way of synthesis of risk factors into risk estimation can be represented in different ways based on cause and effect relationship. Different methodologies have been proposed accordingly in different applications. The following section provides a general risk assessment framework.

7.3 A Belief-Rule Based Generic Hazard Risk Assessment Framework

7.3.1 *Motivation and Rationale*

As discussed in Section 7.2, the nature of risk is usually affected by numerous factors including human errors, in many circumstances; it may be extremely difficult to assess the associated risks due to the great uncertainty involved. The quantitative risk assessment approaches fall short in their ability to permit the incorporation of subjective and/or vague terms as they rely heavily on supporting statistical information that may not be available. Quantification of risk in scalar values is subject to uncertainties for many reasons including difficulties in defining the likelihood and consequence severity and the mathematics of combining them. Collecting sufficient data to base a statistical probability of risk is costly, and in many situations, such data are limited or unavailable due to a lack of research or the complexity of the system/process considered. In addition, it may be extremely difficult to construct an accurate and complete mathematical model to correlate the risk factors and risk levels.

Those quantitative assessments of risk are particularly challenging in domains where undesired events are extremely rare, and the causal factors are difficult to quantify and non-linearly related, e.g., include the difficulty of determining both the probabilities of rare events (such as a nuclear accident, or only incomplete information is available during the very early phases of the system life cycle), and their severity, further, the probabilities may be dynamic, and vary with a variety of factors which are not known in advance.

To overcome the above drawbacks, many approaches have been proposed, among many alternative approaches for knowledge representation and reasoning, it is widely recognized that the *rule-based system* seem to be one of the most common framework for expressing various types of knowledge in an intelligent system (systems that have elements of human reasoning and certain level of intelligence) [6, 31]. As discussed in the above section, in the design and implementation of rule-based systems for supporting human decision making, it is necessary and inevitable to use a scheme for representing and processing imprecise, incomplete and uncertain information in conjunction with precise data. During the last quarter of a century many different types of rule-based systems emerged, certainly including the fuzzy rule-based system, which, as one of the dominant and main framework in rule-based system, has been widely accepted, investigated and applied in many application areas. Fuzzy logic has been also widely applied in risk assessment to different areas and has been regarded as one of the promising methods for the reduction of uncertainties in risk assessment. An important contribution of fuzzy system theory is that it provides a systematic procedure, i.e., fuzzy rule base approach, for capture the uncertainty and the non-linear relationships among the system input and output parameters. Fuzzy rule-based system is constructed using human knowledge in the form of *IF-THEN* rules. In risk assessment risk factors are inputs, and risk estimation is the output. The relationship between risk factors and risk is described by IF-Then Rules. For example, the following is a classical IF-THEN rule for safety analysis [10]:

IF **FR** of a hazard is *frequent* AND **CS** is *catastrophic* AND **FCP** is *likely*, THEN risk estimate is *high* (7.1)

The detailed review of fuzzy logic based risk assessment methodology could be found in Refs [32–34] and mostly recently in Refs. [23] and [35–38], this showed the successful application of fuzzy logic into risk assessment.

Moreover, in recognition of the need to handle hybrid information with uncertainty in human decision making, a new methodology has been proposed recently for modeling a hybrid rule-base using a belief structure and for inference in the belief rule-based system using the evidential reasoning (ER) approach [39]. The methodology is referred to as a belief Rule-base Inference Methodology using the Evidential Reasoning approach – RIMER [40], where a rule-base is designed with belief degrees embedded in the consequent term of a rule, called belief rule-base (BRB), is used to capture nonlinear causal relationships as well as uncertainty. The inference of a rule-based system is implemented using the ER approach. RIMER approach has been further investigated and applied to different areas, such as, among others, work in [10, 11, 41–43].

The main methodologies and technical framework involved in RIMER is summarized in Fig. 7.2 below.

The *RIMER* approach is summarized here, and see ref. 40 for more details. Suppose a belief rule-base is given by $R = \{R_1, \dots, R_L\}$ with the k^{th} rule represented:

R_k: IF U is A^k THEN D with belief degrees β^k, with a rule weight θ_k and attribute weights $\delta_{k1}, \dots, \delta_{kT_k}$ (7.2)

where U represents the antecedent attribute vector $(U_1, \dots, U_{T_k})$, A^k the packet antecedents $\{A_1^k, \dots, A_{T_k}^k\}$, A_i^k $(i = 1, \dots, T_k)$ the referential value of the i^{th} antecedent attribute in the k^{th}

Fig. 7.2 Main methodologies and technical framework in RIMER

rule; T_k is the number of antecedent attributes used in the k^{th} rule. Suppose T is the total number of antecedent attributes used in the rule base, D the consequent vector $(D_1, \ldots, D_N)$, and β^k the vector of the belief degrees $(\beta_{1k}, \ldots, \beta_{Nk})$ for $k \in \{1, \ldots, L\}$, and β_{ik} the belief degree to which D_i is believed to be the consequent if in the k^{th} packet rule the input satisfies the packet antecedents A^k. θ_k is the relative weight of the k^{th} rule and δ_{kT_k} the relative weights of the T_k antecedent attributes in the k^{th} rule. L is the number of all the packet rules in the rule-base. If $\sum_{i=1}^{N} \beta_{ik} = 1$, the k^{th} packet rule is said to be complete; otherwise, it is incomplete. Rule (7.1) is referred to as *a belief rule*.

Accordingly fuzzy rule in (7.1) is extended into fuzzy rules with belief degrees for multiple possible consequent terms in the safety assessment [10]:

R_k: *IF* the FR is *frequent* AND the CS is *critical* AND the FCP is *unlikely*
THEN risk estimate is $\{$(*high*, 0.7), (*Average*, 0.3), (*Fair*, 0), (*Low*, 0)$\}$ (7.3)

where risk estimate is a belief distribution representing that we are 70% sure that risk level is *Fair*, and 30% sure that it is *Poor*, which reflects another kind of uncertainty caused because evidence available is not sufficient or experts are not 100% certain to believe in a hypothesis but only to degrees of belief. This kind of belief rule is able to capture uncertainty and nonlinear relationships between these three parameters and the risk level.

Once given an input, the activation weight w_k for A^k, which measures the degree to which the k^{th} rule is weighted and activated, is calculated by:

$$w_k = \theta_k * \prod_{i=1}^{T_k} \left(\alpha_i^k\right)^{\bar{\delta}_i} \Big/ \sum_{i=1}^{L} \left[\theta_i * \prod_{l=1}^{T_k} \left(\alpha_l^i\right)^{\bar{\delta}_l}\right] \quad \text{with} \quad \bar{\delta}_i = \delta_i \Big/ \max_{i=1,\ldots,T_k} \{\delta_i\} \tag{7.4}$$

where $\alpha_i^k \in [0,1]$ called the *individual matching degree*, is the degree of belief to which the input for U_i belongs to A_i^k of the i^{th} individual antecedent in the k^{th} rule, and α_i^k could be generated using various ways depending on the nature of an antecedent attribute which will be seen in details in Ref. [40].

Having determined the activation weight of each rule in the rule base, the ER approach [39] can be applied to combine the belief distributions of the consequence of all the rules and generate final conclusions. The conclusion generated by aggregating all activated rules by the actual input vector $\mathbf{I} = (I_1, \ldots, I_{T_k})$ for the antecedent vector U can be represented as follows:

$$S(\mathbf{I}) = \{(D_j, \beta_j),\ j = 1, \ldots, N\} \tag{7.5}$$

The result in Eq. (7.5) reads that if the input is given by $\mathbf{I}$, then the consequent is D_1 to a degree $\beta_1, \ldots$, and D_N to a degree β_N. Using the analytical ER algorithm [41], the overall combined degree of belief β_j for D_j in Eq. (7.5) is generated as follows:

$$\beta_j = \frac{\mu \times \left[\prod_{k=1}^{L} \left(w_k \beta_{j,k} + 1 - w_k \sum_{i=1}^{N} \beta_{i,k}\right) - \prod_{k=1}^{L} \left(1 - w_k \sum_{i=1}^{N} \beta_{i,k}\right)\right]}{1 - \mu \times \left[\prod_{k=1}^{L} (1 - w_k)\right]}, \quad j = 1, \ldots, N \tag{7.6}$$

where

$$\mu = \left[\sum_{j=1}^{N} \prod_{k=1}^{L} \left(w_k \beta_{j,k} + 1 - w_k \sum_{i=1}^{N} \beta_{i,k}\right) - (N-1) \prod_{k=1}^{L} \left(1 - w_k \sum_{i=1}^{N} \beta_{i,k}\right)\right]^{-1}.$$

Note that the final result in Eq. (7.5) is still a belief distribution on an estimate, which gives a panoramic view about estimate for a given input. It clearly shows its nonlinear features in aggregating a large number of consequent attributes. The belief theory together with fuzzy logic provides a flexible approach to represent uncertain evidence and uncertain knowledge. The rules represent functional mappings between imprecise information with uncertainty. A fuzzy rule-base designed on the basis of a belief structure is used to capture uncertainty and non-linear relationships between these parameters and the safety level; and the inference of the rule-based system is implemented using the evidential reasoning algorithm. RIMER are an extension of traditional rule based systems and are capable of representing more complicated causal relationships using different types of information with uncertainties.

7.3.2 *Hazard risk assessment framework based on RIMER*

The proposed framework for risk analysis consists of five major components, which are outlined as follows:

Component #1: Identification of causes/factors of a hazard event

In this step, as discussed in Section 7.2, all the anticipated causes/factors to a hazard event are identified. This can be done by involvement of a panel of experts during a brainstorming session.

Component #2: Specify and represent input (e.g., failure rate, consequence severity and failure consequence probability for risk assessment) and output/solution variables (i.e., risk estimates) and create the fuzzy membership functions or utility function for all the related input variables.

Some fundamental parameters used to assess the risk level of system on a subjective basis (using linguistic variables instead of ultimate numbers in probabilistic terms) need to be defined, such as failure rate, consequence severity and failure consequence probability, or some other parameters as discussed in Section 7.2, are more appropriate for analysis using these three parameters as they are always associated with uncertainty. These linguistic assessments can become the criteria for measuring risk levels. The definitions and identifications of those parameters differ from different applications according to different requirements in codes and standards (e.g., safety/risk guidelines, regulations, laws etc.) and different aspects of engineering systems such as fire, explosions, structure, safety system, etc., for example, different definitions can be found in Refs. [27, 44, 45].

Component #3: Construct the rule base with belief structure

7.3.2.1 *Optimization models based on training sample data*

Optimization models procedures are investigated in the *RIMER* framework based on the optimization models for training general belief rules based systems [41], in order to help generate desirable belief rules and other system parameters simultaneously. Figure 7.1 shows the process of training a belief rule base with additional elements to deal with fuzziness, where $\hat{x}_m$ is a given input, $\hat{y}_m$ the corresponding observed output, either measured using instruments or assessed by experts, y_m the simulated output generated by the belief rule based system, and $\xi(P)$ the difference between $\hat{y}_m$ and y_m, as defined later.

In the learning process, a set of observations on the system input and output is required. In the following, we assume that a set of observation pairs (**x**, **y**) is available, where **x** is an input vector and **y** the corresponding output vector. Both **x** and **y** can be either numerical,

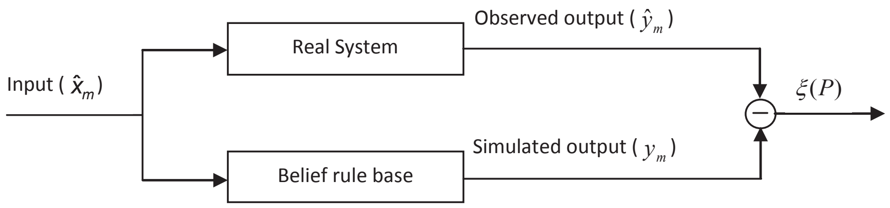

Fig. 7.3 Illustration of Optimal Learning Process

judgmental or both. The format of the objective functions is important for the parameter optimization. Depending on the type of input and output, the optimal learning model can be constructed in different ways, as discussed in details in Refs. [41, 42]: i) optimization algorithms based on the numerical output form; ii) optimization algorithm based on the output in the form of the subjective judgment; iii) optimization algorithm based on the input-output in form of interval.

It is worth note that in this case (ii), a training set composed of M input-output pairs (x_m, y_m) $(m = 1, \ldots, M)$, where y_m can be a subjective judgment, i.e., a distributed assessment on the linguistic value with belief. Notice that the single judgment as one linguistic value can be regarded as a special case of the distribution assessment. The output of *RIMER*-based risk assessment is actually a distribution safety assessment instead of a single numerical score, which provides a panoramic view about the output status, from which one can see the variation between the original output and the revised output on each linguistic term. A distribution is easy to understand and flexible to represent output information than a single average value. Especially it is very useful in the case that the output is difficult to quantify. For example, the linguistic terms in risk (e.g., *high*, *fair*, or *low*, etc.) have no clearly defined bases and are difficult to define quantitatively. So, it is better to draw a conclusion using the same linguistic terms as the ones in the consequent but with different degrees of belief. Such subjective judgments with belief are useful in such areas as safety/risk classification.

In summary, due to the use of belief rules, the *RIMER* method provides an analytical description of relationships between system's inputs and outputs. This enables a belief rule-based system to act as a generic functional mapping from system inputs to outputs and allows powerful learning techniques to be used for parameter training and system updating on the basis of both numerical data and human judgments, this is one of the main feature in the training models.

7.3.2.2 *Construct the rule base with belief structure based on experts*

Due to the qualitative nature of linguistic rule base, the causal relationship between IF part and THEN part is not possible to be obtained due to lack of complete and accurate information regarding the training set, e.g., a new system or rarely happened events. Such a situation typically arises when learning examples are generated by one or several experts, whose subjective evaluation of consequence may be tainted with imprecision and uncertainty. For each expert may not always be able to classify clearly the consequence class with full certainty. He or she may, however, be able to assess the "likelihood" that a certain phenomenon is present in the data. Hence, an approach to obtain belief rule base is to collect the opinions of several experts, and consider for each example the empirical distribution of expert opinions about its class belief. Belief distribution in Eq. (7.2) can be obtained in several different ways [46], called belief elicitation method, which in this framework means any aid that is used to acquire a probability from an expert, including:

direct elicitation from an expert, who is asked to quantify by a real number between 0 and 1 the degree of belief that IF part A_k belongs to each of the N evaluation grade $D_1, \ldots, D_N$. However, people find words more comfortable than numbers probably because the vagueness of words captures the uncertainty they feel about their probability assessments. Since directly assessed numbers tend to be biased, various indirect elicitation methods have been developed. So an alternative is suggested, i.e.,

from an empirical distribution of expert opinions, using the relative frequency:

$$\beta_{ik} = \frac{u_{ik}}{M}, \tag{7.7}$$

where u_{ik} denotes the number of experts (out of M) who assigned IF part A_k $(k = 1, \ldots, L)$ into the evaluation D_i $(i = 1, \ldots, N)$ in THEN part. Alternatively, we could use possibilistic histograms [47] to generate a relative frequency as follows:

$$\beta_{ik} = \frac{u_{ik}}{\sum\limits_{t=1,\ldots,N} u_{tk}}, \text{ where } u_{ik} = \frac{1}{M} \sum_{j=1,\ldots,N} \min(u_{ik}, u_{jk}) \tag{7.8}$$

The above feature and approaches associated with RIMER shows that it can be regarded as data-driven and domain knowledge based risk assessment model. This belief rule base is a great extension of traditional fuzzy rule based systems. In a belief rule based system, while human expert knowledge is used to construct a roughly correct belief rule base, the optimal learning mechanism can help to fine tune system performance if the system input–output data are available. As such, we believe that reasoning with fine-tuned logical rules is more acceptable to human users than the recommendations given by a black box system, because such reasoning is comprehensible, provides explanations, and can be validated by human inspection. It also increases confidence in the system, and may help to discover important relationships and combinations of features [41].

Component #4: Reasoning mechanism based on belief rule-base and evidential reasoning algorithm.

Once rule-base is built up, the knowledge contained is used to perform the inference procedure while the inputs are given. For each global antecedent attribute, the matching degree between the input and each individual antecedent need to be determined and finally get the global matching degree by combining the individual matching degree. These global matching degrees are used as the strength weights of the global attribute. The inference procedure is basically composed of the following steps, and can be summarized as follows:

Step 1: Discretization of the input variables into the distributed representation of linguistic terms in the antecedent;

Step 2: Selection of "AND" connectives to reflect the dependencies of attribute in the antecedent of the rule;

Step 3: Determination of the actual degree of belief of the rule;

Step 4: Fuzzy rule expression matrix of knowledge-base;

Step 5: Rule combination by using evidential reasoning (ER) algorithm.

Component #5: Multi-source risk synthesis

In this component, some aggregation approaches are used in the later stage of the framework to deal with risk synthesis with complexity involving multi-experts or multi-sources, this is to integrate all the possible risk estimates made by a panel of experts or based on different sources. The ranking and interpretation of the final safety/risk synthesis of a system is given.

Assume that there are several sources (including experts) S_i $(i = 1,\dots,K)$. Without loss of generality, suppose input comes from different sources evaluated by different experts. Note that it is likely for selected information sources to be of different importance (or reliability), so the weights of information sources need to be taken into account. The assessment of weight for each information source is an important decision for the analyst to make in view of the safeguards system under scrutiny. Each information source is assigned a weight to indicate the relative importance/reliability in contributing towards the overall evaluation. The analyst must decide which information source has higher reliability and then assign weights accordingly.

We may assume that different sources have different reliability weights, w_{si} $(i = 1,\ldots,K)$. Suppose $A_{ei}(j)$ is an input vector derived from e_i for an event I_j. For each input, we may get a corresponding process estimate D_{ei} using the above RIMER approach, which can be formulated as follows:

IF I_j is $A_{e1}(j)$ THEN $P_{e1}(j)$ is $\{(D_1,\eta_{11}),\ (D_2,\eta_{21}),\ldots,\ (D_N,\eta_{N1})\}$
IF I_j is $A_{e2}(j)$ THEN $P_{e2}(j)$ is $\{(D_1,\eta_{12}),\ (D_2,\eta_{22}),\ldots,\ (D_N,\eta_{N2})\}$
...
IF I_j is $A_{ei}(j)$ THEN $P_{ei}(j)$ is $\{(D_1,\eta_{1i}),\ (D_2,\eta_{2i}),\ldots,\ (D_N,\eta_{Ni})\}$
...
IF I_j is $A_{eK}(j)$ THEN $P_{eK}(j)$ is $\{(D_1,\eta_{1K}),\ (D_2,\eta_{2K}),\ldots,\ (D_N,\eta_{NK})\}$

where $\{(D_1,\eta_{1i}),\ (D_2,\eta_{2i}),\ldots,\ (D_N,\eta_{Ni})\}$ results from Eq. (7.5) obtained using the RIMER approach. Then the actual risk estimate of a specific hazard event $P(j)$ can be generated by synthesizing multi-expert assessments, i.e., by aggregating $\{P_{e1},\ P_{e2},\ldots,\ P_{eK}\}$ using the ER algorithm, which is represented as

$$S(P(j)) = \left\{(D_i,\eta_i^j);\ i=1,\ldots,N\right\}, \quad j=1,\ldots,d \tag{7.9}$$

The risk assessment and synthesis framework is summarized and illustrated in Fig. 7.4.

7.4 A Belief-Rule Based Generic Hierarchical Risk Assessment Framework

Section 7.3 outlines the general individual hazard risk assessment framework using RIMER approaches. However, due to the complexity and uncertainty of real world systems and risks, it is necessary to assess the risks by considering the organization of risk information and risk mechanism in different level. Hierarchical framework method is considered to be straightforward and effective to deal with complexity. Then hierarchical assessments are conducted to evaluate the risks of components first and then the whole system. In risk assessment, one of the most valuable and critical contributions of hierarchical framework is its ability to facilitate the evaluation of subsystems risks and their corresponding contributions to the risks of the overall system. Particularly, its ability to model the intricate relationships among the various subsystems and to account for all relevant and important elements of risk and uncertainty renders the risk assessment process more tractable, representative, and encompassing [48].

In general, a hierarchical risk assessment model is composed of risk attributes (sometimes also referred to as risk variables or risk parameters) that represent risk subproblems.

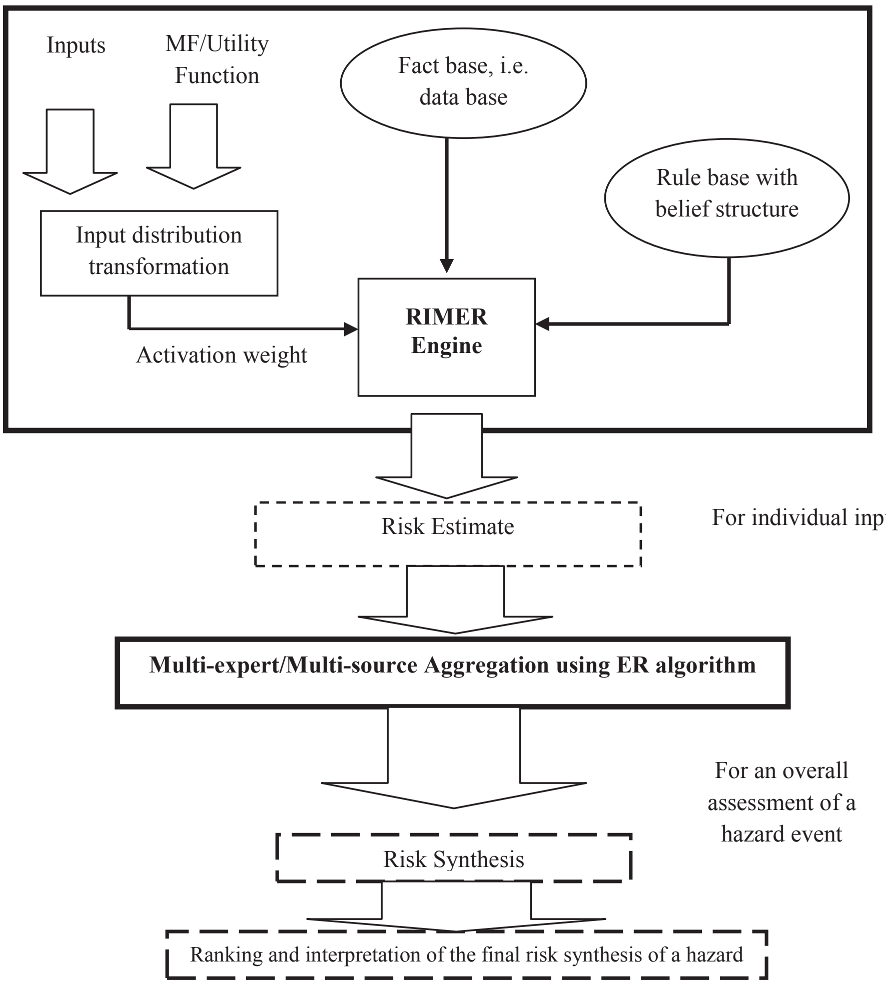

Fig. 7.4 Generic individual hazard risk assessment framework using RIMER Approaches

They are organized hierarchically so that the risk attributes that occur on higher levels of the hierarchy depend on lower-level risk attributes.

Example 7.1. A hierarchical model for the assessment of patient's risk status is shown in Fig. 7.5 [49]. It consists of three main groups of attributes: *history* (data about previous ulcers and amputations), *present status* (data on symptoms, deformities and other changes), and the results of *tests* (loss of protective sensation, absence of pulse).

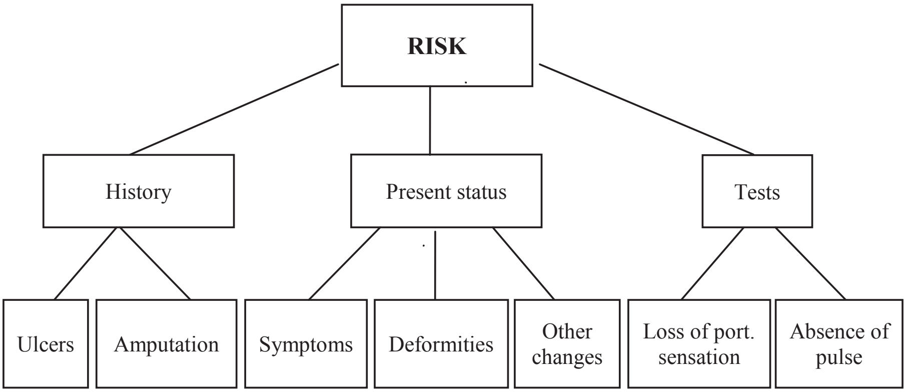

Fig. 7.5 The hierarchical structure of model for risk assessment in diabetic foot care

Associated with each node, there are transition links that explicitly describe the risk relationships between each other. Belief rule base can be carefully designed so as to determine the higher level risk level based on lower level factors. It is clear that the attributes in a lower level are different from each other in types and representations, also different from the high level attributes. The leads to the difficult to establish the mathematical model to correlate their relationship, IF-THEN rule is more appropriate here to model the nonlinear relationship, and belief IF-THEN rule could be further utilized to reflect the uncertainty.

Example 7.2. A hierarchical model for the assessment of cancer risk is shown in Fig. 7.6 [49], which is assessed using a four-valued scale, and is derived from features such as age, regularity of menstruation and fertility duration.

Similarly, the risk of cancer can be evaluated by hieratical belief-rule base, which can be defined by the experts. As an example, consider Table 7.2 that shows the rule that determines the risk with respect to *menstrual cycle* and derives it from two input attributes: *fertility duration* and *regularity*: *stability of menstruation*. Here, the fertility duration can be either short (up to 30 years of menstrual period), average (30–40 years), or long (longer than 40 years). Menstruation cycle can be either regular with a period of less than 28 days (R-28), regular with a period longer than 29 days (R29_) or irregular (*N*).

For each combination of fertility duration and menstruation regularity: stability, the experts assessed the risk related to menstrual cycle and expressed it using a three-level scale: low, medium, and high. Each row in the table can thus be interpreted as an elementary *if-then* rule that assesses the risk for the corresponding values of the two input attributes.

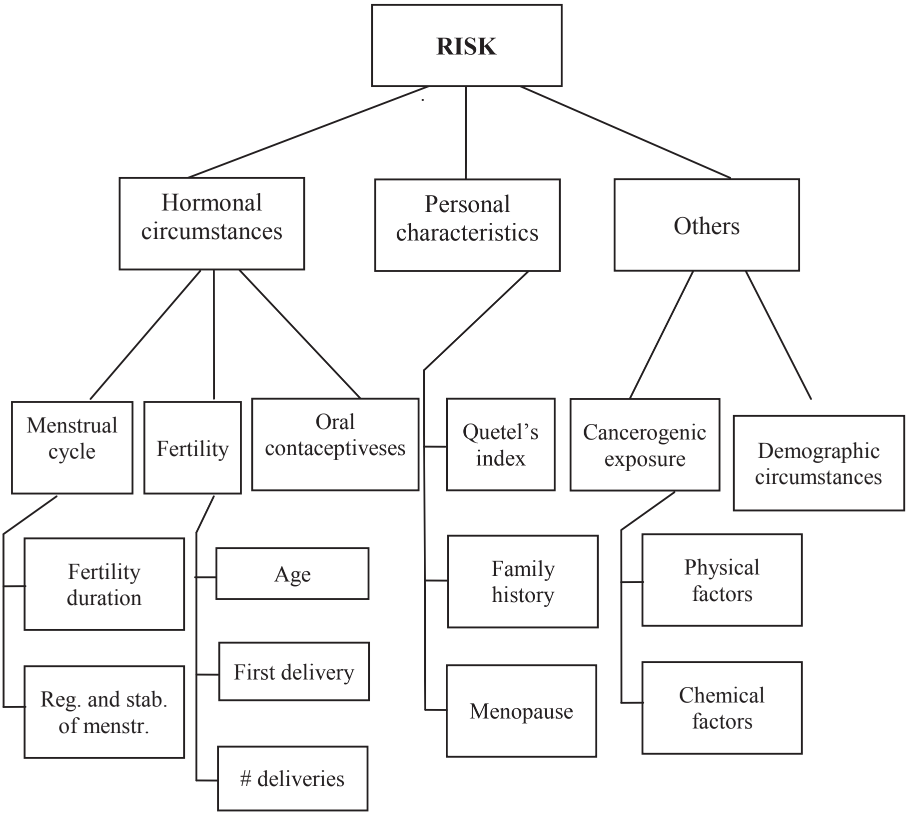

Fig. 7.6 The structure of breast cancer risk assessment model

Also, each row represents a point in the space determined by all the three attributes. It is clear from Table 7.1 that those classical IF-THEN rules shown some limitation which cannot distinguish some rules even they have the different antecedent terms, e.g., when Fertility duration is Long, whatever Regularity is R-28, R29+ or N, Menstrual cycle is always High risk. Using belief IF-THEN rule could simply solve this problem without loss of any information:

IF Fertility duration is Long and Regularity is R28+ THEN Menstrual cycle is {(High risk, 0.9), (Moderate risk, 0.1), (Low risk, 0)}
IF Fertility duration is Long and Regularity is R-28 THEN Menstrual cycle is {(High risk, 0.8), (Moderate risk, 0.2), (Low risk, 0)}

Table 7.2 Decision rule to assess the risk specific to menstrual cycle [49]

	Fertility duration	Regularity/stability of menstruation	Menstrual cycle
1	Average	R-28	High risk
2	Long	R-28	High risk
3	Long	R29+	High risk
4	Long	*N*	High risk
5	Short	R-28	Moderate risk
6	Average	R29+	Moderate risk
7	Short	R29+	Low risk
8	Short	*N*	Low risk
9	Average	*N*	Low risk

IF Fertility duration is Long and Regularity is *N* THEN Menstrual cycle is {(High risk, 0.7), (Moderate risk, 0.2), (Low risk, 0.1)}

Belief rule base can be established to model the relationship between lower level and higher level following the hierarchical structure in Fig. 7.6. The overall risk can be achieved by integrating all the sub-belief rule based inference processes.

Example 7.3. A scheme of the three-level hierarchical social risk assessment system is presented in Fig. 7.7 [50].

A social risk model can be designed as a hierarchical structure with several inputs and one output. The social risk of the studied region is assessed based on the hyrdo-meteorological and seismic information taking into account the social vulnerability. The social risk assessment from the natural hazards is done under the subjective and uncertain conditions. The number of inputs corresponds to the linguistic variables (indicators), which described the environmental risk and social vulnerability. The output represents a social risk assessment from natural disasters. Five indicators for the social risk assessment are defined using the expert knowledge, statistical data and published thematic maps for the seismic, and flood hazards [50]. The inputs are defined as follow:

- Input 1 “Extreme temperature”;
- Input 2 “Floods”;
- Input 3 “Seismic hazard”;
- Input 4 “Population density”;
- Input 5 “Socioeconomical status”.

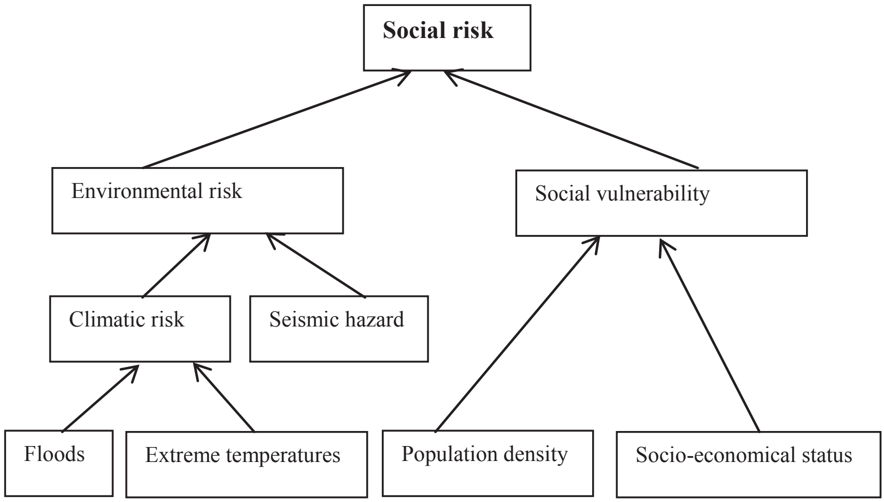

Fig. 7.7 Three-level hierarchical system for social risk assessment

The risk model is designed as a three-level belief rule based hierarchical model with previously defined five inputs. The first level includes one RIMER subsystem. The second level includes two RIMER subsystems. The third level includes only one subsystem. The each RIMER subsystem has two inputs. The hierarchical system output gives the social risk assessment of the natural hazards. The value of the complex assessment is a criterion for final decision making about the degree of social risk for the considered areas. The higher value corresponds to the higher risk degree.

Inherently qualitative features of the indicators are rather than quantitative values, which are usually represented by linguistic variables. Some of the belief rules are defined as follow:

IF "Extreme temperature" is "Middle" and "Floods" is "Low" THEN "Climatic risk" is {(Very high, 0), (High, 0), (Middle, 1), (Low, 0), (Very low, 0)};
IF "Extreme temperature" is "High" and "Floods" is "Middle" THEN "Climatic risk" is {(Very high, 0), (High, 0.8), (Middle, 0.2), (Low, 0), (Very low, 0)};
IF "Climatic risk" is "Middle" and "Seismic hazard" is "Low" THEN "Environmental risk" is {(Very high, 0), (High, 0), (Middle, 0.1), (Low, 0.9), (Very low, 0)};
IF "Climatic risk" is "High" and "Seismic hazard" is "Middle" THEN "Environmental risk" is {(Very high, 0), (High, 0.2), (Middle, 0.8), (Low, 0), (Very low, 0)};

IF "Population density" is "Low" and "Socio-economic status" is "Middle" THEN "Social vulnerability" is {(Very high, 0), (High, 0), (Middle, 0.1), (Low, 0.9), (Very low, 0)};
IF "Population density" is "Middle" and "Socio-economic status" is "High" THEN "Social vulnerability" is {(Very high, 0), (High, 0.2), (Middle, 0.8), (Low, 0), (Very low, 0)};
IF "Environmental risk" is "Low" and "Social vulnerability" is "Low" THEN "social risk from natural disasters" is {(Very high, 0), (High, 0), (Middle, 0), (Low, 0.2), (Very low, 0.8)};
IF "Environmental risk" is "High" and "Social vulnerability" is "Low" THEN "social risk from natural disasters" is {(Very high, 0), (High, 0.7), (Middle, 0.2), (Low, 0.1), (Very low, 0)};
IF "Environmental risk" is "High" and "Social vulnerability" is "High" THEN "social risk from natural disasters" is {(Very high, 0.7), (High, 0.3), (Middle, 0), (Low, 0), (Very low, 0)}.

Similarly, after setting up the belief rule base, once given the input in the bottom level, then the resulting social risk can be estimated using the hierarchical risk assessment scheme based on the framework proposed in Section 3 from bottom level to top level.

7.5 Conclusions and Outlook

Based on the brief review of risk assessment specification and hierarchical nature in the complex situation, the paper proposes a generic hazard risk assessment framework based on the belief rule based inference methodology – called RIMER for modeling, analyzing and synthesizing risk-related information with various uncertainties. In this framework, risk factors are described using linguistic variables with belief, and an IF-THEN rule base with a belief structure, i.e., IF-THEN rules with belief degrees for all possible output terms in the consequent, is to capture uncertain causal relationships between the risk factors and the special risk estimate. Moreover, the antecedent of each IF-THEN rule is considered as an overall attribute, which is assessed to an output term in the consequent of a rule with a belief degree. Actual input can be transformed into a distributed representation for a linguistic term of an individual antecedent indicator. Finally, the inference of the rule-base is implemented using the evidential reasoning algorithm, where an activation degree is used as the weight of an overall attribute. The input information for each risk can be provided from different sources which are normally managed by different experts. Once given an input, RIMER can be used to inference and generate an output. The modeling framework of multi-experts/multi-source synthesis is then provided based on the evidential reasoning approach, i.e., a combination of evidences from different sources.

This general individual hazard risk assessment framework is then followed by the illustrative analysis of hierarchical structure nature of the real world risk assessment model. How can the above discussed risk assessment framework be incorporated to form a multi-layer belief rule-base risk assessment model is finally specified.

The proposed risk assessment framework is able to analyzing risks and safety of complex systems, products and processes involves multiple factor analysis and handling uncertain information of both a quantitative and qualitative nature. The belief rule based system is flexible, can be adapted to represent complicated systems, and is a valid novel approach for risk assessment. In order to make all the processes of rule generation and rule-based inference more efficient, a software package called an intelligent decision support tool based on belief rule-based inference methodology has been developed [51], which provided necessary support for the work proposed and enhanced the applicability of the methodology in different application.

Dedications

This paper is dedicated to the memory of our close friend, an excellent, passionate, and dedicated scientist, Prof. Dr. Da Ruan, who recently passed away in the age of only 50. We will miss you forever, Da!

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Chapter 8

Fuzzy semantics in closed domain question answering

Mohammed-Amine Abchir, Isis Truck, and Anna Pappa

University Paris-8, 2, rue de la Liberté, 93526 Saint-Denis, France

In this chapter we describe fuzzy semantics in a disaster question answering domain.

Emergency management implies to go from reports or descriptions of the disaster into rescue work. These descriptions are usually expressed linguistically by witnesses and must be transformed into comprehensible data.

The aim of our approach is to achieve a multiple interest: modeling data through (un)balanced fuzzy 2-tuples should permit to decrease the CPU time while keeping an adequate approximation. Another interest lies in the recourse to the natural language processing (NLP) that should offer a multi-lingual interface to non-expert users. Thanks to our method, these users will be helped to express their diagnosis (of the disaster consequences) which will be translated into a dataset representing the catastrophic event.

8.1 Introduction

To be able to help populations just after a disaster takes place, it is necessary to conceive tools such as decision support systems for logistics of intervention in disasters and emergencies that can forecast unknown variables as soon as possible to support the decision making process. The aim is to be able to give clues (fatalities, injuries, homeless people, etc.) to NGOs to estimate the magnitude of a disaster, according to quantifiable and hardly quantifiable data. Regarding the hardly quantifiable data (e.g. a vulnerability measure of the area), we know how imprecise and uncertain they may be, that is why fuzzy logic typically is a good framework to manage them. In this chapter two main fields are referred to. We consider both the fuzzy 2-tuple framework [12] and the natural language processing (NLP). Besides, ontologies coupled with NLP will provide for a general framework able to adapt to different kinds of disaster. Since ontology defines concepts and relations between

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concepts, research focuses on ontology technology involved risk management systems [18] for acquisition, extraction and creation of specified knowledge process. Long term, the aim is to be able to obtain *ad hoc* data, whatever the disaster type.

The fuzzy 2-tuple framework should be used to create semantic dependencies in both clearly explicitly stated expressions and vague ones according to user's diagnosis of consequences of the disaster. The query processing expressed in natural language is reflecting different types of real world reasoning (classical reasoning or plausible reasoning). A grammar of affirmative, interrogative and negative sentence forms is needed and parts of text recognition should be determine thanks to syntax. Syntax is related to semantics, consequently used to disambiguate closed assigned semantic roles. However, disambiguation meaning and plausible inference from hidden structure needs semantics contribution to create reasonable evidence. Fuzzy semantics in this disaster management question answer domain is how to combine incomplete or hidden information to a similar meaning words set so we can produce a clear diagnosis of the catastrophe.

This chapter is structured as follows: Section 8.2 introduces disaster or emergency management revising in short the different phases that have to be addressed. Section 8.3 reviews various NLP techniques that should be useful in our context while Section 8.4 presents a way to deal with imprecision in the particular context of emergency management. First, the 2-tuple fuzzy linguistic representation model is reviewed and second, an *ad hoc* method is proposed including both another 2-tuple representation model inspired by the first one and some NLP techniques. Section 8.5 concludes this chapter.

8.2 Disaster or Emergency Management

Disaster management is an important domain for researchers since several years. When a catastrophe happens, it is crucial to be able to obtain as clear an assessment of the situation as is possible in order to alleviate short-term suffering and to learn enough form this assessment to prevent future hazards to become disasters. For example, the ALADDIN (Autonomous Learning Agents for Decentralised Data and Information Networks) project aims to develop techniques, methods and architectures for building decentralised systems that can bring together information from a variety of heterogeneous sources in order to take informed actions and to recover the situation (see `http://www.aladdinproject.org/`).

Another example lies in SEDD (a Spanish acronym for Expert System for Disaster Diagnosis) [21] that is a decision support system to enable intervention in disasters. The system aims at forecasting unknown or ill-known variables as soon as possible as the catastrophe has occurred. It helps non-governmental organizations (NGOs) to know or at least to estimate the magnitude of the catastrophe through information such as reports on damage, fatalities, injured, homeless population, etc.). This kind of information is very often tainted with imprecision or incompleteness, that makes the estimation more difficult.

Experts such as Cuny defines emergency management as being composed of four phases in a loop [6]: mitigation, prepareness, response, and recovery (see Figure 8.1).

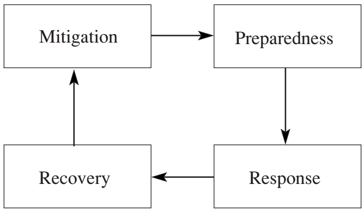


Fig. 8.1 General scheme for disaster management.

Mitigation deals about prevention, *i.e.* the efforts that must be done in order to avoid disasters, or in order hazards or risks don't turn into catastrophes. Authors such as Zou *et al.* have proposed linguistic approaches for risk analysis. The presented method better expresses information, comparable and incomparable, by use of linguistic hedges and antonyms [26]. They construct a linguistic-valued lattice implication algebra whis is suitable for expressing semantics of ten evaluating linguistic values. The reasoning process is directly performed and linguistic values are given to describe the risk analysis. Due to the imprecision of knowledge and of linguistic statements, the proposed approach deals with fuzzy environments.

Disaster management is also often linked to climate change and sustainable development and energy. Prevention can lead to evaluate scenarios to avoid risks. For example, a model has been proposed for evaluating long-term sustainable energy scenarios [7]. The selection of the energy policy is based on the decision analysis that can manage different types of information (numerical, interval-valued and linguistic) with the aim to verbalize the results to facilitate their understanding.

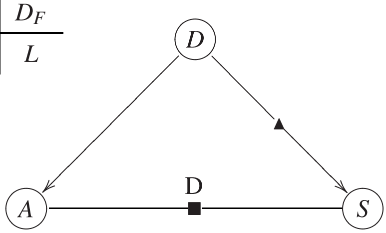
The second phase, prepareness, follows mitigation and is just after the catastrophic event has occurred. It corresponds to the way behaviors are changed to limit the impact of the disaster on people. This phase may have something to do with psychology and applied behavior analysis. This is quite far away from our major issue in this chapter.

Response is the phase where the necessary resource is mobilized. It corresponds to the *action* phase. The mobilization of the emergency services requires two steps. First select the services that have the needed *functional* properties (e.g. firemen, electrician, doctors, policemen, etc.); second, choose among those services the best one(s) (*i.e.* the quickest (the most available), the most qualified, the one(s) with the best equipment, etc.). We have proposed in [4] a model (the LCP-nets for Linguistic Conditional Preference Networks) that represents preferences on a graph (actually a network) to deal with this kind of problems. Indeed the choice between alternatives is usually complex because it depends on several other criteria. For instance, if the service is very far away from the injured (let us say that the injured have musculoskeletal trauma), it is preferable to have an emergency medical transport very quickly. Otherwise it is preferable to ask for a doctor that is an orthopedic surgeon. If no orthopedic surgeon is available, then another surgeon or a general practitioner will do. This means that the preferences about a service depend on the features of the available services.

Figure 8.2 shows an LCP-net with three nodes: D stands for the distance between the service and the injured; A for the ambulance or medical transportation and S for surgeon or doctor that can look after the injured. Three preference tables are attached to each node (the glossary is given below) and a line must be understood as follows: "If D is (more or less) D_{VC} then the preference is (more or less) H". When the table has two dimensions it means that the rule has two inputs. A simple arc (e.g., between D and A) exhibits a conditional preference (see the table attached to A), an arc with a black triangle ▲ exhibits an unconditional preference (see the table attached to S that does not depend on D), and an arc with a black square ■ (a ci-arc) exhibits a conditional relative importance preference (in the example, the preference on A or S depends on the value taken by node D: if D is (more or less) D_{VC} then optimizing S is prefered to optimizing A). Indeed the conditional importance table attached to the ci-arc between A and S contains three lines. Each line exhibits a relation such as $X \triangleright_z Y$ where $\triangleright$ represents a preference relation, i.e. optimizing X is prefered to optimizing Y if $Z = z$.

The glossary that has been used in this example is the following:

D_{VC}	D_C	D_F
H	M	L



	A_L	A_M	A_H
D_{VC}	L	M	H
D_C	VL	L	VH
D_F	VVL	VL	VVH

$S \triangleright_{D_{VC}} A$
$S \triangleright_{D_C} A$
$A \triangleright_{D_F} S$

S_L	S_H
L	H

Fig. 8.2 An LCP-net for a vital supply (medicine).

D_{VC}	service is very close to the injured
D_C	service is close to the injured
D_F	service is far away from the injured
A_L	ambulance has low equipment (similar to a taxi)
A_M	ambulance has medium equipment
A_H	ambulance has high equipment (a real emergency medical transport)
S_L	"low-level" surgeon (a general practitioner)
S_H	"high-level" surgeon (a specialist of the disease)
VVL	very very low preference
VL	very low preference
L	low preference
M	medium preference
H	high preference
VH	very high preference
VVH	very very high preference

This model permits to pre-compute the *functional* services upstream. Downstream, at the very last moment, we can ask for the best service(s) available among the functional ones. This system is conceived to adapt to services that are not stable (services appear and disappear any time).

Recovery is the last phase, when it is time to restore the area to its previous state. It deals with several kinds of tasks: restore traffic, restore electricity, supply water, but also restore livelihood (fishery, agriculture, buildings with rehabilitation and reconstruction program, etc.). This last phase is also quite far away from our major issue in this chapter.

From a computer scientist point of view, to manage such events is necessary to have a total view on information and knowledge fusion. It is also required to have feedback from the decisions taken (what were the consequences of such a decision? Were they what was expected?) in order to link sensors and effectors in the system. Moreover, the objectives that must be achieved are in particular environments: imprecision, incompleteness, ambiguity, uncertainty, vagueness, changing data, etc. And all the related works we have cited share a common point: to deal with language and imprecision. This is probably the most important thing since NGOs are composed of human beings and only human beings can organize themselves to rescue injured people. That is why we now propose natural language processing techniques to cope with disaster management.

8.3 Using Natural Language Processing (NLP) Techniques

Relating NLP techniques to Risk management we find two kinds of relationship: the first one is the probability approach relationship which deals with risk definitions in documents and considers the difficulty of assigning to linguistic terms the relation with risk definition and management [14]. So we consider that the dimension of risk could be seen as a fuzzy value between the uncertainty (something that could happen) and the effect dimension (the risk materialized), instead of attempting to determine meanings associated to some particular common probability-related terms. The second relationship considers that the probability is interpreted as a constant value in a fuzzy logic approach to risk inference from a natural language description. Actual applications of NLP techniques like automatic text classification, clustering and opinion extraction are related to the risk management domain by the analysis of large collection of textual feedback data [22].

The first NLP techniques between the sixties and the eighties to deal with natural language were the use of complex sets of hand-written rules [23, 24], but machine learning algorithms have revolutionized NLP in introducing decision trees and statistical models (cache language models) to try to understand and disambiguate sentences [5, 17]. Of course, the context that is highlighted in the speech corpus is also very important in NLP. Transcription of oral corpora is a large field of research where style (meaning the character of the speech) is coming after spelling, grammar or syntax like the PFC (French acronym for Phonology of Contemporary French) project which is based on orthography indexation [15]. Among the various tasks that are very common in NLP there are the identification of the discourse structure, the morphological segmentation (using e.g. word stems) and the syntactic analysis (parsing). We note that grammar component is used throughout most automatic linguistic tools mainly of its role to specifying the acceptable phrases in a human language. Grammar dictates syntactic rules that allow words combination for well formed sentences. There are many research works in grammar, which inspired most syntactic parsers. We mention some of them that influenced our work.

First, we follow Harris school for its theoretical framework, which extends grammar so that incorrect expressions appear in a regular way [10]. The parser is used like a pre-processor. The technique is about filling a questionnaire which assigns parts of a phrase in table columns. Although this kind of tree analysis is restrictive in knowledge representation, it is easier to convert to an intermediate treatment like transfer to query language of database.

Second, we adapt unification grammars in a syntactic model with semantic features. It's interesting to mention that all formalisms proposed by functional unification grammars are computational adaptive. Most linguistic description paradigms are directly encoded in a *feature/value* structure. These structures were proposed by computer scientists like generalized mechanisms of data type knowledge representation, and were largely used in language comprehension and speech understanding. Semantic grammar is a free context grammar in which the choice of the non terminal and the rule production are governed by an altogether syntactic and semantic function. But in these functions is quite difficult to describe linguistic patterns like deletions (unspecified nouns and verbs, lack or referential index), distortions (complex equivalence, presuppositions) or generalizations like universal quantifiers and modal operator of necessity or possibility.

Semantics comes just after, not because the meaning is not the goal of any phrase analysis but because we need all the elements of grammar and syntax altogether so we could determine the best "machine" comprehension or interpretation if translation is operated. Therefore, there is an order of different operations leading to "understanding"; in the first place, language recognition; is it about English or French? Does this word belong to English dictionary or another one? Second, the words' order or syntax, which confirms the language choice and sets the rules for further semantic analysis. For instance, in some languages like French we have both syntactical and semantic opposition: the place of the adjective in the phrase illustrates this opposition, adjective could precede or follow the noun. In English this redundancy is removed, but other problems still remain like words' polysemy as written below.

To make discourse analysis, part-of-speech (PoS) tagging — which is a grammatical tagging [8], *i.e.* algorithms which associate terms in accordance with a set of descriptive tags — can be used to help disambiguating words (e.g. "close" can be an adjective, a noun, an adverb, or a verb) [10]. This kind of ambiguity is common in languages with little inflectional morphology because there is a lot of such words. When analyzing a text, sequences of tokens are defined to determine its structure according to a grammar, for instance noun inflexion for singular or plural number. Inflected forms of words express different grammatical categories, e.g. tense, conjugation, person, gender, etc. However these techniques permit to "understand" sentences without ambiguity in a closed domain context but they don't consider any imprecision or vagueness in the meaning.

8.4 How to deal with imprecision in our context?

The first approaches to deal with this uncertainty come from Zadeh when he introduced in 1965 the fuzzy set theory, the fuzzy logic and the concept of linguistic variables [25]. The fuzzy sets could be employed to integrate vagueness throughout the relational structure of meaning including both the concept of structure and reference that a term denotes. Experimental psychology demonstrated the difference that exists between what people 'would do' under some supposed conditions and what people do when the conditions are real. Some NLP techniques can help to identify these language regularities which real speakers follow and/or establish in discourse or short texts empirically [20].

In practice, how to deal with imprecision in disaster management? First of all an *ad hoc* lexicon is necessary, dedicated to emergency management. There exist several lexicons in English that gather typical terms used for disaster description and management, see e.g. [3, 16]. As an example in this chapter, we have chosen the vocabulary about a hurricane, i.e. the Beaufort scale, and the wave height. Richer than the lexicons are the ontologies that formally represent not only knowledge as a set of concepts within a domain but also the relationships between those concepts. The consequence of this richer representation is that it can be used to reason about the entities within that domain. In theory, an ontology is a "formal, explicit specification of a shared conceptualisation" [9].

Second, a convenient model is necessary to represent the entities.

8.4.1 *The 2-tuple fuzzy linguistic representation model*

We quickly review the fuzzy linguistic 2-tuple model that we were inspired by. Since 1965, many models have been proposed but one seems the most appropriate in our case: the 2-tuple fuzzy linguistic model [12] because it deals with words and uses a simple internal representation of them.

The idea is to deal only with words or linguistic expressions in translating them into a linguistic pair (s_i,α) where s_i is a triangular-shaped fuzzy set and α a symbolic translation, both representing a linguistic term. It is required that in the linguistic term set there exist: (1) a negation operator: $\mathrm{Neg}(s_i = s_j)$ such that $j = g - i$ ($g + 1$ is the cardinality), (2) an order: $s_i \leqslant s_j \equiv i \leqslant j$. Therefore, there exists a min and a max operator. The semantics of the terms are given by fuzzy numbers defined in the $[0,1]$ interval.

If α is positive then s_i is reinforced otherwise s_i is weakened. This model is also interesting because it permits to reduce CPU time: we free ourselves from the fuzzy sets — at least in the computations — while keeping a linguistic semantics attached to the data. Indeed, the 2-tuple is composed of two floating-point numbers instead of a membership function (represented by equations of the first degree or higher-degree equations) that consumes more CPU resources. Besides, it is necessary to keep the linguistic terms in the reasoning process because the estimation of the disaster magnitude is performed for humans (from NGOs).

If the information is perfectly balanced (i.e. the distance between words is exactly the same, then all the s_i values are equally distributed on the axis). But if not — that may happen when talking about distance, for instance, “at the same place” and “close to” are closer to each other than “near” and “far away” — the s_i values may not be equally distributed on the axis. That is why another model has been proposed by the same team to deal with such information that they call multigranular linguistic information [13]. To do this, they use linguistic hierarchies composed of an odd number of triangular fuzzy sets of the same shape, equally distributed on the axis, as a fuzzy partition. A word may have one or two linguistic herarchy(ies) and the representation of a notion (such as “distance”) can be made up of several hierarchies. Thus the fuzzy sets obtained are still triangular-shaped but not always isosceles triangular-shaped and the notation s_i^j permits to keep both the hierarchy and the linguistic term. See [19] for a deeper review of these models and [11] for a methodology to deal with unbalanced linguistic term sets.

8.4.2 *An* **ad hoc** *method to deal with disaster management*

However, in recent papers, we have shown that despite its advantage, the 2-tuple model or unbalanced linguistic term sets doesn't fit our needs perfectly especially when one (or more) linguistic expression is very far away from its next neighbor [1, 2]. The new model we have proposed fully takes advantage of the symbolic translations α that become a very important element to generate the data set. Our 2-tuples are twofold. Indeed, except the first one and the last one of the partition, they all are composed of two half 2-tuples: an upside and a downside 2-tuple. The choice of our 2-tuple model is relevant since the linguistic terms used in the emergency management, such as geolocation context are usually unbalanced.

The methodology we have used to deal with imprecision inside the natural language is inspired by the PoS recognition and the PoS tagging. We simplify the analysis using a semantic tagging because the context (disaster management) is known. As an example, let us take the following preference (see also Figure 8.2 where an LCP-net about the same example is given): "If the injured are far away, I prefer to optimize the quality of the ambulance than the specialized medical field. Otherwise, it is the contrary". Tokens are processed (classified and recognized) using NLP techniques detailed above (see section 8.3) and ontologies. A first tentative of ontology has been proposed for disaster management, where each abstracted object is identified through a URI (Unified Resource Identifier) or more precisely a URN (Unified Resource Name), such as `urn:univ-paris8:disaster:medicalEmergency:medicalEquipment:ambulance` or `urn:univ-paris8:disaster:affectedPopulation:injured`.

Then tokens are tagged in an XML file, such as the following one:

```
<tokens>
  <token gram="CONJ" sem="COND_PREF">If</token>
  <token gram="DET">the</token>
  <token gram="NOUN" sem="ANTECEDENT">injured</token>
  <token gram="VERB">are</token>
  <token gram="ADV" sem="FUZZY_DIST">far away</token>
  <token gram="ADV">I</token>
  <token gram="VERB">prefer</token>
  <token gram="VERB">to optimize</token>
  <token gram="DET">the</token>
```

```
  <token gram="NOUN">quality</token>
  <token gram="PREP">of</token>
  <token gram="DET">the</token>
  <token gram="NOUN" sem="THEN_CONSEQUENT">ambulance</token>
  ...
  <token gram="NOUN" sem="ELSE_CONSEQUENT">contrary</token>
</tokens>
```

A tree using a simplified tree-adjoining grammar (TAG)-based is then created, where each leaf node represents the semantic tag of a token from the lexicon, e.g. in Relax NG compact syntax:

```
PREF=TYPE,ANTECEDENT,THEN_CONSEQUENT,ELSE_CONSEQUENT?
TYPE=COND_PREF|UNCOND_PREF
ANTECEDENT=FUZZY_MODIFIER?,FUZZY_VAR
FUZZY_VAR=FUZZY_DIST|FUZZY_TIME|...
...
THEN_CONSEQUENT=FUZZY_MODIFIER?,FUZZY_VAR
...
```

Upstream a fuzzy partition with our 2-tuple model has been performed by experts for each imprecise piece of data. For example, the expert gives 5 terms: A, B, C, D, E that are by default uniformly distributed on their axis. But, looking for synonyms (e.g. `http://www.crisco.unicaen.fr/cgi-bin/cherches.cgi` that exhibits a French dictionary) and the distance between the terms, our algorithm permits to obtain 5 synonym bags. Resemblance rates between bags are then computed in order to obtain new positions of A, B, C, D, E on the axis. Downstream the semantic tokens (e.g. “close”) are expressed through 2-tuples and compared to the fuzzy partition. It is to notice that adverbs such as “very” modify their associated 2-tuple through the α value. In the following we propose a modelling of a use case with two different fuzzy models.

The use case we have chosen is about an alert when wave height becomes too big (Beaufort scale). This scale admits 12 levels that are defined through a Beaufort number, a linguistic description, the wind speed, the wave height, the sea conditions and/or the land conditions (see *e.g* `http://en.wikipedia.org/wiki/Beaufort_scale`):

- 0: calm
- 1: light air
- 2: light breeze
- 3: gentle breeze
- 4: moderate breeze
- 5: fresh breeze
- 6: strong breeze
- 7: strong wind
- 8: gale
- 9: strong gale
- 10: storm
- 11: violent storm
- 12: hurricane

The software has been written in Java, using jFuzzyLogic with the extension we have proposed [2] that implements the FCL (Fuzzy Control Language) specification (IEC 61131-7). We remind that FCL is a simple language, actually a "control language" to define a fuzzy inference system. Its main concept is a "control block" which has some input and output variables.

The FCL script below uses three different partitions for the input Distance.

```
FUNCTION_BLOCK Hurricane
VAR_INPUT Wave_Height_V1:LING; Wave_Height_V2:LING;
END_VAR
VAR_OUTPUT  Alert_Level:REAL;
END_VAR
FUZZIFY Wave_Height_V1
TERM S := ling Calm Light_Air Light_Breeze Gentle_Breeze Moderate_Breeze
          | Fresh_Breeze Strong_Breeze Strong_Wing
          | Gale Strong_Gale Storm Violent_Storm Hurricane, extreme extreme;
END_FUZZIFY
FUZZIFY Wave_Height_V2
TERM S := pairs (Calm, 0.0) (Light_Air, 0.2)
                (Light_Breeze, 0.5) (Gentle_Breeze, 1.0)
          [...]
```

```
          (Hurricane, 30.0);
END_FUZZIFY
DEFUZZIFY Alert_Level // 5 linguistic terms
TERM Min := trian 0.0 0.0 5.0;
[...]
TERM Max := trian 85.0 100.0 100.0;
METHOD : LM; // 'Center Of Gravity'
END_DEFUZZIFY
RULEBLOCK Rules
RULE 1: IF Wave_Height_V1 IS Calm THEN Alert_Level IS Min;
...
END_RULEBLOCK
END_FUNCTION_BLOCK
```

Figure 8.3 and Figure 8.4 show both partitions for the input: the partition generated by the linguistic 2-tuple model from Herrera *et al.* (Wave_Height_V1) and our 2-tuple partition (Wave_Height_V2). The comparison between both models permits to show that our partition fits better reality while keeping a bigger unbalancement than the first one. What is interesting to keep in mind is that with these models, any linguistic assessment can be modelled (when there is much unbalancement, our model fits better). In emergency management such models are thus very useful.

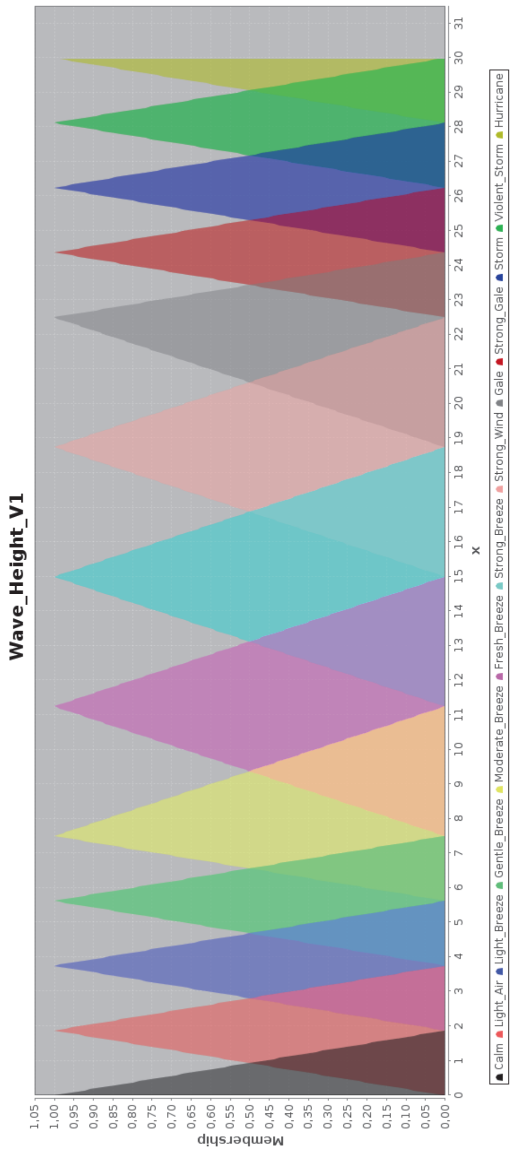


Fig. 8.3 Partition with Herrera *et al.* linguistic 2-tuple model.

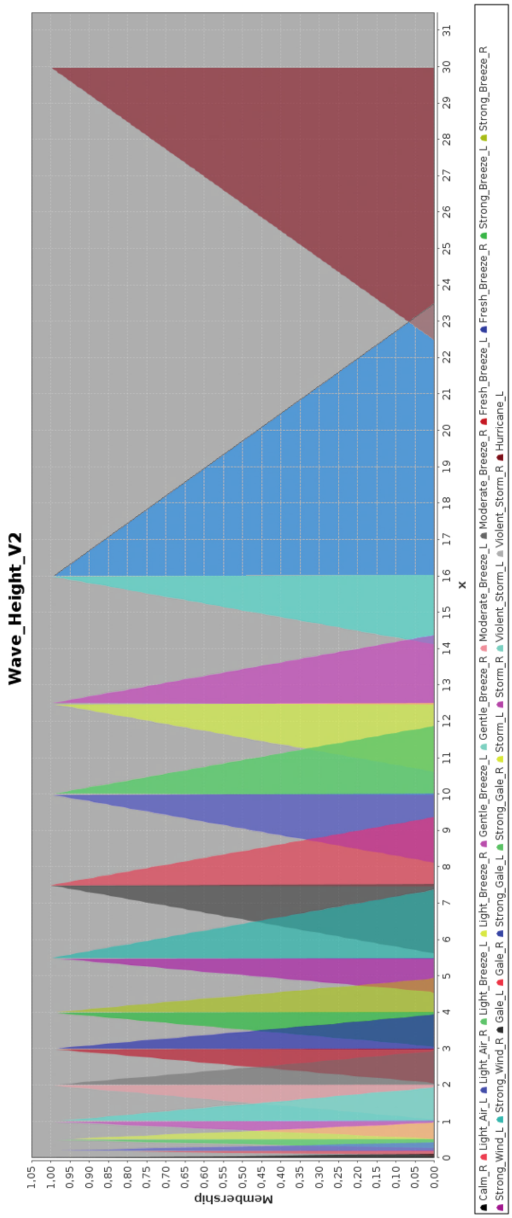


Fig. 8.4 Partition with our linguistic 2-tuple model.

A diagram to illustrate the overall technical framework of our proposal is given in Figure 8.5.

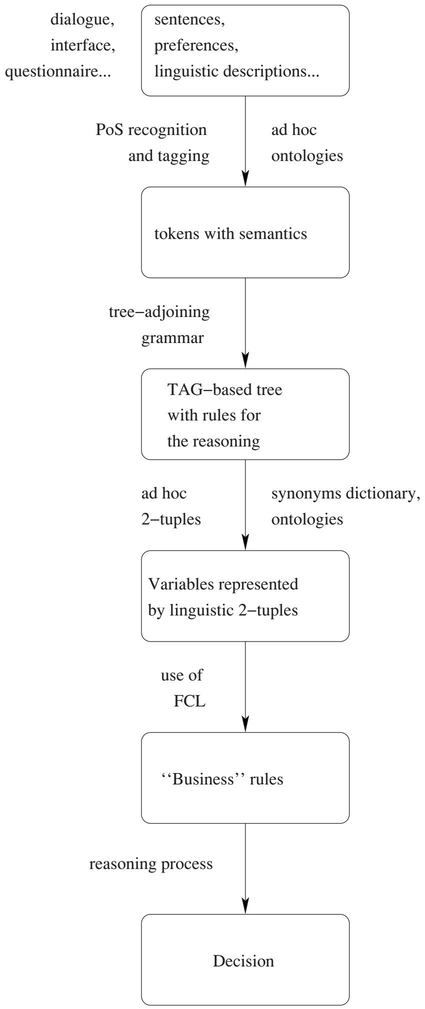


Fig. 8.5 General scheme of our proposal.

8.5 Conclusions

In this chapter we have presented principles of disaster management that is composed of four phases where knowledge is expressed through natural language. As usual in such cases, imprecision and imperfection taint the knowledge that let the decision harder to make. The discussions and methods we propose aim at reducing imprecision in taking into account it through a 2-tuple representation model coupled with natural language processing techniques. A linguistic conditional preference network paradigm described in previous works is also shown to be efficient in such situations. Indeed two in four phases are addressed in the paper and the proposed methods have shown to be useful. Future works will have to cope with a best understanding of the natural language and with the definition of more dedicated ontologies.

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Chapter 9

Decision Making with Extensions of Fuzzy Sets: An Application to Disaster Management

H. Bustince, M. Pagola, E. Barrenechea, C. Lopez-Molina, J. Fernandez

Universidad Publica de Navarra

Email: {*bustince,miguel.pagola,edurne.barrenechea,carlos.lopez, fcojavier.fernandez*}*@unavarra.es*

In this chapter we propose an extension of the weighted voting method to the interval-valued setting. In this way, we allow the use of interval-valued information in those situations in which the lack of knowledge prevents the expert from providing more precise information. We also provide some simple examples of our method.

9.1 Introduction

A disaster can be defined as as a situation in which the capacities and means of a given group to recover the previous equilibrium are overcome, in such a way that survival of the considered group is seriously compromised.

The literature on expert systems or decision making in disaster management is wide, starting from the 80s last century Wallace and De Balogh [26]. Nevertheless, the different approaches that have been considered display common problems. One of the most relevant ones is that they are not suitable to be applied to any disaster at any place Aleskerov *et al.* [1], Mendonca *et al.* [22]. In order to reach such a solution, we shall first analyze the common characteristics of disaster situations. In this work we focus on how to model the potential inaccuracy of the information the systems are fed with. In this sense, we do not pretend to provide a general solution, but rather an improvement of an already existing solution that can be applied to more cases.

Automatic disaster management is a complicated goal that is likely to require a long research before being solved, especially if we intend to generate scenario-in pendent solu-

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tions. However, automatic systems become of paramount importance to solve the problems associated with human decision-based strategies, whose performance is severely affected by factors such as stress and death risk (e.g. crowd disasters Helbing *et al.* [16], Krausz and Bauckhage [21]). A initial step can be the development of algorithms that do not depend closely on the different situations Mendonca *et al.* [22] but can be applied to other simple situations. In this, sense one of the most widely used algorithms in decision making is the weighted voting, mainly due to its ability to adapt to rather different situations that require to choose an alternative between several of them Huellermeier and Brinker [17]. In particular, this algorithm only requires a fuzzy preference relation to be constructed, independently of the way in which it is created Huellermeier and Vanderlooy [18]. In some situations, however, this algorithm may not be able to provide a single alternative as an answer, due, for instance, to the lack of precise knowledge by the experts Sanz *et al.* [23]. The use of extensions of fuzzy sets to overcome this situation has a long history Burillo and Bustince [5, 6], Chen and Tan [10], Tan and Chen [25]. In this way, in the present chapter we propose the use of interval-valued fuzzy sets as a mean to solve this difficulty in some particular situations.

Our goal is to extend the weighted voting method to an interval-valued setting in such a way that our proposal is able to decide between several alternatives in some cases in which the usual weighted voting method is not able to do so. Of course, we are not providing a universally working algorithm, but rather a hint on how the use of interval-valued fuzzy sets can help to improve the behaviour of classical decision making algorithms at least in some particular cases. On the other hand, our approach is quite simple, so we expect that our generalization can be further extended or adapted. Notice that along the text we will freely use the mathematical equivalence between Atanassov's intuitionistic fuzzy sets and interval-valued fuzzy sets Atanassov [2], Deschrijver and Kerre [13]

The structure of this is work is as follows. In the next Section we recall some preliminary definitions. Next, in Section 9.3 we present a construction method of interval-valued fuzzy preference relations from fuzzy preference relations. In Section 9.4 we propose two algorithms for solving decision-making problems, and in Section 9.5 we illustrate them with some examples. Finally, conclusions are presented in Section 9.7.

9.2 Preliminary concepts

To start with, we recover some well-known concepts that are necessary for our subsequent developments. The first step is to recall the definition of a fuzzy set.

Definition 9.1 (Zadeh [29]). A fuzzy set A defined on a non-empty universe U is given by

$$A = \{(u_i, \mu_A(u_i)) \mid u_i \in U\}.$$

$\mathscr{FS}(U)$ will denote the set of all fuzzy sets over the referential U. We know that a binary fuzzy relation R is a fuzzy subset of the Cartesian product $U \times U$, that is $R : U \times U \to [0,1]$. We denote by $\mathscr{FR}(U \times U)$ the set of all fuzzy relations over $U \times U$.

In fuzzy theory, a function $N : [0,1] \to [0,1]$ is a strict negation if N is strictly decreasing, continuous, $N(0) = 1$ and $N(1) = 0$. If N is also involutive (i.e., $N(N(x)) = x$ for all $x \in [0,1]$), then N is called a strong negation.

Definition 9.2. An automorphism of the unit interval is a continuous, strictly increasing function $\varphi : [0,1] \to [0,1]$ with $\varphi(0) = 0$ and $\varphi(1) = 1$.

A triangular norm (t-norm for short) $T : [0,1]^2 \to [0,1]$ is an associative, commutative, non-decreasing function such that $T(1,x) = x$ for all $x \in [0,1]$. Examples of t-norms are the minimum t-norm ($T_M(x,y) = min(x,y)$) and the product t-norm ($T_P(x,y) = x \cdot y$). A triangular conorm (t-conorm for short) $S : [0,1]^2 \to [0,1]$ is an associative, commutative, non-decreasing function such that $S(0,x) = x$ for all $x \in [0,1]$. Examples of t-conorms are the maximum t-conorm ($S_M(x,y) = \max(x,y)$) and the probabilistic sum t-conorm ($S_P(x,y) = x + y - x \cdot y$).

The associativity allows to extend each t-norm T and t-conorm S in a unique way to an n-ary operation in the usual way by induction, defining for each n-tuple $(x_1, x_2, \ldots, x_n) \in [0,1]^n$ (see page 9 of Klement *et al.* [20]).

$$\mathop{T}_{i=1}^{n} x_i = T\left(\mathop{T}_{i=1}^{n-1} x_i, x_n\right) = T(x_1, x_2, \ldots, x_n)$$

$$\mathop{S}_{i=1}^{n} x_i = S\left(\mathop{S}_{i=1}^{n-1} x_i, x_n\right) = S(x_1, x_2, \ldots, x_n)$$

Therefore, a t-norm T or a t-conorm S can take a different number of arguments.

In this chapter we are going to deal with interval-valued fuzzy sets.Let's consider the set

$$L([0,1]) = \left\{\mathbf{x} = [\underline{x}, \overline{x}] \mid 0 \leqslant \underline{x} \leqslant \overline{x} \leqslant 1\right\}$$

Given an interval $\mathbf{x} \in L([0,1])$, one of its characteristic features is its length, given by $W(\mathbf{x}) = \overline{x} - \underline{x}$.

Definition 9.3. An interval-valued fuzzy set (IVFS) over the finite referential set U is an expression A given by

$$A = \left\{(u_i, [\underline{A}(u_i), \overline{A}(u_i)]) \mid u_i \in U\right\}$$

with $[\underline{A}(u_i), \overline{A}(u_i)] \in L([0,1])$ for all $u_i \in U$.

When we consider an interval-valued membership, its length can be understood as a measure of the lack of knowledge of the expert in assigning the membership of the considered element Bustince *et al.* [9]. We denote by $\mathscr{IVFS}(U)$ the set of all IVFS over the referential set U. Notice that any fuzzy set $A = \{(u_i, \mu_A(u_i)) \mid u_i \in U\}$ can be seen as the interval-valued fuzzy set $A = \{(u_i, [\mu_A(u_i), \mu_A(u_i)]) \mid u_i \in U\}$; that is, a fuzzy set can be understood as an interval-valued fuzzy set such that the memberships of all the elements in the referential set are given by intervals of length equal to zero.

In $L([0,1])$ we consider the following partial order: For any $\mathbf{x}, \mathbf{y} \in L([0,1])$, $\mathbf{x} \leqslant_L \mathbf{y}$ if $\underline{x} \leqslant \underline{y}$ and $\overline{x} \leqslant \overline{y}$. With this order $L([0,1])$ becomes a complete lattice with infimum given by $\mathbf{0}_L = [0,0]$ and supremum given by $\mathbf{1}_L = [1,1]$.

This order can be extended to a total one as follows Xu and Yager [27]. Let $\mathbf{x}, \mathbf{y} \in L([0,1])$. We say that $\mathbf{x} < \mathbf{y}$ if and only if

- $score(\mathbf{x}) < score(\mathbf{y})$
- $score(\mathbf{x}) = score(\mathbf{y})$ and $accuracy(\mathbf{x}) < accuracy(\mathbf{y})$

where $score(\mathbf{x}) = \underline{x} + \overline{x} - 1$ and $accuracy(\mathbf{x}) = \underline{x} - \overline{x}$.

Let's consider now the extension of the usual fuzzy theory concepts to the setting of IVFSs.

Definition 9.4 (Bustince *et al.* [7], Deschrijver *et al.* [12]). An interval-valued fuzzy negation is a function $\mathbf{N} : L([0,1]) \to L([0,1])$ that is decreasing (with respect to $\leqslant_L$) such that $\mathbf{N}(\mathbf{0}_L) = \mathbf{1}_L$ and $\mathbf{N}(\mathbf{1}_L) = \mathbf{0}_L$. If for all $(\mathbf{x} \in L([0,1]), \mathbf{N}(\mathbf{N}((\mathbf{x})) = \mathbf{x}$ it is said that $\mathbf{N}$ is involutive.

An interval-valued fuzzy binary relation R' Burillo and Bustince [5, 6] is defined as an interval-valued fuzzy subset of $U \times U$, that is, $R' : U \times U \to L([0,1])$. We denote by $\mathscr{IVFR}(U \times U)$ the set of all interval-valued fuzzy binary relations (IVFR)on U.

Following the ideas of Gerstenkorn and Manko [15], for $A, B \in \mathscr{IVFS}(U)$, its correlation can be defined as

$$C(A,B) = \sum_{u_i \in U} \underline{A}(u_i)\underline{B}(u_i) + (1 - \overline{A}(u_i))(1 - \overline{B}(u_i)) \tag{9.1}$$

Notice that the value provided by this correlation is a real number.

9.2.1 *Implication operators*

In this work we consider a fuzzy implication operator as an implication in the sense of Fodor and Roubens [14].

Definition 9.5. An implication is a function $I : [0,1]^2 \to [0,1]$ that satisfies the following properties:

(I1) $x \leqslant z$ implies $I(x,y) \geqslant I(z,y)$ for all $y \in [0,1]$.
(I2) $y \leqslant t$ implies $I(x,y) \leqslant I(x,t)$ for all $x \in [0,1]$.
(I3) $I(0,x) = 1$ for all $x \in [0,1]$ (dominance of falsity).
(I4) $I(x,1) = 1$ for all $x \in [0,1]$.
(I5) $I(1,0) = 0$.

Remark 9.1. Properties (I3), (I4) and (I5) imply that I is an extension of the standard Boolean implication. Indeed, it holds that $I(0,0) = I(0,1) = I(1,1) = 1$ and $I(1,0) = 0$.

Depending on the application, the following properties can also be demanded:

(6) $I(1,x) = x$ (neutrality of truth).
(7) $I(x, I(y,z)) = I(y, I(x,z))$ (exchange property).
(8) $I(x,0) = N(x)$ where N is a strong negation.
(9) $I(x,y) \geqslant y$.
(10) I is a continuous function (continuity).

A wide study of these properties can be found in Baczynski and Jayaram [4], Bustince *et al.* [8].

9.3 Construction of Interval-valued Fuzzy Preference Relations from Fuzzy Preference Relations

Let us consider the problem of constructing interval-valued fuzzy preference relations from fuzzy preference relations. We start introducing a way of building elements in $L([0,1])$ from two elements in $[0,1]$ such that

- the first one represents the degree of preference given by the expert of one alternative over another;
- the second one represents the ignorance of the expert in the assignation of the first value.

The construction method of elements in $L([0,1])$ is described in Theorem 9.1.

Theorem 9.1. *Let $F_\mu : [0,1]^2 \to [0,1]$ such that*

(F1) $F_\mu(x,0) = x$ *for all* $x \in [0,1]$*;*
(F2) $F_\mu(x,y)$ *is increasing in the first argument;*
(F3) $F_\mu(x,y)$ *is decreasing in the second argument;*
(F4) $F_\mu(1,x) = 1-x$ *for all* $x \in [0,1]$.

In these conditions the following items hold:

(1) $F_\mu(x,y) \leqslant x$ *for every* $x,y \in [0,1]$*;*
(2) $F_\mu(x,1) = 0$ *for every* $x \in [0,1]$*;*
(3) $F_\mu(0,x) = 0$ *for every* $x \in [0,1]$*;*
(4) *The mapping* $F : [0,1]^2 \to L([0,1])$ *given by*

$$F(x,y) = [F_\mu(x,y), F_\mu(x,y)+y]$$

is such that $W(F(x,y)) = y$ *for all* $x,y \in [0,1]$, *where* W *denotes the length of the interval.*

Proof. (1) By (F1), (F3) $x = F_\mu(x,0) \geqslant F_\mu(x,y)$. (2) By (F2), (F4) $F_\mu(x,1) \leqslant F_\mu(1,1) = 0$. (3) By (F1), (F3) $F_\mu(0,x) \leqslant F_\mu(0,0) = 0$. (4) By (F2), (F4) it is clear that $F_\mu(x,y)+y \leqslant 1$. By construction, we have that $W(F(x,y)) = y$. □

Example 9.1.

$$F_\mu(x,y) = \begin{cases} \max\left(0, x - \dfrac{y}{2}\right) & \text{if } x + \dfrac{y}{2} \leqslant 1 \\ 1-y & \text{otherwise} \end{cases}$$

Next we propose a method for constructing F_μ functions from implication operators in such a way that we can use the different construction methods of implication operators that appear in the literature.

Lemma 9.3.1. *Let* $F_\mu : [0,1]^2 \to [0,1]$ *satisfying* (F1)–(F4). *Then, the function*

$$I : [0,1]^2 \to [0,1] \text{ given by}$$
$$I(x,y) = N(F_\mu(x,y))$$

is an implication operator for all negation N.

Proof. (I1) and (I2) follow from (F2) and (F3) respectively. (I3) $I(0,x) = N(F_\mu(0,x)) = N(0) = 1$. (I4) $I(x,1) = N(F_\mu(x,1)) = N(0) = 1$. *(I5)* $I(1,0) = N(F_\mu(1,0)) = N(1) = 0$ from (F4). □

Theorem 9.2. *A function* $F_\mu : [0,1]^2 \to [0,1]$ *satisfies properties* (F1)-(F4) *if and only if there exists a function* $I : [0,1]^2 \to [0,1]$ *satisfying* (I1), (I2), (I6) *and* (I9) *with respect to the standard negation such that*

$$F_\mu(x,y) = 1 - I(x,y). \tag{9.2}$$

Proof. (Sufficiency) (I1), (I2) by (F2), (F3). (I6) $I(1,x) = 1 - F_\mu(1,x) = 1 - (1-x) = x$ by (F4). (I9) $I(x,0) = 1 - F_\mu(x,0) = 1 - x$ by (F1).
(Necessity) $F_\mu(x,0) = 1 - I(x,0) = x$ by (I9) and with N the standard negation. (F2), (F3) by (I1), (I2). $F_\mu(1,x) = 1 - I(1,x) = 1 - x$ by (I6). □

Remark 9.2. From Theorems 9.1 and 9.2, $F : [0,1]^2 \to L([0,1])$ is given by

$$F(x,y) = [1 - I(x,y), 1 - I(x,y) + y].$$

For F to be well-constructed, I must satisfy $I(x,y) \geqslant y$ (I10). Bustince *et al.* [8] proved that if I satisfies (I1), (I6) then I also satisfies (I10).

Example 9.2.

- If taking Reichenbach implication $I(x,y) = 1 - x + xy$ then

$$F(x,y) = [x(1-y), 1 - (1-x)(1-y)].$$

- If taking Lukasiewicz implication $I(x,y) = \min(1, 1 - x + y)$ then

$$F(x,y) = [\max(0, x-y), \max(x,y)].$$

- If taking Kleene-Dienes implication $I(x,y) = \max(1-x,y)$ then

$$F(x,y) = [\min(x, 1-y), \max(0, 1-x-y)].$$

Corollary 9.1. *In the setting of Theorem* 9.1 *and* 9.2*, if I is strictly monotone and also satisfies* (I7) *and* (I13)*, then there exists an automorphism in the unit interval such that*

$$F_\mu(x,y) = \varphi^{-1}(\varphi(x) - \varphi(x)\varphi(y)). \tag{9.3}$$

Proof. Direct taking into account that $I(x,y) = N(\varphi^{-1}(\varphi(x)\varphi(N(y))))$, as shown in Bustince *et al.* [8]. □

Remark 9.3. Notice that for Expression (9.3) to satisfy *(F4)* it is necessary to take $N(x) = 1-x$. So $F_\mu(x,y) = \varphi^{-1}(\varphi(x)\varphi(1-y))$.

Example 9.3. If taking $\varphi(x) = x$ then

$$F(x,y) = [x(1-y), x(1-y)+y].$$

9.4 Two generalizations of the weighted voting strategy

In this section we apply our previous developments for presenting two new decision-making algorithms that generalize the weighted voting strategy (see Subsection 9.4.1) and that make use of interval-valued fuzzy preference relations. Our starting point will be a finite set of alternatives, $X = \{x_1, x_2, \ldots, x_n\}$ and we assume that we have homogenized the information about the preferences into a FPR.

Recall that a fuzzy preference relation R on X is a fuzzy binary relation $R : X \times X \to [0,1]$. The value $R(x_i, x_j) = R_{ij}$ denotes the degree to which alternative x_i is preferred to alternative x_j Chiclana *et al.* [11].

In a similar way, an interval-valued fuzzy preference relation R' on X is defined as $R' : X \times X \to L^*$. The interval-valued membership value $R'(x_i, x_j) = R'_{ij} = [\underline{R'}_{ij}, \overline{R'}_{ij}]$ provides an upper and a lower bound for the "actual" value of the preference of alternative x_i over alternative x_j.

In order to deal also with fuzzy data, in both of our proposed algorithms we start from a FPR and construct an IVFPR taking into account the ignorance of the expert when providing that FPR. The concept of weak ignorance is defined by Sanz *et al.* [23] as a measure of the lack of knowledge that the expert suffers in the assignation of a numerical value to the membership of an element to a set (see also Bustince *et al.* [9]).

Definition 9.6. A function $g : [0,1] \to [0,1]$ is called a *weak ignorance function* if it satisfies the following conditions:

($g1$) $g(x) = g(1-x)$ for all $x \in [0,1]$;
($g2$) If $x = 0.5$ then $g(x) = 1$;
($g3$) $g(x) = 0$ if and only if $x = 0$ or $x = 1$.

Next we justify the three properties demanded to weak ignorance functions.

- Based on the additive reciprocal property of FPR, that is, $R_{ij} + R_{ji} = 1$, the ignorance associated to the preference R_{ij} must be the same as the ignorance associated to R_{ji}, so $g(R_{ij}) = g(1-R_{ij}) = g(R_{ji})$.
- If an expert assigns the value 0.5 to his/her preference of alternative x_i over x_j, we understand that he/she is not able of choosing between both alternatives and hence his/her ignorance is maximal.
- We consider that the expert's ignorance is minimal when he/she is absolutely sure of his/her preference of one alternative over another. That is, if $R_{ij} = 1$ or $R_{ij} = 0$.

In Theorem 9.3 we present a construction method of weak ignorance functions from t-norms.

Theorem 9.3. *Let T be a t-norm such that $T(x,y) = 0$ if and only if $x \cdot y = 0$ and without zero divisors. Then the function*

$$g(x) = \begin{cases} \dfrac{T(x,1-x)}{T(0.5,0.5)} & \text{if } T(x,1-x) \leqslant T(0.5,0.5) \\ \dfrac{T(0.5,0.5)}{T(x,1-x)} & \text{otherwise} \end{cases}$$

is a weak ignorance function.

Proof. Direct. □

Example 9.4. If taking $T = T_M$ then

$$g(x) = 2 \cdot \min(x, 1-x) \text{ for all } x \in [0,1].$$

In Theorem 9.4 we present the construction method of IVFPRs from F functions studied in Section 9.3 and from weak ignorance functions.

Theorem 9.4. *Let $R \in \mathscr{FR}(X \times X)$ and let g be a weak ignorance function. The relation R' given by*

$$R'_{ij} = F(R_{ij}, g(R_{ij})) \text{ for all } R_{ij} \in R$$

is an interval-valued fuzzy relation such that $W(R'_{ij}) = g(R_{ij})$.

Proof. Direct. □

Remark 9.4. The amplitude of each element of the IVFPR is the same as the ignorance of that element of the FPR by construction method of Theorem 9.1.

One of the most commonly required properties in decision-making algorithms is the reciprocity of the FPR Chiclana *et al.* [11], Kacprzyk [19], Switalski [24]. In this work we say that $R \in \mathscr{F}\mathscr{R}(X \times X)$ is reciprocal if there exists a negation N such that $R_{ij} = N(R_{ji})$ for every $i, j \in \{1, \ldots, n\}$ with $i \neq j$. Analogously, we say that $R' \in \mathscr{I}\mathscr{V}\mathscr{F}\mathscr{R}(X \times X)$ is reciprocal if there exists an interval-valued fuzzy negation such that $R'_{ij} = \mathbf{N}(R'_{ji})$ for every $i, j \in \{1, \ldots, n\}$ with $i \neq j$. If using $\mathbf{N}([x,y]) = [1-y, 1-x]$ we have that $\underline{R'}_{ij} = 1 - \overline{R'}_{ji}$ and $1 - \overline{R'}_{ij} = 1 - \underline{R'}_{ji}$ Deschrijver *et al.* [12].

In Theorem 9.5 we analyze under which conditions the IVFPR built as in Theorem 9.4 is a reciprocal IVFPR.

Theorem 9.5. *In the setting of Theorem* 9.4*, let* $R \in \mathscr{F}\mathscr{R}(X \times X)$ *be reciprocal with respect to* $N(x) = 1 - x$. *If taking* $F_\mu(x,y) = x(1-y)$ *then* $R' \in \mathscr{I}\mathscr{V}\mathscr{F}\mathscr{R}(X \times X)$ *is also reciprocal with respect to* $\mathbf{N}([x,y]) = [1-y, 1-x]$.

Proof. Direct taking into account that $g(R_{ij}) = g(1 - R_{ij}) = g(R_{ji})$. □

9.4.1 *Weighted voting strategy*

The weighted voting strategy Huellermeier and Brinker [17], Huellermeier and Vanderlooy [18] is one of the simplest and most widely used methods for solving decision-making problems. In this algorithm, the preference value R_{ij} is considered as a weighted vote for the alternative x_i. In this way, the final evaluation of each alternative x_i is calculated as a sum of votes:

$$\sum_{1 \leqslant i \neq j \leqslant n} R_{ij}. \tag{9.4}$$

The alternative that obtains the highest amount of votes is the one chosen as solution.

9.4.2 *First generalization of the weighted voting strategy*

In this subsection we present the first adaptation of the voting method to solve decision-making problems with IVFPRs. Algorithm 1 is based on the arithmetic operations on interval-valued fuzzy sets obtained by extending those given given by Atanassov [3] for Atanassov's intuitionistic fuzzy sets. Take $[x_1, y_1]$, $[x_2, y_2] \in L^*$, the sum operator is defined as

$$[x_1, y_1] + [x_2, y_2] = [x_1 + y_1 - x_1 y_1, x_2 + y_2 - x_2 y_2] \in L([0,1]). \tag{9.5}$$

Remark 9.5. This expression can be rewritten in terms of the probabilistic sum S_P as follows: $[x_1, y_1] + [x_2, y_2] = (S_P(x_1, x_2), S_P(y_1, y_2))$.

To calculate the evaluation of each alternative we replace the sum of preferences given in Expression (9.4) by the sum of elements of $L([0,1])$ given in Expression (9.5). We will use the total order relation based on *score* and *accuracy* functions to determine the final ranking of alternatives.

The schema of Algorithm 1 is the following:

1. Select a function F_μ and a weak ignorance function g.
2. Build the IVFPR R' from the FPR R as in Theorem 9.4.
3. FOR each alternative $x_i \in X$ calculate the interval

$$\left(\underset{1 \leqslant j \neq i \leqslant n}{S_P} \underline{R}ij, \underset{1 \leqslant j \neq i \leqslant n}{S_P} \overline{R'}ij \right)$$

   END FOR
4. Order in a decreasing way the alternatives, following the *score* and *accuracy* of the values calculated in step 3.

Algorithm 1

Although Algorithm 1 is a natural adaptation of the voting strategy, we can see by means of the following example that, in some cases, it is not a good approach to solve decision-making problems. Given the FPR:

$$R = \begin{pmatrix} - & 0.9 & 0.9 & 0.9 \\ 0.1 & - & 0.4 & 1 \\ 0.1 & 0.6 & - & 0.3 \\ 0.1 & 0 & 0.7 & - \end{pmatrix}$$

1. We take $F_\mu(x, y) = x(1-y)$ and $g(x) = 2 \cdot \min(x, 1-x)$.

2. We build the IVFPR R' (See Table 9.1)

3. We calculate the intervals associated to each of the alternatives

- x_1 : $[0.9780, 0.9995]$

Table 9.1 Interval-valued fuzzy binary relation R' constructed by Algorithm 1.

	x_1	x_2	x_3	x_4
x_1	-	[0.72,0.92]	[0.72,0.92]	[0.72,0.92]
x_2	[0.08,0.28]	-	[0.08,0.88]	[1,1]
x_3	[0.08,0.28]	[0.12,0.92]	-	[0.12,0.72]
x_4	[0.08,0.28]	[0,0]	[0.28,0.88]	-

- $x_2 : [1,1]$
- $x_3 : [0.2876, 0.9839]$
- $x_4 : [0.3376, 0.9136]$

4. We order the alternatives

- x_1 : $\text{score}([0.9780, 0.9995]) = 0.9775$
- x_2 : $\text{score}([1,1]) = 1$
- x_3 : $\text{score}([0.2876, 0.9839]) = 0.2715$
- x_4 : $\text{score}([0.3376, 0.9136]) = 0.2512$

The order of the alternatives is $x_2 > x_1 > x_3 > x_4$. Observe that, attending to the preference of the expert given in the FPR, x_1 is preferred over the rest of the alternatives. However, x_1 is not the solution that we obtain. This is due to the fact that if the expert expresses the preference of an alternative with a high value, as in the case $R_{24} = 1$, the final evaluation of this alternative is maximum, without taking into account the rest of preferences of this alternative. This is due to the use of t-conorms to calculate the sum of votes for each alternative.

This behaviour leads us to propose a new generalization to solve the problems detected in Algorithm 1.

9.4.3 *Second generalization of the weighted voting strategy*

In this subsection we present a new adaptation of the weighted voting strategy. The scheme of Algorithm 2 is the following:

1. Select a function F_μ and a weak ignorance function g.
2. Build the IVFPR R' from the FPR R as in Theorem 9.4.
3. FOR each alternative $x_i \in X$ evaluate

$$\sum_{1 \leqslant j \neq i \leqslant n} (\underline{R'}_{ij} + \overline{R'}_{ij} - 1)$$

END FOR
4. Take as solution the alternative x_i of greatest evaluation.

Algorithm 2

Notice that we are adding the scores of the interval memberships of each of the rows. On the other hand, we can we justify Algorithm 2 from the point of view of correlation between interval-valued fuzzy sets

9.4.4 *Algorithm 2 and correlation*

Correlation between interval-valued fuzzy sets is used in the literature about decision-making problems to rank the alternatives [28]. In particular, Ye [28] considers the "excellent" alternative given by

$$A^* = \{((x_i,x_j),[1,1]) \mid j \in \{1,\ldots,n\},\ i \neq j \text{ and } (x_i,x_j) \in X \times X\}. \tag{9.6}$$

In the present work we also consider the worst valued alternative, namely,

$$A_* = \{((x_i,x_j),[0,0]) \mid j \in \{1,\ldots,n\},\ i \neq j \text{ and } (x_i,x_j) \in X \times X\}. \tag{9.7}$$

We can represent each alternative x_i as an IVFS A_i given by

$$A_i = \{((x_i,x_j),[\underline{R'}_{ij},\overline{R'}ij) \mid j \in \{1,\ldots,n\},\ i \neq j \text{ and } (x_i,x_j) \in X \times X\} \tag{9.8}$$

Using correlation between interval-valued fuzzy sets given in Expression (9.1), we present the following results.

Proposition 9.1. *Let A^*, A_* and A_i given by Expressions* (9.6), (9.7) *and* (9.8). *The following items hold:*

i) $C(A_i,A^*) = \sum_{1 \leqslant j \neq i \leqslant n} \underline{R'}_{ij}$.

ii) $C(A_i,A_*) = \sum_{1 \leqslant j \neq i \leqslant n} 1 - \overline{R'}_{ij}$.

Proof. Direct. □

Given a decision-making problem such that each alternative is represented by an *A-IFS* as in Expression (9.8), we consider that the best alternative x_i is that one whose correlation with A^* (excellent alternative) is maximal and at the same time its correlation with A_* (worst alternative) is minimal. In this way, the evaluation of each alternative is exactly that we have considered in Algorithm 2.

9.4.5 *Semiautoduality*

Our definition of sum of intervals was based on the use of the probabilistic sum. Nevertheless, other definitions can be considered. In particular, we want to mention here those based in the use on semiautodual functions.

Definition 9.7. Let $A : [0,1]^2 \to [0,1]$ be an aggregation function and N a strong negation. A is said to be semiautodual (with respect to N) if:

$$A(x,y) + N(A(N(x),N(y)) \leqslant 1$$

The minimum provides an example of a semiautodual aggregation function with respect to the standard negation. Now observe that, if A is semiautodual, it follows that for any $x, y \in [0,1]$ it holds that $[A(x,y), 1-N(A(N(x),N(y)))]$ is an interval on $[0,1]$. In particular, if taking $N(x) = 1-x$ as strong negation, we have that, if A is semiautodual with respect to N, then $[A(x,y), A(1-x,1-y)]$ is also an interval, whatever $x, y \in [0,1]$ are. In this way, we can define other additions. Nevertheless, these would require a deep study that it is out of the scope of this chapter.

9.5 Two examples

In this section we consider two decision-making problems that make clear the effectiveness of Algorithm 2. To check how they work, we compare the results of Algorithm 2 with those of the voting strategy. We see that Algorithm 2 is efficient in some problems in which the weighted voting is not able to provide a unique solution.

In the following example we assume that we are dealing with the following situation. There are four possible routes to provide help after an earthquake, none of them completely safe. An expert is asked to provide the preference of route i over route j. Of course, this is a toy problem, but we expect them to clarify the advantages of our approach.

In this section, we take for step *1.*

$$F_\mu(x,y) = x(1-y)$$
$$g(x) = 2\cdot\min(x, 1-x).$$

9.5.1 *First example: Obtaining the same result as with the voting strategy*

Given the reciprocal FPR:

$$R = \begin{pmatrix} - & 0.33 & 0.48 & 0.65 \\ 0.67 & - & 0.61 & 0.58 \\ 0.52 & 0.39 & - & 0.6 \\ 0.35 & 0.42 & 0.4 & - \end{pmatrix}$$

2. We build the IVFPR R' (see Table 9.2)

Table 9.2 Interval-valued fuzzy binary relation R' from Example 9.5.1.

	x_1	x_2	x_3	x_4
x_1	-	[0.1122,0.7722]	[0.0192,0.9792]	[0.1950,0.8950]
x_2	[0.2278,0.8878]	-	[0.1342,0.9142]	[0.0928,0.9328]
x_3	[0.0208,0,9808]	[0.0858,0.8658]	-	[0.12,0.92]
x_4	[0.1050,0.805]	[0.0672,0.9072]	[0.08,0.88]	-

3. We evaluate each alternative

- $x_1 : -0.0272.$
- $x_2 : 0.1896.$
- $x_3 : -0.0068.$
- $x_4 : -0.1556.$

4. We choose the alternative with greatest evaluation.

$$x_2 > x_3 > x_1 > x_4$$

Notice that results are in agreement with the ones obtained with the weighted voting strategy.

9.5.2 *Second example: Improving the solution obtained with the voting strategy*

There exist problems for which the weighted voting strategy is not able to choose between two alternatives (two alternatives obtain the same sum of votes). We present an example in which Algorithm 2 solves this problem. Take the reciprocal FPR:

$$R = \begin{pmatrix} - & 0.78 & 0.60 & 0.28 \\ 0.22 & - & 0.75 & 0.69 \\ 0.40 & 0.25 & - & 0.44 \\ 0.72 & 0.31 & 0.56 & - \end{pmatrix}$$

2. We build the IVFPR R' (see Table 9.3)

Table 9.3 Interval-valued fuzzy binary relation R' from Example 9.5.2.

	x_1	x_2	x_3	x_4
x_1	-	[0.4368,0.8768]	[0.12,0.92]	[0.1232,0.6832]
x_2	[0.1232,0.5632]	-	[0.375,0.875]	[0.2622,0.8822]
x_3	[0.08,0.88]	[0.125,0.625]	-	[0.0528,0.9328]
x_4	[0.3168,0.8768]	[0.1178,0.7378]	[0.0672,0.9472]	-

3. We evaluate each alternative

- $x_1 : 0.16$.
- $x_2 : 0.0808$.
- $x_3 : -0.3044$.
- $x_4 : 0.0636$.

4. We choose the alternative with largest evaluation

$$x_1 > x_2 > x_4 > x_3$$

Notice that if we apply the weighted voting strategy to the FPR R, the ranking that we obtain is

$$x_1 = x_2 > x_4 > x_3$$

In this case, this strategy is not able to decide between x_1 and x_2 for the best alternative. However, using the ignorance in the construction of the interval-valued fuzzy preference relation, Algorithm 2 allows to order the alternatives and select the best one.

9.6 Advantages of the method

Natural disaster management requires sudden decisions to be taken, forcing the environmental data to be quickly collected. This data can come either in the shape of physical measurements or as human evaluations derived from experience. In any case, time limitations do not allow careful evaluations or repeated measurements, what might affect severely the quality of the data. We have considered those environments in which we can estimate the inaccuracy of the measurement units or the expert, and manage to express it in a numerical way. Intervals (in our case, interval-valued information) provide a mathematical framework to handle situations where the system is provided with both a (possibly inaccurate) evaluation and a prediction of its uncertainty.

Although practical and intuitive, the interval information incorporates several problems, among which we must highlight the lack of proper ranking methods, which constitute the grounds of any decision making algorithm. Indeed, very few proposals have appeared in the literature able to handle interval valued information, what forces the information to be considered precise, and lead to unwanted results. Moreover, note that by not using the information about the uncertainty of the data, we are missing half of the available information. Hence, we believe that the ability to deal with imprecise information will be a key in further developments of disaster management systems, whether this is done by expressing the data as intervals or using any other mathematical tool.

9.7 Conclusions

In this work we have presented a decision-making algorithm to obtain a solution in some cases in which classical methods are not able to decide between two alternatives. To do so, we have proposed a construction method of IVFPRs from the FPRs given by experts. This method quantifies by means of weak ignorance functions the lack of knowledge of the expert in the assignation of the numerical values of the fuzzy preferences.

Our construction method, our algorithm departs from the FPR given by the expert, so the results of our algorithm can be compared to those obtained with any other classical decision-making method. In the illustrative examples, we have checked that Algorithm 2 provides a solution in some cases in which the voting strategy does not distinguish between two alternatives. This algorithm can hence be a good choice for those cases in which the weighted voting method does not arrive to a unique solution.

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Chapter 10

Classification of Disasters and Emergencies under Bipolar Knowledge Representation

J. Tinguaro Rodríguez*, Begoña Vitoriano, Daniel Gómez, Javier Montero

Faculty of Mathematics, Complutense University of Madrid 28040, Madrid, Spain

E-mail: {jtrodrig,bvitoriano,javier_montero}@mat.ucm.es

A fully precise numerical evaluation of disasters' effects is unrealistic in the time-pressured, highly uncertain decision context taking place just after a disaster strike. This is mainly due to some features of the available information in such a context, but also because of the imprecise nature of some of the relevant categories (think about the number of affected people, for instance). Instead of a numerical evaluation, in this work is considered that it is rather more plausible and realistic to *classify* the severity of the consequences of a disaster in terms of the relevant scenarios for the NGO's decision makers. Therefore, the abovementioned practical problem of evaluation of disaster consequences leads to a classification problem in which the classes are identified with the linguistic terms that describe those relevant scenarios. In order to carry out this classification and ensure the linguistic adaptation and the understandability of the proposed solution, the methodology of the *descriptive* fuzzy rule-based classification systems has been adopted in this work. Nevertheless, some features of that context, as the ordering and gradation of the consequences or the need of avoiding the risk of underestimation of the effects of disasters, entail the necessity of considering and assuming an *structure* over the set of classes or linguistic labels, somehow modeling those features *inside of* the classification model. Such an structure is introduced here by means of the notion of dissimilarity between classes, leading to a bipolar knowledge representation framework which allows to adequate the classification models to the constraints and requirements of the NGO context.

10.1 Introduction

Natural and anthropogenic disaster management constitutes a main research stream not only because of the tremendous impact of disasters in directly affected people, but also because of the deep consequences they can have in infrastructures, economy and the political

*Corresponding author. E-mail address: jtrodrig@mat.ucm.es

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system of the affected regions, which could lead to political and social instability, especially in developing countries, and affect international relations and security. Therefore, the development of technologies and procedures to mitigate the potential consequences of disasters is a key issue in today's global world, beside humanitarian arguments.

At this respect, developed countries invest a huge amount of funds, usually by means of development assistance and other more disaster-mitigation concerned policies in regions they consider geo-strategically sensible, in order to avoid the risks of political and social destabilization produced by disasters (see [17]). However, most of this funding is channeled through United Nations agencies and international Non-Governmental Organizations, on the basis of their supposed political neutrality and links with the target populations. This allows these actors, for example, to access politically unstable countries which otherwise would not accept any external interference. For these reasons, the importance of these agencies and organizations is, in practice, highly significant.

Moreover, in the context of these organizations, it is fundamental to manage the available resources with transparency and efficiency. As a consequence, humanitarian logistics [29] is an emerging field of research, with a growing importance, which is at the same time drawing attention to some interesting problems in management sciences and operations research. In this sense, humanitarian response to disasters implies a complex decision making, in which a number of key strategic and operational decisions have to be faced in a time-pressured context and with low quality information.

The long term objective of the project containing this work is to develop and implement a general, standard decision support system (DSS) for disaster management, specifically designed to address a part of this complexity and help NGO's decision makers involved in the design of humanitarian relief operations. Particularly, this work focuses on SEDD (the Spanish acronym for Disaster Diagnostic and Evaluation System), which is the part of such a global DSS concerned with the assessment of the consequences of disasters with the very first information available after the strike (see [30] for a description of other parts of such a global DSS being developed in this project). As discussed in [21, 24], SEDD constitutes one of the first proposals in the direction of providing NGOs with disasters' consequences evaluation procedures specifically designed for them.

Let us recall with [21, 23] that SEDD's inference capability is based on fuzzy machine learning procedures (see [9]), particularly on the methodology of descriptive fuzzy rule based classification systems (FRBCS, see [6, 10–12]). This is, SEDD's methodology is a mixture between fuzzy inference systems [6], that enable inference to be carried out in terms of a linguistically expressed (see [32, 33]), interpretable set of rules and information, and data mining (see for instance [1, 9]), that allows these rules to be obtained from adequate databases. In this sense, SEDD extracts its rules from EM-DAT (Emergency Database, see www.em-dat.be), the most exhaustive and complete public database about disasters and emergencies. Moreover, as shown in [25], fuzzy rule based systems outperforms ordinary statistical techniques and most state-of-the-art machine learning techniques in the task of providing a simultaneously accurate and interpretable (in the sense of [16]) assessment of disaster consequences.

This paper continues the work in [23] by studying the characteristic *structure* of the classification problem that underlies the disaster severity assessment provided by SEDD. Particularly, the relationships between the *structure* assumed on the set of classes and the requirements of the decision context are analyzed, showing that a significant improvement in the behavior of the classification methodology of SEDD in terms of its adaptation to such requirements is obtained when certain *structures* are assumed and introduced inside the classification models.

In this sense, as shown for instance in [22], in a supervised classification context it is possible to introduce relations between the classes by means of the notion of semantic antagonism or *dissimilarity* proposed in [20]. Thus, in this work the effect of different dissimilarity structures is discussed in terms of their ability to replicate and adapt to some of the requirements and features of the disaster management context.

This work is structured as follows: in Section 10.2, the problem SEDD tries to address is described with some detail, focusing on its strategic features, that will allow to identify it with a structured classification problem in Section 10.3. SEDD's extension to these problems is presented in Section 10.4, discussing the adaptation of diverse dissimilarity structures to the task of modeling different context requirements. Finally, some conclusions are shed in Section 10.5.

10.2 Problem description

Just after a disaster strikes somewhere in the world, international NGOs start a decision process intended to reach a conclusion about the pertinence of a relief operation and about whether or not suitable conditions exist to initiate it. It is possible that a specific disaster scenario does not fit the NGO's requirements or constraints regarding the nature of an intervention, size of disaster, or logistical capabilities. Therefore, the decisions to be made in a first stage have an strategic nature, being more concerned with assessing the degree of involvement of the organization in a possible response operation than with the specific content of such an operation.

However, precisely because they determine the *shape* and guidelines of the actions to be done, strategic decisions have a major influence on the subsequent logistical and on terrain decision processes (see Fig. 10.1 below), which evaluate the amount of aid to send and how it will be delivered to the affected country and the suffering population. As a consequence, strategic decision-making takes place in a highly time-pressured context, since any delay at this stage could affect the position of the NGO in the international coalition delivering aid, thus affecting the NGO's prestige and reputation, and slow down the subsequent decision processes, thus delaying the reception of aid by the affected population.

Notice that this strategic decision process has to be *flexible*, in the sense that it has to be able to be carried out for every combination of disaster type and place, since NGOs are possibly specialized in covering some part of the relief tasks (as water sanitation, shelter and site management, health care, etc.) but are not specialized in response to, for instance, earthquakes in Haiti, floods in Pakistan or any other specific disaster scenario (despite the geo-strategic *priorities* a particular NGO could have as a result of the interests of its donors). This is, rather than the specific geographic features of the affected location or the nature of the implied natural or anthropogenic phenomenon, what matters in terms of NGO's strategic decisions is the extent and the severity of the *humanitarian disaster* that is taking place as a consequence of whatever factors.

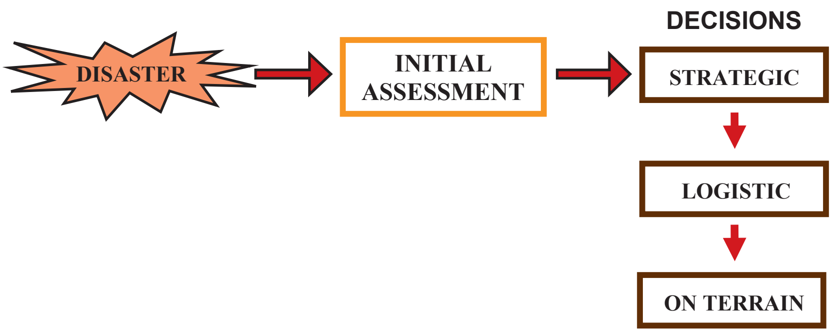

Fig. 10.1 Hierarchy of decisions for disaster response. An initial assessment of disaster consequences is crucial in order to start the decision process.

Therefore, as shown in Fig. 10.1, strategic decision-making (and thus all the subsequent decision processes) is strongly dependent on a correct assessment of the consequences of a disaster and the resulting needs of the affected population. In fact, recall that humanitarian relief operations are assumed to follow the quality standards established by the Humanitarian Charter of the Sphere Project (see [28] and www.sphereproject.com), which, among other things, emphasize the correct estimation of needs as a critical step for success in these operations. This is, the fulfillment of the quality standards in the delivery of aid presupposes an adequate assessment of the kind of relief actually needed by the affected population.

However, the available information just after the impact of a disaster uses to be affected by different kinds of *uncertainty*. The first reports are usually pretty incomplete, if not directly confusing and contradictory. Moreover, when it exists, relevant information is usually expressed linguistically, and thus it could be vague and imprecise. In fact, due to the effects an adverse phenomenon has on the informational system of a region, a more or less exhaustive and precise picture of the situation could not be obtained until some days (or even weeks) after the moment of the strike. This poses a strong difficulty in the development of the mentioned strategic decision-making process, since in this context the urgency of the decisions to be made in order to relief the people affected by a disaster *clashes* with the need of a correct estimation of the consequences of such a disaster, i.e. of the needs of the affected populations.

In the spirit of [31], all this complexity suggests as a promising alternative the development and application of inference techniques enabling a fast, flexible and correct assessment of disasters' consequences in the presence of uncertainty. Nevertheless, some constraints must be imposed on the nature of these techniques. For example, the procedures leading to such an assessment have to be understandable and *interpretable* by the decision makers, in order to guarantee the usability of such an inference tool.

Even more important are the infrastructure and data requirements of a decision support tool operating in the context of NGOs. It is necessary to make realistic assumptions in this area if the DSS have to be used in organizations or countries where the operational infrastructure can not supply highly sophisticated data, as, for example, real-time remote sensing information [18], exhaustive building census [26] or precise meteorological data [4]. It is important to remark that this question is a critical issue when considering disaster management from the point of view of NGOs or developing countries, as complex data could be unavailable or the trained personnel requirements for its usage could be too high (see [2, 13] for a discussion about the *rigidity* of most current DSS for disaster management).

With these ideas in mind, SEDD was designed to be a low-cost, tailor-made solution for NGO-oriented assessment of disasters consequences. It is not the aim of this paper to describe SEDD's methodology in deep. However, it is important to remark that, as shown in [23], SEDD's inference capability relies on a set of *data easily accessible* from the first description of a potential disaster. Moreover, the reasoning method that sustains such an inference capability is *interpretable*, since it is based on the usage of (a rather small number of) rules expressed in terms of a natural language (i.e. fuzzy rules). Also, since its knowledge (i.e. the rules) is *learnt* from the EM-DAT database by means of appropriate machine learning procedures, SEDD is able to produce an assessment of any disaster scenario for which enough similar historical information is available. Therefore, SEDD's *flexibility* depends on the existence of appropriate data, but its methodology is in principle able to face any possible combination of disaster type and location. Some further details about SEDD are given in Section 4 of this chapter. A complete description of its methodology and its performance can be found in [25].

10.3 Strategic disaster severity assessment as an structured classification problem

As explained above, the strategic decision-making about the involvement of an NGO on a disaster response operation is strongly dependent on the initial assessment of the consequences of such a disaster. However, a fully precise numerical evaluation of disasters' effects, as casualties, homeless people or the extension of the material damage, is unrealistic in such a decision context. In fact, even a more or less complete and precise description of these consequences is usually not available by the time in which such (urgent) strategic decisions have to be already taken.

This is mainly due to the uncertainty and the referred features of the available information just after a disaster strike, but it is also because of the imprecise nature of some of the relevant categories. For example, the notion of *affected people* shows such an imprecision, since it could be not always clear whether a person has been affected or not. As a consequence, the number of affected people is usually stated through an implicitly imprecise quantity, as happens when it is said that a disaster produced, for instance, 40.000 affected people.

Nevertheless, it is important to notice that a totally precise and exhaustive evaluation of consequences is not actually needed in order to perform the above described strategic decision-making. As pointed out above, strategic decisions determine the shape of an operation but not its specific contents. As the decision process in Fig. 10.1 develops, decisions need information to be more and more precise, since decisions become more and more concrete. In this sense, NGOs usually deliver experts on the affected location in order to be able to acquire such a more precise evaluation for its logistical and on terrain decisions. But the decision of acquiring such a further evaluation is a strategic decision that has to be taken in the first moments after the strike, when little information is available, i.e. on the basis of the initial reports of the disaster. However, such an initial assessment of consequences needs to be correct or accurate, but not necessarily fully precise.

For example, consider the estimation of the variable *number of homeless people*. This variable measures the number of people that become homeless as a consequence of a disaster. For NGOs, such a quantity constitutes a key indicator of the size of the efforts a potential relief operation should place in matter of temporary shelter and site management. This also provides an idea of the efforts to be placed in the water sanitation area, for instance. In practice, at a first stage, for an NGO decision maker it is not important at all to distinguish whether 50.000 or 70.000 people become homeless as a consequence of a disaster, since anyway such a number is going to be considered *large* and the strategic decisions in terms of both the subsequent actions and the size and nature of the required relief operation are going to be similar.

Therefore, in the first moments after a disaster strike, NGO decision makers assess disaster severity (and thus also the needs of a potential intervention) in a *qualitative* (rather than *quantitative*) way. As said, their problem has a big-scale, strategic nature, rather than a small-scale, tactic or operative nature. In other words, their problem consists on evaluating, in a context of highly uncertain and imprecise information, the *magnitude* of the consequences of a disaster in relation with the relevant scenarios and decisions that can arise regarding the implementation of a relief operation. In such a context, it is even possible that an assessment stated in crisp and precise terms could result little trustable to those decision makers.

However, a linguistic description of the magnitude order of the consequences coming from a reliable source, for example stating that there are *a lot* of casualties or that buildings took a *several* damage, will be much more trustable to decision makers, despite its implicit imprecision. This kind of linguistic information is enough relevant to elaborate a first perception of the disaster scenario, providing a base for the subsequent strategic decision making.

Thus, in order to obtain such an initial assessment giving rise to an adequate strategic decision making, we consider that instead of a numerical evaluation, it is rather more plausible and realistic to *classify* the severity of the consequences of a disaster in terms of the relevant scenarios for the NGO's decision makers. Therefore, the abovementioned practical problem of evaluation of disaster consequences leads to a *classification* problem in which the *classes* are identified with the linguistic terms that describe those relevant scenarios, as *no casualties* or *a lot of injured people*. These linguistic labels or *classes*, assessing the magnitude of the different relevant consequences of a disaster, have to be assigned on the basis of the description or *attributes* of such a disaster given by the first available information, as the type of disaster, its intensity and the features of the affected location (e.g. its vulnerability, see [15]).

Notice that, as shown in [23], SEDD is able to produce assessments with different levels of precision, accordingly to the characteristics of the information needed in each decision stage. Particularly, SEDD provides three types of output or assessment of each of the disaster consequences it addresses (those present in the EM-DAT database, as we shall see in Section 10.4): a) numerical; b) intervals; and c) linguistic labels or classes. In this work we focus on the classification methodology of SEDD, which is therefore associated to the support of the strategic decision-making of NGOs.

10.3.1 *Structure of the set of classes*

Consider now one of the variables that have to be linguistically evaluated in order to obtain such a first initial assessment. For instance, let us focus on the variable *number of casualties* (*CAS*). This variable estimates the number of people that were killed as a result of the strike of an adverse phenomenon. As just explained, in a first stage a fully precise estimation of such a number is not strictly necessary, but just a qualitative, linguistic assessment. In this way, for instance we can measure the magnitude of a disaster scenario, in terms of the casualties it produced, by means of the labels *no casualties*, *very few*, *few*, *quite a lot* and *a lot of casualties*. These labels represent the classes in which such a disaster scenario has to be classified in order to provide an initial assessment of the relevant consequence *CAS*.

The particular meaning of these labels has to be specified by means of intervals, or more generally, through fuzzy subsets of the range of the underlying numerical variable, in

Table 10.1 Intervals associated to the linguistic labels defined for the variable *number of casualties* (*CAS*).

Class	Label	Interval
CAS1	No casualties	$[0, 10)$
CAS2	Very few	$[10, 100)$
CAS3	Few	$[100, 1000)$
CAS4	Quite a lot	$[1000, 10000)$
CAS5	A lot	$[10.000, +\infty)$

this case the positive integers. Moreover, such meanings have to be related to the different scenarios that are relevant in terms of the decisions to be made. For example, each label can be associated with a different order of magnitude of the number of casualties, in an increasing way, as shown in Table 10.1 above. Notice that these intervals are just a simplification of the more flexible and robust semantics specified by the fuzzy sets depicted in Figure 10.2.

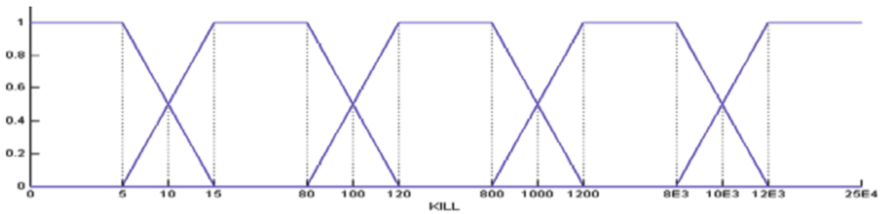

Fig. 10.2 Fuzzy partition for the variable *number of casualties* (*CAS*).

Notice that, as they are associated to different orders of magnitude of the consequences of a disaster, these labels can be considered as ordered from the lowest (*no casualties*) to the greatest (*a lot of casualties*) level of magnitude of such consequences. This is, the classes associated to the variable *CAS* (in the first column of Table 10.1) are *linearly ordered*, i.e. $CAS\, i < CAS\, j$ whenever $i < j$.

This assumption of *linearity* on the effects of a disaster is quite general, since what decision makers try to assess in a first stage is precisely the order of magnitude or severity of these consequences, or equivalently the order of magnitude of the efforts that a relief operations should consider in order to adequately alleviate such consequences. As explained above, these orders of magnitude are not necessarily powers of ten of the underlying numerical variable, but rather they are associated to the different relevant scenarios that can arise, which can be also considered as ordered attending to the *gravity* of the humanitarian crisis taking place in each of such scenarios.

Thus, in this setting classes are not independent, unrelated items, but they conform a valuation structure, in which some relationships hold between the valuation states given by the classes. This is, following [14] in this context the set of classes presents a relevant *structure*, which should be taken into account in the process of assessing the severity of a disaster scenario under study from the very first information available. For example, we do not commit the same error when a disaster scenario having *no casualties* (*CAS1*) is assessed as one with *very few casualties* (*CAS2*), than when it is evaluated as having produced *a lot of casualties* (*CAS5*). Therefore, the abovementioned problem of disaster severity assessment can be understood as a classification problem with a structured set of classes, i.e., as a *structured classification problem*.

10.3.2 *Context requirements*

As stated above, the notion of structure of the set of classes is introduced in order to capture some relevant relationships that hold between the concepts represented by the classes. These relationships are given by the features of each particular application context, which provides the specific meaning or semantics attributed to the classes. However, it is important to notice that these relationships not only depend on the semantics of the classes, but they also have to reflect the criteria and requirements of the decision context.

For instance, the set of classes introduced before for the variable *CAS* in principle fits into a linear structure, since classes are semantically associated to orders of magnitude of the consequences. As a consequence of this assumption, the classifier could be required to show a gradable, smooth behavior, in the sense that small variations on the attributes that describe a disaster scenario should not produce a large variation on the predicted consequences. Some classes are *closer* than others to a given class, and thus different error levels can be distinguished according to such a *distance*.

However, notice that the error committed by assessing a $CAS1$ scenario as a $CAS5$ one is also different from that committed when a $CAS5$ scenario is evaluated as verifying $CAS1$. In the first case, overestimation error is committed, while in the second case scenarios are underestimated. Though the two types of errors are relevant, notice that underestimation of disaster consequences could lead to much more dangerous situations than overestimation in terms of the prestige of an NGO and the relief of the affected population.

In this sense, overestimation of consequences may lead to an initial overreaction, but as soon as observers are deployed on terrain and further information is available the scenario can be reassessed and the decisions reconsidered without too many difficulties. However, when a disaster scenario is underestimated, it uses to attract less attention and to be considered as less important, which could lead to not properly ask for further information or even to ignore it in a first moment, thus potentially affecting the timing of the strategic decision-making stage (with the resultant delays on the subsequent logistical and operational decision phases) as well as the NGO's reputation.

Consequently, NGO decision makers usually tend to avoid the risk of underestimation of disaster effects, for instance by carrying out a worst-case analysis of the scenarios under study. In this way, initial assessments of a disaster scenario could be required to be developed under the assumption of avoiding underestimation risk. In this sense, such a decision-related requirement entails introducing a somehow asymmetric configuration in the linear structure of the classes, since different error levels are then attained depending on whether a disaster scenario under study is underestimated or overestimated. Therefore, as pointed out above, the structure of the set of classes has to capture both the relevant aspects of the semantics of the classes as well as the objectives and requirements related with the decision context in which the classifier is used.

10.3.3 *Dissimilarity structures*

Notice that the assumption of asymmetry on the linear structure of the set of classes forces to look for more general structures than orders. In this work, we adopt the notion of *dissimilarity structure* proposed in [20] in order to provide a formal definition of the structure of the set of classes in an structured classification problem. Recall that dissimilarity structures are based on the notion of semantic antagonism (also proposed in [20]), that provide a formal framework to model the opposition relationships between a set of concepts in which such an opposition is allowed to be asymmetric. Therefore, by adopting the notion of dissimilarity or antagonism instead of that of linear order, we somehow translate the semantic *distance* between two classes, coming from the linear ordering of the consequences, into the *degree of opposition* among them, which is however allowed to be asymmetric in order to reflect the requirement of underestimation risk avoidance.

Moreover, as we shall see in next section, dissimilarity structures provide an easy and effective method of introducing the relationships between the classes into the classification models, i.e. in the learning and reasoning processes of the classifiers. In this context, the opposition between classes represented in the dissimilarity structure enable to distinguish *significant exceptions* to a classification rule from simple, logical counterexamples, which leads to introduce a *negative* confidence degree of the rules. Such a negative degree together with the usual, positive confidence degree, constitute then a bipolar evidence pair for the evaluation of classification rules, which leads to a bipolar fuzzy rule-based classification framework ([18, 22] for further details).

Therefore, let us denote by $\zeta = \{C_1, \ldots, C_N\}$ the set of concepts or classes into consideration. Recall that a dissimilarity structure can be built upon this set by means of a *dissimilarity matrix* $\Delta = (d_{ij})_{N\times N}$, such that the value $d_{ij} \in [0,1]$ expresses the degree up to which the class C_j is opposite, antagonistic or dissimilar to the class C_i, i, $j = 1, \ldots, N_C$. Notice that Δ is allowed to be non-symmetric, thus enabling the underlying dissimilarity notion to be asymmetric.

This way, for example, a matrix $\Delta^I = 0$ represents a situation in which no class is opposite to any other. On the other side, a matrix $\Delta^{III} = 1 - \mathrm{Id}$ describes a situation in which every class is totally opposite to each other. As we shall see in the next section, the consideration of a dissimilarity matrix allows to introduce and take into account some of the requirements and constraints of the application context *inside of* the classification model. Therefore, there exist a wide range of possibilities, lying between these extreme cases, in order to model specific dissimilarity conditions. The choice of a particular dissimilarity matrix will of course depend on the specific semantic requirements to be fulfilled.

10.4 SEDD's bipolar classification methodology

Recall that, as it was described in [23] and [25], SEDD's fuzzy rule-based classification methodology does not explicitly consider any structure on the set of classes (though a multi-classification procedure was given in order to enable predictions formed by several *adjacent* classes, introducing a *pessimistic* reasoning method in order to avoid underestimation, see [23] for the details). Therefore, in this section we illustrate the ideas above by adapting the methodology of SEDD to an structured classification framework. To this end, we adopt the bipolar fuzzy rule-based classification framework proposed in [18, 22]. Thus, here we study the capability of different dissimilarity structures (i.e. of different dissimilarity matrices Δ) to capture the semantics and the requirements of the disaster response NGO strategic decision context as well as to produce a correct classification result, i.e. a correct assessment of disaster consequences, through the bipolar classifiers proposed in [22].

10.4.1 *Some basics about SEDD*

For the sake of an adequate understanding of the example we will propose in next section in order to illustrate the feasibility of the proposed approach, let us first recall some basics about SEDD.

Firstly, recall that SEDD can be understood as a fuzzy rule based classification systems (see [6, 10, 11]). As such, the knowledge or rules that guides the classification process have to be learned from training examples, and the reasoning process that assigns a class to a query needs such a query to be described in the same terms as the learning examples. Training examples for SEDD are provided by EM-DAT (Emergency Database, see www.em-dat.be), the most exhaustive and complete public database about disasters and emergencies. However, EM-DAT provides a rather incomplete description of the locations affected by disasters. For this reason, EM-DAT has been merged with both UNDP data about the Human Development Index (*HDI*), that provides an estimation of the *vulnerability* of the affected locations in the moment of the strike, as well as with US Census historical data on population densities (*POP*). Also, EM-DAT informs on the type of adverse phenomenon that produced each registered disaster, its *magnitude* (*MAG*) or intensity as well as on the effects it produced in terms of a set of consequences, that range from the number of casualties (*CAS*) to the number of homeless people or the extent of the material damages (see Table 10.2 below).

The descriptive variables *MAG*, *HDI* and *POP* are taken as explanatory or independent, while those related to effects or consequences, as *CAS*, are taken as dependent variables to be assessed. As a consequence, SEDD need a disaster scenario to be described in terms of these three independent variables in order to produce an assessment of its consequences. Also, SEDD is only able to assess the consequences registered in EM-DAT, though these constitute a enough relevant description for NGO decision makers in the first moment after the strike. It is important to notice that EM-DAT poses a difficult classification problem, since the variability of the consequences or classes is huge for similar values of the independent variables, and also the sample is highly unbalanced (e.g. there are much more training examples from class *CAS*1 than from class *CAS*5) as can be observed in Figure 10.3 below.

Secondly, SEDD needs to translate the raw, numerical data of EM-DAT in terms of the linguistic labels that are used in both the premises and the consequents of the rules. To this end, a fuzzy partition is defined on the range of each variable, according to the desired semantics of the labels, similarly to what was done when defining the semantics of the labels for the variable *CAS*, see Fig. 10.2 again. The labels and partitions defined

Table 10.2 Relevant variables contained in EM-DAT (after being merged) for each disaster type. In SEDD, the first three variables are taken as independent and the remaining ones as dependent.

Variable	**Description**
Magnitude	*Intensity* of the adverse phenomena:degrees on the Richter scale for earth quakes, inundated area in km^2 for floods, etc.
HDI	Human Development Index: an estimation of the affected country's *vulnerability* at the moment of the strike.
Population Density	Population density of the affected country at the moment of the strike: an estimation of the affected place's *population-at-risk*.
Casualties	Number of casualties produced by the disaster.
Injured	Number of injured people.
Homeless	Number of homeless people.
Affected	Number of affected people.
Damage	An estimation of the amount of infrastructural damage in thousands of US dollars.

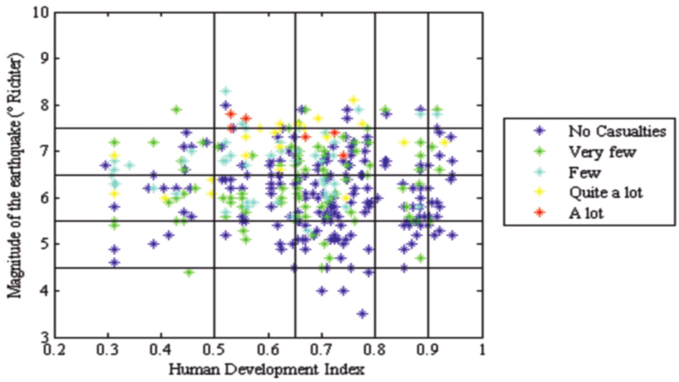

Fig. 10.3 EM-DAT sample for *disaster type* = *earthquakes*. Classes for the variable *CAS* are obtained through the intervals defined in Table 10.1.

for the variable *MAG* and *HDI* are depicted in Fig. 10.4. The labels and partitions for the remaining variables are omitted, since they are not relevant for the example exposed in next section.

Thirdly, a learning procedure has to be applied in order to extract the rules from the data. Therefore, let us denote by $X_1,\ldots,X_n$ the n attributes or independent variables that are used to describe a disaster scenario, and assume that a set of $m$historical disaster scenarios $(x_1^p,\ldots,x_n^p;C^p)$ is available as learning sample, where for each $p = 1,\ldots,m$, C^p is one of the classes in $\zeta = \{C_1,\ldots,C_N\}$ defined to (linguistically) assess the consequence or

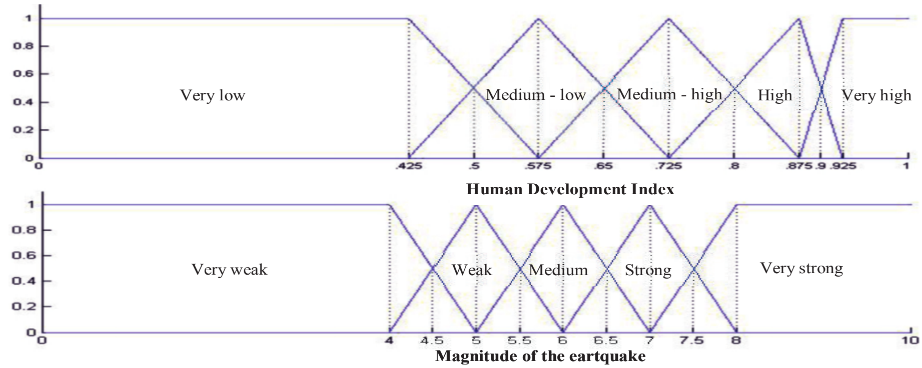

Fig. 10.4 Fuzzy partition and linguistic labels for the variables *Magnitude of an earthquake* (*MAG*) and *Human Development Index* (*HDI*).

dependent classification variable Y. Assume also that a dissimilarity matrix $\Delta = (d_{ij})_{N\times N}$ has been defined modeling the opposition relationships between the classes in ζ. For all $i = 1,\ldots,n$ let us also denote by $A_{i1},\ldots,A_{ic_i}$ the c_i linguistic labels defined for each attribute X_i, in such a way that $\mu_{A_{ij}}(x_i) \in [0,1]$ represents the degree up to which the value x_i fulfills the label A_{ij}. A premise A of a rule is given by the combination of a different label A_{ij_i} of each attribute, i.e. $A = A_{1j_1} \times \cdots \times A_{nj_n}$. The degree of fulfillment of a premise A by a description $x = (x_1,\ldots,x_n)$ is usually obtained through a t-norm (see [27]) T, i.e. $\mu_A(x) = T(\mu_{A_{1j_1}}(x_1),\ldots,\mu_{A_{nj_n}}(x_n))$.

In these conditions, following [22], a rule with premise A and having as a consequent a class $C_j \in \zeta$ is evaluated by means of a pair of confidence degrees

$$r_j^+(A) = \frac{\sum_{p=1,\ldots,m/C^p=C_j} \mu_A(x^p)}{\sum_{p=1}^{m} \mu_A(x^p)}, \qquad r_j^-(A) = \frac{\sum_{p=1}^{m} \mu_A(x^p)\cdot\mu_{\Delta C_j}(C^p)}{\sum_{p=1}^{m} \mu_A(x^p)},$$

where $\mu_{\Delta C_j}(C_i) = d_{ji}$. Notice that $r^+,\ r^- \in [0,1]$ and that it holds that $r^+ + r^- \leqslant 1$ (and see [3]). As explained in [22], $r_j^+(A)$ and $r_j^-(A)$ respectively estimate the proportion of positive examples and significant exceptions (or negative examples) of the rule $A \Rightarrow C_j$ out of the total number of training patterns fulfilling the premise A. Therefore, the dissimilarity structure is introduced in the evaluation of the rules by means of the negative confidence degree. Different procedures (see for instance [5]) can be used to obtain the set of premises A for which rules $A \Rightarrow C_j$ $(j = 1,\ldots,N)$ have to be built, basically ensuring that each training pattern is *covered* by at least one rule. Once this learning stage is finished, a set of rules or *rule base* is available, which represents the knowledge of the classifier. It is important to remark that a main advantage of descriptive fuzzy classifiers (like SEDD) is that they provide rules expressed in terms of a natural language, so their knowledge is explicit and interpretable.

Lastly, it is possible to apply a fuzzy reasoning method (see [6]) in order to produce an assessment of a disaster scenario $x = (x_1, \dots, x_n)$ under study. Following [19, 22], here we apply the VA1 (*one-dimensional additive veracity*) reasoning method, that proceeds by computing the *degree of veracity* $t_j(A) = \max\{r_j^+(A) - r_j^-(A), 0\}$ for each of the R available rules $R^q : A^q \Rightarrow C_j$, and then obtaining the evidence degree $t_j(x)$ for the classification of the scenario x in each class C_j by means of the expression

$$t_j(x) = \frac{\sum\limits_{q=1,\dots,R} \mu_{A^q}(x) \cdot t_j(A^q)}{\sum\limits_{q=1,\dots,R} \mu_{A^q}(x)}.$$

Therefore, the vector $t(x) = (t_1(x), \dots, t_N(x))$ constitutes the final output of SEDD, assessing the degree of evidence for each class or level of consequences. If a crisp prediction is needed, then it is usual to assign the scenario x to the class with maximum evidence, i.e. to the class C_h such that $t_h(x) = \max_j t_j(x)$.

10.4.2 *Dissimilarity structures for disaster assessment*

Here we illustrate the effect of different dissimilarity structures on the assessment provided by SEDD. Particularly, in order to be able to produce a *picture* of the assessments obtained by using each dissimilarity matrix Δ, we drop the population density *POP* from the set of independent variables, which leaves the variables *MAG* and *HDI* as the only explanatory variables to be used. Similarly, in this example we will focus on just one consequence variable, the number of casualties *CAS*, and on one type of disaster, *earthquakes*. Therefore, it is $n = 2$ and $N = 5$ (the same classes as in Table 10.1 are used for the variable *CAS*). The training sample for these explanatory and dependent variables is shown in Fig. 10.3, and it is $m = 386$. As the maximum number of premises is quite small $(5 \cdot 5 = 25)$, we adopt a grid-based learning procedure, i.e. rules are built for all possible premises. However, a support threshold ($\delta = 0.01$) is defined in order to avoid those rules built from a too small sample. Therefore, those premises A such that

$$\sum_{p=1}^{m} \mu_A(x^p) < \delta$$

are discarded.

In order to illustrate and compare the effects of each matrix Δ, the behavior of the resulting VA1 classifiers is simulated in a dense mesh of points of the input space of the attributes *MAG* and *HDI*, in such a way that a picture of the predictions and class boundaries produced by each dissimilarity structure is obtained. Also, two error measures are used in order to measure the performance of the different classifiers applied below: 1) %CC represents the rate of correct classifications obtained over the training sample, thus evaluating the predictive accuracy of each classifier; 2) to measure both the deviation of the predictions from the real classes and the risk of underestimation, the average cost AVCOST of the predictions is computed over the training sample, where the cost of classifying a instance from the class i in the class j is given by the element $COST_{ij}$ of the matrix

$$COST = \begin{pmatrix} 0 & 1 & 2 & 3 & 4 \\ 2 & 0 & 1 & 2 & 3 \\ 4 & 2 & 0 & 1 & 2 \\ 6 & 4 & 2 & 0 & 1 \\ 8 & 6 & 4 & 2 & 0 \end{pmatrix}.$$

10.4.2.1 *No dissimilarity*

Let us start by assuming that no opposition relationships hold between the classes, i.e. by taking $\Delta \equiv 0$. In this case, it is $r_j^-(A) = 0$ for every premise A and consequent C_j, so it is $t_j(A) = r_j^+(A)$ for all rules $A \Rightarrow C_j$. Therefore, this case corresponds to a non-structured classification framework, in which a usual non-bipolar fuzzy classifier, identical to that used by SEDD in [23], is obtained. As no structure is assumed on the set of classes, the resulting classifier treats all the classes as independent items. Consequently, the classifier will be biased towards the classes with more training examples. This is clearly shown in Fig. 10.5, where the results of the simulation are depicted. Note that a huge part of the input space of the attributes is assigned to the lowest class $CAS1 =$ *no casualties*, i.e. that with the highest proportion (54.4%) of training patterns. This entails a great risk of underestimation of consequences. Furthermore, the behavior of the classifier is not smooth at all, since predictions present sharp variations. Table 3 presents the performance measures for this non-bipolar classifier. Though we will use these results for comparison with the rest of classifiers, it is important to remark that almost all the correct classification rate (%CC= 54.15) is due to examples of class $CAS1$. In fact, notice that %CC is in this case almost equal to the proportion of examples from the class $CAS1$.

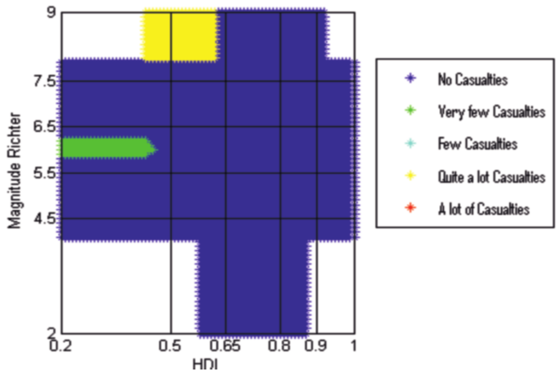

Fig. 10.5 Simulation result of the non bipolar classifier with $\Delta \equiv 0$.

Table 10.3 Performance measures of the non-bipolar classifier ($\Delta \equiv 0$).

%CC	**AVCOST**
54,15	1,453

10.4.2.2 *Total opposition*

As explained above, dissimilarity matrices move between the extreme cases given by $\Delta \equiv 0$ and $\Delta = 1 - \text{Id}$. Let us analyze now this last case, that corresponds to a situation in which each class is totally opposite to the others. Notice that now it is $r_j^-(A) = 1 - r_j^+(A)$, and thus $t_j(A) = \max\{2r_j^+(A) - 1, 0\}$. Therefore, since all classes are equally related, the same bias as before towards the more abundant classes is obtained. However, a rule $A \Rightarrow C_j$ will obtain $t_j(A) = 0$ unless $r_j^+(A) > 0.5$, i.e. unless more than a half of the training examples compatible with the premise A belong to class C_j. If no class fulfill this condition, then it is $t_j(A) = 0$ for all j. As a result, it is possible for a query x to keep unclassified if no activated rule have a positive veracity degree. The simulation of this classifier clearly illustrates this point, as shown in Fig. 10.6. A half of the input space is left unclassified, while the other half is assigned to the majority class $CAS1$, the only one that reaches the 0.5 threshold for some premises. In this sense, if the previous classifier predicts the class with the greatest (positive) evidence, then it is possible to say that the present classifier only give a prediction if the evidence for a class is much larger than for the others. To some extent, this classifier can be associated with a requirement of not giving an assessment unless robust, strongly supported predictions are feasible. In this sense, it can be used for a first assessment of whether a scenario have no consequences at all or not. Table 10.4 shows the

Table 10.4 Performance measures under the assumption of a total opposition between classes ($\Delta \equiv 1 - \text{Id}$).

%NC	**%CC**	**AVCOST**
43.78	38.86	0.811

performance measures of this classifiers. Notice that 43.78% and 38.86% of the $m = 386$ training examples are respectively left unclassified and correctly classified. This gives an error rate of only 17.36% (the previous was 45.85%), though at the price of not-classifying almost a half of the sample. Similarly, the average cost is significantly lower, since a great part of the instances from the highest classes are left unclassified.

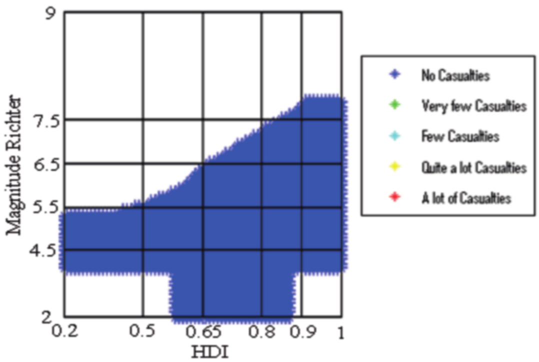

Fig. 10.6 Simulation result of the non bipolar classifier with $\Delta \equiv 1 - \text{Id}$.

10.4.2.3 *Restricted asymmetric linear order*

In order to reproduce the semantics of linear order associated with the classes, let us now introduce the dissimilarity matrix

$$\Delta_1 = \begin{pmatrix} 0 & 0.2 & 0.2 & 0.5 & 1 \\ 0 & 0 & 0.2 & 0.5 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

This matrix produces a structure in which the higher classes are gradually more and more dissimilar to the two lowest classes, $CAS1$ and $CAS2$, but not symmetrically, i.e., the lower classes are not dissimilar to the higher ones. Moreover, classes $CAS3$-$CAS5$

Table 10.5 Performance measures for the restricted asymmetric linear structure ($\Delta \equiv \Delta_1$).

%CC	AVCOST
55.18	1.069

are completely unrelated between them. Therefore, in this situation the classes $CAS1$ and $CAS2$ receive negative information from the higher ones in a progressive way, but not conversely, representing the linear structure of the classes together with the requirement of avoid underestimation risk. As a consequence, classes $CAS1$ and $CAS2$ will obtain a lower veracity degree in the presence of the higher classes, thus requiring more evidence for the former classes in order to be predicted. However, if it is estimated that such a risk can be disregarded for the higher classes (e.g. if $CAS3$ and higher scenarios are always further assessed), then it is possible to restrict the linear order structure to the first two classes and allow the classes to compete freely between them, similarly to what happened for all the classes when $\Delta \equiv 0$. These are the assumptions behind the matrix Δ_1 above. Compared to those of the non-bipolar classifier in Fig. 10.5, the simulation results now show a smoother behavior, in which the class $CAS3$ (in light blue in Fig. 10.7) appears in the transition zone between the lower and the upper classes. Notice that, in general, the upper classes obtain a greater portion of the input space than before. In fact, as shown in Table 10.5, this classifier obtains an average cost of 1.069, thus reducing the underestimation risk of the non-structured case. Furthermore, this classifier obtains a better classification rate (%CC $= 55.18$) than the non-bipolar one, i.e. the consideration of a dissimilarity structure leads in this case to a more accurate classifier than without it.

10.4.2.4 *Worst-scenario analysis*

Finally, let us consider the requirement of a total avoidance of the underestimation risk. To this end, consider now the dissimilarity matrix

$$\Delta_2 = \begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

This leads to an structure in which each class is totally opposite to all the classes lower than it, but not conversely. Therefore, in this setting there is not a explicit linear structure, but just the assumption of a total asymmetry between the lower and the higher classes.

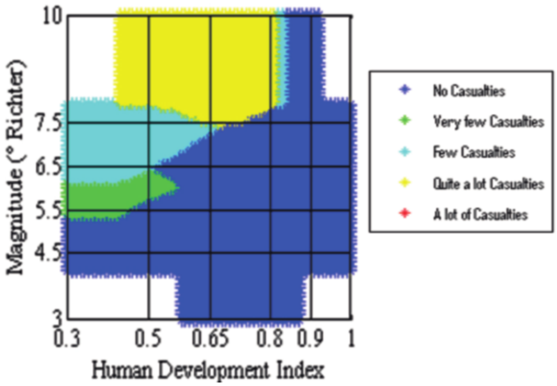

Fig. 10.7 Simulation result of the non bipolar classifier with $\Delta \equiv \Delta_1$.

Table 10.6 Performance measures for the worst case scenario analysis ($\Delta \equiv \Delta_2$).

%CC	**AVCOST**
50.52	0.968

Each class receives the positive confidence of all the higher classes as negative information. Thus, the lower the class, the harder it is for such class to be predicted. In this sense, matrix Δ_2 fits to the requirement of performing a worst case analysis of the disaster scenario under study. Notice that in this setting, no class is guaranteed to be predicted unless it attains a positive confidence $r^+ > 2/3$, except the highest, which is predicted whenever its confidence is bigger than 1/3. Consequently, the class *CAS*5 appears for the first time in the simulation results of this classifier, as shown in Fig. 10.8. Note also the improved smooth behavior of the classifier, producing a soft transition between classes. In fact, a straight line could be drawn in the input space passing through all the classes in order. More importantly, this classifier enable to distinguish a clear trend in the consequences, in such a way that worst consequences are associated with lower HDI values (and thus with a greater vulnerability) and greater intensities of earthquakes. This trend is logically expected, but notice that no one of the previous classifiers could express it so clearly. The performance measures of this classifier, shown in Table 10.6, presents a further reduction of the average cost (AVCOST = 0.968) and thus of the underestimation risk, that could be even more important since the rate of correct classification (%CC = 50.52) is lower than before (with the subsequent increment of non-zero costs).

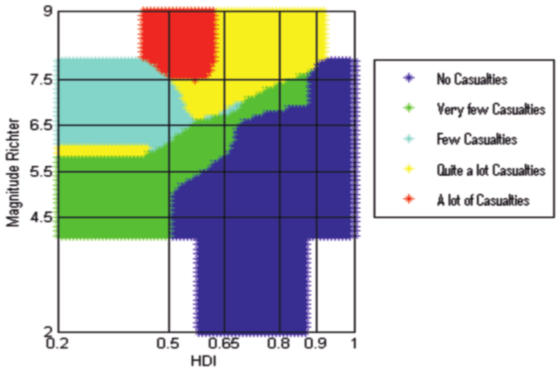

Fig. 10.8 Simulation result of the non bipolar classifier with $\Delta \equiv \Delta_2$.

10.5 Conclusions

In [23], the problem of assessing the severity of a potential disaster from the first information available, a key problem in humanitarian logistics, was reformulated as a classification problem, in which the classes are associated to the different orders of magnitude of the consequences of such a disaster. However, the semantics of these classes makes it necessary to consider them as related, in such a way that the set of classes can be regarded as having a certain structure. This leads to the notion of structured classification problem, which has been studied in this work in relation with the abovementioned problem of disaster severity assessment.

Particularly, it has been shown that different semantic (e.g. the linear order of the classes) and decision-related (e.g. the avoidance of the underestimation risk) requirements of the NGO context can be associated to different structures of such set of classes, which have been constructed and introduced in the classification models by means of the notions of semantic antagonism and dissimilarity structure. As a result, a bipolar methodology for SEDD has been obtained, which allows a more accurate and adapted assessment of disaster consequences.

Acknowledgments

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Chapter 11

A Network Transshipment Model for Planning Humanitarian Relief Operations after a Natural Disaster

Alistair Clark* and Bernadette Culkin

Department of Engineering Design and Mathematics, University of the West of England, Bristol, BS16 1QY, United Kingdom

Every year, natural disasters and humanitarian crises affect approximately 200 million people, requiring the quick movement of goods and people to ease the human suffering and to return the population to some sense of normality. With contributions to humanitarian relief programmes falling short of what is required, programme managers need to become more cost-efficient and do more with less. The field of operational research (OR) has developed many models to help the commercial sector examine current practices and find ways of becoming more cost efficient. However, much of this good practice has not transferred to the humanitarian field.

This paper develops a mathematical transshipment multi-commodity supply-chain flow model for use within humanitarian relief operations. A small data set, based on real life data from the South Asian Earthquake of October 2005, is used to validate the model solutions compared to the real life situation. Several variants of the model are developed to add realism and flexibility over a number of possible scenarios. From the variant solutions several recommendations are made to provide guidance on planning for humanitarian relief operations.

11.1 Introduction

Every year, natural disasters and humanitarian crises affect approximately 200 million people, often temporarily displacing up to five million people [36]. Responding rapidly to these situations relies on the quick movement of goods and people to ease the human suffering and to return the population to some sense of normality.

A disaster, which can take a variety of forms, is described in Van Wassenhove [42] as a disruption that physically affects a system as a whole and threatens its priorities and

*Corresponding author: Alistair.Clark@uwe.ac.uk

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goals. However, the occurrence of a disaster does not necessarily mean that humanitarian assistance is required. Many disasters occur throughout the year without becoming a crisis. It is neither the size nor magnitude of the disaster that constitutes a crisis, but rather the need for intervention. If the disaster can be dealt with using existing routines then the situation is an emergency rather than a crisis [38]. A crisis evolves into a disaster when it challenges the traditional values shared by the organization, the incumbent response mechanisms become saturated and overwhelmed, and external help is required [38]. Such foreign intervention of food, shelter and services by other governments and non-government organisations (NGOs) is known as relief or humanitarian assistance [23, 26, 36].

When a disaster occurs, the right goods and people must be sent to the right place, at the right time and in the right quantity [21]. This movement of goods and people accounts for 80% of any disaster relief operation and is often the most expensive part of any relief operation, making it a crucial factor in determining whether the humanitarian effort has been a success or a failure [36, 42].

However, each year contributions of resources have often fallen short of what is required, leading to humanitarian organisations managing programmes more efficiently, doing more with less [26]. Cost efficiency has been a particular focus within the commercial sector for a number of years, achieved by making improvements to supply chains through the examination of cross-functional solutions to address some of the barriers that inhibit improvements [15]. However, much of this good practice has not crossed over to the humanitarian sector where organizations are 15 to 20 years behind their private sector counterparts in terms of supply chain development [36, 42]. Indeed, as one researcher puts it, it is paradoxical that a sector which has such extreme requirements in terms of timeliness, affordability and oversight is so underdeveloped. It is precisely this paradox that creates what we see as a great opportunity for advancement of the field and of the humanitarian mission [36].

Operational Research (OR), known as Operations Research in the USA, has contributed widely to the commercial sector by developing models to help plan logistics and transportation operations. However the humanitarian sector has been relatively neglected [5] until recently. A post-1980 literature survey [1] of OR research and disaster management operations found just 109 articles relating specifically to the use of OR in disaster management, of which 31 were related to natural disasters and just 1 to humanitarian situations. However, since 2006, there has been an increased interest in humanitarian logistics as evidenced by recent overviews [8, 43].

Yet the aim of humanitarian relief operations is to mitigate the urgent needs of a population with sustainable reduction of their vulnerability in the shortest amount of time and with the least amount of resources [38], a challenge that is ideal for OR approaches such as mathematical optimisation and discrete-event simulation. The Association of European Operational Research Societies has also recognised the growing need to develop new methodologies or new variants of old ones, such as emergency logistics, devoting its Management Science Strategic Innovation Prize in 2006 to this area. The British OR Society's 2006 annual Blackett Lecture was also devoted to humanitarian aid logistics [42].

As a contribution in that direction, this paper develops a transshipment network flow model to assist policy makers and planners to design an effective supply chain so that goods and service reach those in need as quickly as possible. The paper is organised as follows: Section 11.2 defines the humanitarian principles and discusses the planning required for effective supply chain management. Section 11.3 then considers the models that have been developed for use in humanitarian relief operations. Section 11.4 goes on to develop an initial network flow model. Several variants of this model are proposed and tested with South Asian data in Section 11.5. The modelling and optimisation outcomes are discussed from a strategic planning perspective. Section 11.6 concludes by discussing some general implications for planners of supply chains in humanitarian relief operations.

11.2 Planning For Humanitarian Relief Operations

Planning for relief operations needs to abide by the humanitarian principles which are fundamental to the operations of humanitarian organisations [42]. Three principles define humanitarianism: humanity, impartiality and neutrality. These state, in short, that suffering will be alleviated wherever it is found, giving priority to the most urgent needs and without discrimination [38, 42].

These principles are described in the Code of Conduct for the International Federation of Red Cross and Red Crescent Societies [19], developed in 1994 to define a standard of behaviour expected of NGOs working in disaster-affected countries. Following this, a group of organisations drew up a humanitarian charter in 1997, together with minimum standards to be attained during any relief operation which came to be known as the Sphere Project [35]. These principles guide the work of NGOs and their planning activities.

Planning, or preparedness, outlines a set of actions to be taken in the event of a disaster occurring [1]. It is essential to ensure proper co-ordination and anticipate problems that may occur in the supply chain at an early stage [2, 13, 24, 27, 28, 37, 42]. Put simply, preparedness is essential for a timely, competent and cost-effective emergency response [27].

Planning for efficient humanitarian supply chains can be seen as a part of disaster recovery planning, defined by the United Nations International Strategy for Disaster Reduction as a set of actions, arrangements and procedures taken in anticipation of an emergency to ensure a rapid, effective and appropriate response that may save lives and livelihoods [40]. The World Conference on Disaster Reduction in January 2005 called for governments to prepare for effective response and recovery by identifying and allocating existing resources from the establishment, development and emergency budgets for disaster and risk management to greater effect in the realization of sustained risk reduction [41]. This is endorsed by NGOs who state in their Code of Conduct that governments should seek to provide a coordinated disaster information and planning service [20].

Many authors, e.g. Oloruntoba and Gray [28], report that there is frequently a lack of planning in humanitarian supply chains, resulting in inefficiencies. Some authors believe that planning is difficult during the initial stages of the humanitarian response because each disaster is unique [23, 27]. However, the Pan-American Health Organisation [32] disputes this point, stating that most disasters and their arising needs are usually predictable and so, by studying past humanitarian assistance programmes, accurate forecasts can be made [27], allowing regions at risk to prepare themselves and for relief agencies to prepare their efforts [23, 46]. In this way, an international humanitarian organisation was able to devise a top ten list of commodities required in most emergencies and arrange pre-purchase agreements with suppliers [25].

Rather than planning for cost-effective programmes, McGuire [27] describes the objective of humanitarian relief operation in its initial stages as being able to improvise and set up a supply chain which can deliver at all, rather than contemplating optimal and cost-efficient solutions. However, Van Wassenhove [42] affirms that a successful response to a disaster is not improvised. This view is also endorsed by the PAHO who state that the erroneous idea that logistics may be improvised at the moment of a disaster depending on needs indicated by the situation must be eliminated [32].

Two types of planning are identified in [22], namely, strategic and tactical.

(1) Strategic Planning can be thought of as long term planning. It identifies available resources and allows policy-makers and planners to assess the strengths and weaknesses of a system based on a number of likely disaster scenarios.

(2) Tactical/Operational Planning is short term planning and plans current daily or weekly operations. In the humanitarian sector this would occur when a disaster strikes and humanitarian aid is needed.

Strategic planning is common within the commercial sector. For example, the Kellogg Company inputs estimated costs and demand forecasts into their strategic model in order to optimally source products, allowing them to establish financial budgets, space for inventory and transportation requirements [6]. The models are also used to test alternative scenarios of a particular problem. Proctor and Gamble have also used such models to look at the impact of closing particular plants [7]. The use of strategic models, as in the commercial sector, can aid in identifying necessary resources and budgets.

Strategic planning practice can be used within the humanitarian sector through the use of data from past operations which can provide important post-event learning [36]. The use of feedback models can help operational decision-makers in humanitarian organizations understand the complexity of humanitarian relief efforts and learn how to design, plan and manage such operations [39]. One reason why these types of strategies have not yet filtered into the humanitarian sector could be due to lack of financing as NGOs can find funds for relief but not for planning for relief [42].

11.3 Models Developed by other Researchers

Many studies into disaster management make use of mathematical programming and incorporate well established models such as goal programming [29, 45], inventory-allocation models [17, 34], supply chain models [33], vehicle routing models [31], location-distribution models [47], network models [3, 9, 30], multi-criteria optimization models [16, 44] and inventory-control models [4]. A variety of objective functions have been used, the most common of which is minimising the cost of the operation [3]. However, planning operations based on costs alone may conflict with the IFRC Code of Conduct [19], which states that aid should be distributed based on need.

The IFRC Code of Conduct is adhered to by Ozdamar *et al.* [31] who sets the objective function to minimise the amount of unsatisfied demand in their model. Unsatisfied demand is also included in the objective function by Yi and Ozdamar [47] together with a priority weighting for each commodity. The model developed by Hwang [17] minimises the amount of pains and starving , but there is no information about how this is calculated. However, cost cannot be totally ignored because humanitarian organisations are becoming increasingly accountable to their donors on how funds are spent [42] and are required to plan more cost-effective programmes due to a shortfall in funding contributions [27]. This is acknowledged in [3] who not only minimise the costs of the operation but also include a penalty cost for unmet demand.

All the authors above acknowledge that their models can be used to plan for humanitarian relief operations. However, few authors makes recommendations for use in preparing for a disaster. Instead, the focus tends to be on inputting data and analysing the results from that particular data set.

One of the difficulties in planning for humanitarian relief operations is that information changes quickly, particularly at the beginning of operations, a reality that must be reflected in any model that is developed. The model in [31] incorporates this by allowing new plans to be developed at given time intervals once updated information has been received. The model in [3] is an attempt at planning where supply and arc capacities are determined in the pre-event stage for each earthquake scenario. This information is then extracted for the actual event.

It is not clear whether these models are flexible enough to use in other kinds of disasters. The model in [31] focuses specifically on logistics planning after a natural disaster, but it is only tested on a relief operation after an earthquake, and gives no indication of whether it is suitable in other natural disasters. The model in [3] also gives little indication of its generality. Although its development was based on a number of earthquake scenarios, it is not clear whether it is applicable to other types of disaster.

11.4 A Network Transshipment model for Emergency Relief

We now develop a basic transshipment model for exploratory strategic planning. A humanitarian supply chain can be thought of as starting at multiple suppliers, then passing through various transshipment points and finally arriving at the multiple recipients.

Figure 11.1 shows a humanitarian supply chain as a network transshipment model in which items are pulled through the supply chain to meet the demands of the recipient. The quantity of items sent along the chain is dependent upon the demand at the final destination.

The model is strategic, rather than operational, and aims to identify whether there are sufficient resources, suppliers, modes of transport, inventory and storage capacity along the supply chain. It includes all the necessary nodes within the supply chain as defined in the

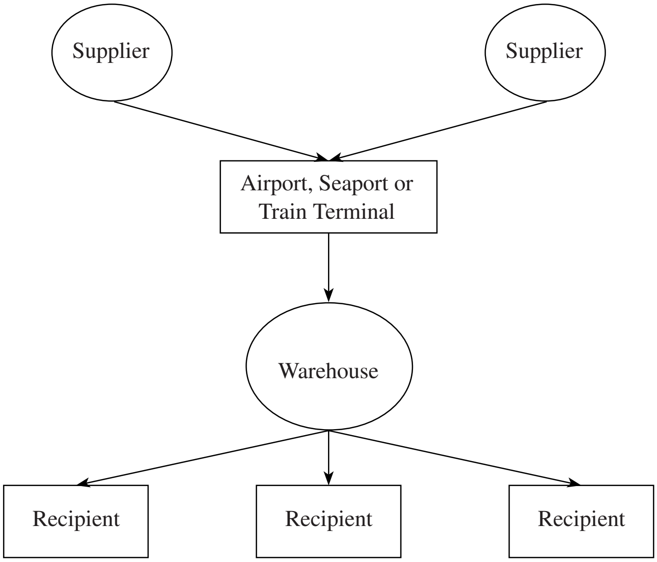

Fig. 11.1 A humanitarian supply chain

conceptual model. Suppliers, warehouses, airports, seaports and rail terminals and recipients are all nodes along the supply chain with possible intermediate demand for certain items.

Users of the model can flexibly define supply and demand parameters at each node as well as capacity levels for flows along each arc. The model can represent a variety of resources and constraints such as the type and number of transport vehicles available or limits on the number of items sent to each warehouse. The use of a flow model also allows restrictions on arcs to model the impacts of natural disasters on the supply chain such as impassable roads.

Comment. To specify and formulate the model more precisely, consider the following index sets:

- S suppliers
- W warehouses
- R recipients (people)
- A airports

F seaports

B rail terminals

I items

E types of vehicles available

K of nodes $k \in \{S \cup W \cup R \cup A \cup F \cup B\}$ of the supply chain

G of intermediate nodes $k \in \{S \cup W \cup A \cup F \cup B\}$

L links between successive nodes

The index i represent items transported, and v denotes vehicles. The indices j and k represents the network nodes in the supply chain such as suppliers, airports, seaports, terminals, warehouses, and recipients .

The index t represents a day within the planning horizon. Thus $t = 1, \dots, 10$ means a ten-day horizon with decisions at the start of each day, including the current one (for which $t = 1$). Non-positive values of t represent the past, so that, for example, $t = 0$ would be the day before the current one, $t = -1$, the day before that, and so on. The inclusion of on-positive values of t is allowed to appropriately model the effect of transportation lead times, as in, for example, the definition of data parameter T^0_{kjvit} below.

The following parameters contain all the information that planners should (ideally) know:

Cap_t available capacity time in each period t.

I^0_{ki} current initial inventory at node k of item i (i.e., at the end of day 0)

D_{kit} demand at node k for item i on day t

U^0_{ki} current unsatisfied demand at node k for item i

VC_v maximum capacity that each vehicle v can carry in metric tonnes

VA_{kvt} number of vehicles available at node k of a vehicle type v on day t (integer)

L_{kjv} lead time from node k to node j using a vehicle of type v

T^0_{kjvit} amount of item i already sent from node k to node j, using a vehicle of type v, i at past times $t = -L_{kjv}, \dots, 0$

F_{kjv} fixed transport cost to include driver, fuel, maintenance etc. of using each vehicle type v between node k and node j

W_i weight of each item i

C_k capacity limits of each node k

The decisions to be taken correspond to the following variables:

T_{kjvit} amount of item i sent from node k to node j, using vehicle type v, on day t

V_{kjvt} number of vehicles of type v sent from node k to node j on day t (integer)

The outcomes of these decisions are the following variables:

I_{kit} inventory at node k of item i at the end of day t

U_{kit} unsatisfied demand (backlog) at node k for item i at the end of day t

The model, being strategic, is designed to plan and analyse flows through the supply chain in advance of a natural disaster occurring, exploring possible scenarios. The decision variables give information about the amount T_{kjvit} of items transported from one node to another and the number of vehicles V_{kjvt} needed to do so. The inventory outcome variable I_{kit} allows planners to investigate the amount of storage required for the supply chain to operate effectively and efficiently. However, the unsatisfied demand outcome variable U_{kit} is probably the most important as it provides information on how many recipients will still be waiting for each item at the end of each day in the planning horizon.

Any humanitarian operation has at its heart the requirement to ease the suffering of others, and so the objective function of this model is to minimise unmet need, defined as unsatisfied demand accumulated over time. However, cost cannot be completely ignored and so needs to be minimized and included in the objective function. This leads to the use of the weighted-sum multi-objective function (11.1) below that not only minimises need but also transportation and inventory costs. In using such a multi-objective model, the organisation should carefully consider its priorities as these can affect the cost of the humanitarian relief operation. Is minimising unsatisfied demand in the shortest amount of time more important than minimising transportation costs? What action should be taken if some recipients do not receive items? How much capacity can be unused in each mode of transport or should vehicles be filled to capacity? These discussions are then useful in determining the weightings that should be given to each of the components in the objective function.

The humanitarian organisations' Code of Conduct requires that aid must be delivered based on need and not cost [20, 35]. Accordingly, the objective function (11.1) below pre-emptively places much greater priority on minimising need before transportation and inventory costs:

$$\text{Minimise} \quad \sum_{kit} U_{kit} + 0.001 \sum_{kjvt} F_{kjv} V_{kjvt} + 0.01 \sum_{kit} I_{kit} + \sum_{kjvt} V_{kjvt} \qquad (11.1)$$

The weight values of 1, 0.001, 0.01 and 1 in expression are somewhat arbitrary, and here simply reflect the relative magnitude each particular component in the policy of the organization. For this paper, we wished the items to be delivered to recipients as quickly as possible, hence the high relative weighting given to $\sum_{kit} U_{kit}$. The units of measurement of each component must also be taken into account. At first glance it may appear that there is a greater weighting given to inventory than transport. However, the magnitude of the transportation costs means that its weighting has to be scaled down in order for transportation costs to approximately equal inventory costs. The danger with using weightings is that if there was a small transportation cost and a large inventory then these weightings may be inappropriate leading to the inventory component having a greater influence than the transportation costs weighting. The weightings have been verified so that this problem should not occur. Technical normalisation methods can also be used to help determine appropriate relative weightings [11].

The final component $\sum_{kjvt} V_{kjvt}$ of the objective function also minimises the number of vehicles used. It has been added because transportation costs from suppliers are assumed to be paid for by the supplier, and so the number of vehicles used are not minimised by the fixed costs component $\sum_{kjvt} F_{kjv} V_{kjvt}$ in the objective function. If policy makers knew the cost for these journeys then this component could be removed from the objective function.

Varying the relative weights in the objective function (11.1) allows different polices to be explored, and the consequent impact on the time taken to satisfy demand. However, a more direct and comprehensive way of investigating the impact of different policies, would be to directly introduce constraints on, for example, the permitted amount of inventory, or other components of the objective function. This type of multi-objective decision making would need to be undertaken interactively with planners, making use of methods that explore the efficient frontier of Pareto-optimal decisions [14], for example, the eta-constraint technique [10].

To establish initial conditions, constraint (11.2) and (11.3) specifies the current unsatisfied demand and inventory of each item at each node, i.e., at the end of day 0:

$$U_{ki0} = U_{ki}^0 \text{ for all nodes } k\text{, and items } i \tag{11.2}$$

$$I_{ki0} = I_{ki}^0 \text{ for all nodes } k \text{ and items } i \tag{11.3}$$

Each time the model is re-run during the course of the relief operation, the values of parameters U_{ki}^0 and I_{ki}^0 would be updated to reflect the situation at the time of planning.

Initially, unsatisfied demand U_{ki}^0 at day 0 is set at zero because it is assumed that the recipients had no need for any extra items before the natural disaster occurred, i.e., demand was being dealt with by existing systems. However, when using the models during relief operations, unsatisfied demand would be the number of recipients still requiring items at the current point in time.

Constraint (11.4) defines the amount of each item sent between pairs of nodes before the disaster has occurred but which are still in transit and so have not yet arrived at the destination node:

$$T_{kjvit} = T^0_{kjvit}$$

for all nodes k & j, vehicles v, items i, and past days $t = -L_{kjv}, \ldots, 0$ (11.4)

The parameter T^0_{kjvit} has a default value of 0 as it is assumed that it is not known that a disaster is imminent and therefore items were not pre-ordered. If the natural disaster is expected then operations planners may have pre-ordered certain items which can then be entered into the model using T^0_{kjvit} for past days $t = -L_{kjv}, \ldots, 0$. The same reasoning applies when the model is re-run during a humanitarian relief operation.

In a network flow model, supply must balance demand, inventories, and backlogs over time. Constraint (11.5) ensures that no more items are sent than are received and/or taken from the local inventory:

$$\sum_{jv} T_{jkvi,t-L_{jkv}} + I_{ki,t-1} - U_{ki,t-1} = \sum_{jv} T_{kjvit} + I_{kit} - U_{kit} + D_{kit}$$

for all nodes k, items i and days t (11.5)

Constraint (11.5) states that, on any given day and at any given node, the items arriving from previous nodes, together with the items inherited from the previous day's ending inventory, less the unmet demand from the previous day, should equal in quantity the items sent to the next nodes, plus the demand and the amount put into inventory, less any unsatisfied demand.

In the model, unsatisfied demand U_{kit} can be thought of as backlog. The model does not allow backlogs to occur at intermediate nodes because it is only at the final destination (where recipients are based) that planners would need to know whether there is still unsatisfied demand. Thus unsatisfied demand at intermediate nodes is fixed to be zero.

Observe how the lead time value L_{jkv} in constraint (11.5) is used to correctly calculate the amount of an item i coming into a given node k via vehicle v during day t. It is not needed to calculate the amount of items going out of a node. It thus partly determines the values of U_{kit} and IU_{kit} which feature directly in the objective function. As a result, lead time features only indirectly in the objective function (11.1).

The use of lead time in constraint (11.5) highlights one of the main differences between this and other models developed for humanitarian operations after a natural disaster. Lead time is an important consideration as it affects the decisions made about sourcing supplies and consequently how long recipients are deprived of help. It will influence decisions about the minimum inventory of items to keep in local warehouses or pre-agreed purchase agreements to deal with initial demand.

Constraint (11.6) ensures that there are enough vehicles to transport items between nodes:

$$V_{kjvt} \geqslant \frac{0.001 \sum_i T_{kjvit} W_i}{VC_v} \text{ for all nodes } k \text{ and } j, \text{ vehicles } v, \text{ and days } t \tag{11.6}$$

The coefficient 0.001 converts the item weights in kilograms to metric tonnes, the units of vehicle capacity.

Constraint (11.7) ensures that the weight of all inventory items is within the node capacity limits, again multiplying by 0.001 to convert from kilograms to metric tonnes:

$$0.001 \sum_i I_{kit} W_i \leqslant C_k \text{ for all nodes } k, \text{ items } i, \text{ and days } t \tag{11.7}$$

Thus our basic model is formulated as objective function (11.1) and constraints (11.2) to (11.7).

11.5 Computational Analysis and Model Refinement

The basic model was tested and further developed over a 10-day planning horizon with data representing 5 items, 4 vehicle types and 54 nodes as follows: 25 suppliers, 6 warehouses, 8 recipients, 8 airports or heliports, 1 seaport, and 6 rail terminals. A larger instance was then implemented with 5 items and 4 vehicle types as before, but now with 83 nodes as follows: 49 suppliers, 6 warehouses, 13 recipients, 8 airports or heliports, 1 seaport, 6 rail terminals. The data was adapted from that on the UNJLC website for the Pakistan Earthquake in 2005.

The model was implemented using AMPL [12] and solved using Cplex 9.1 [18] on a Sun V208 Dual Opteron 252 processor running under Linux with a processing speed of 2.6 GHz and 4GB of RAM. Almost all the model refinements below took less than 10 seconds to optimally solve, as discussed in more detail later in the paper.

11.5.1 *Analysis with the Uncapacitated Model*

If there are no capacity limits, then all supplies are dispatched to recipients in the disaster zone on day 1. All supplies are sent to the airport that has the shortest lead times and cheapest transportation costs as the objective function requires the model to reduce unsatisfied demand in the shortest amount of time, at minimum cost and with the the least inventory.

When deciding where to send items, the model considers which recipients are closest to the point of entry, i.e., which have the shortest lead times. If there is no difference in the lead time of two or more recipients then the model considers which of these has cheaper transportation costs.

Helicopters are used to transport items to heliports. Even though they are more expensive, helicopters are chosen because they can get items to where they are needed quickly thus satisfying the objective that unsatisfied demand should be minimised in the shortest amount of time. The recipients with the cheapest helicopter rates are chosen to receive items. Trucks are then used to transport items from heliports to warehouses and onward to recipients.

Those recipients without access to heliports are in danger of not receiving items because these need to be delivered by truck, a journey which has a longer lead time than the same journey by helicopter. Consequently the time taken to minimise unsatisfied demand increases. In addition, these recipients are also further away from the initial points of entry and so have larger transportation costs, increasing the value of the objective function. Special attention might need to be given to this group of recipients to ensure that they are given consideration when distributing aid.

11.5.2 *Airport Arrival Capacity*

The model does not take into account a problem that is identified in many situation reports, namely airport congestion. Is there enough space for all aeroplanes to land? Are there sufficient resources to deal with the volume of items being delivered? If not, then this will delay the arrival of aeroplanes on subsequent days and so prolong the time taken to deliver items, extending time needed to meet (or minimise) unsatisfied demand. To be realistic the model should be adapted to include a limit on the number of aeroplanes that can arrive at each airport on any given day.

To allow planners to investigate the impact of imposing limits on the number of aeroplanes arriving at each airport, an airport capacity parameter AC_{jvt} is added to the model in an additional constraint (11.8) limiting the number of aeroplanes that can arrive each day.

$$\sum_{k} V_{kjv,t-L_{kjv}} \leqslant AC_{jvt} \quad \text{for all nodes } j\text{, vehicles } v\text{, and days } t \tag{11.8}$$

Constraint (11.8) states that the total number of vehicles $V_{kjv,t-L_{kvt}}$, sent $t-L_{kjv}$ days ago from nodes k to j to arrive on day t, must not exceed the airport capacity AC_{jvt} at node j for each vehicle type v on a given day t. Indexing the airport capacity parameter over t allows planners to change the limits on a given day to take account of the number of staff available to deal with arriving items, space for aeroplanes, weather, etc., at each airport.

When airport capacity is limited, the number of days over which airports are used increases, because there are not enough spaces at each airport for the planes to land and so the model staggers the delivery of items. This leads to an increase in the amount of time in which recipients are waiting for items.

Items initially arrive at the airport closest to the disaster zone until it has reached its capacity. At this point, arrivals are switched to the airport that has the next shortest lead times and cheapest transportation costs, and so on. The total number of planes increases, due to the transfer of items by air from airports further away than those closest to the disaster zone. Items are transferred by plane rather than by road due to the objective function, which requires that unsatisfied demand should be minimised in the shortest amount of time. The model chooses the route and vehicle with the shortest lead times which results in items being transferred by aeroplane to the airport closest to the disaster zone where helicopters and trucks are then used to transport items to their final destination.

11.5.3 *Limiting Vehicle Availability at Nodes*

So far, there is an unlimited supply of vehicles. Although this provides useful information about where vehicles are needed and the ideal number required, it is not realistic. Adding constraint (11.9) below allows planners to examine the impact on the objective function of a limited availability VA_{kvt} of vehicles:

$$\sum_{j} V_{kjvt} \leqslant VA_{kvt} \quad \text{for all nodes } k\text{, vehicles } v\text{, and days } t \tag{11.9}$$

Indexing by day t allows planners to flexibly specify the number of vehicles available over time so as to model, for example, NGOs donating extra vehicles. Note that this is still a simplistic constraint - it does not model the movement of vehicles among nodes as they transport items, such as in [9]. Such information has to be explicitly provided on a day-by-day basis via the values of the parameter VA_{kvt}.

11.5.3.1 *Limited Helicopters*

Initially, $VA_{kvt} = 10$ for $v =$ `Helicopters` at each node k and day t. This has no effect on the arrival of items into the disaster zone. All items are still sent by suppliers on day 1, arriving at the airport closest to the disaster zone. The model initially uses helicopters to transfer items to those recipients with cheaper transportation costs. When all helicopters have been used, the model then has to consider alternative forms of transport which still minimise unsatisfied demand in the shortest amount of time. This leads the model to choose trucks and to send these to the place with the cheapest transportation costs for trucks. Transferring remaining items by truck ensures that there are no items left in the inventory, fulfilling the third component of the objective function which states that inventory should be minimised. However, the time taken to deliver items increases, compared to the uncapacitated model, as items sent by road have longer lead times than if sent by helicopter.

11.5.3.2 *Limited Trucks*

A limited availability of trucks at each node causes the use of a greater number of airports to receive items, even though capacity is not reached at each airport. The reason for this is because of a problem further down the supply chain.

The objective function requires that items should be delivered as quickly as possible in order to minimise unsatisfied demand in the shortest amount of time. This results in items being sent to the airport closest to the disaster zone. Items are initially transferred by helicopter to those recipients with the cheapest transportation costs. However, delivery stalls when there are no more trucks available to transport items from heliport to warehouse, causing an increase in the time taken to deliver items.

One may think that items could be delivered to the heliport and stored there until they are ready to be transferred by truck but the next component in the objective function states that inventory should be minimised. Thus, rather than have items stored in inventory, items are sent to recipients by road, to be delivered the following day. So when after as many items as possible are delivered by helicopter, the model then uses all its trucks to transfer deliver items to recipients. When all these trucks have been used, suppliers send items to the next airport so that the trucks there can be used to deliver items to recipients.

Items are delivered to a greater number of places than when transport is not limited. Some of these recipients are further away from the initial point of entry, and consequently have higher transportation costs which contribute to increased transportation costs.

11.5.4 *Helicopters and Road Access*

Delivery by road when helicopters are unavailable works well when there is no disruption to the road network. However, should this happen, as occurs frequently after earthquakes, then delivery of items may be affected.

Items continue to be sent by helicopter to the recipient with the cheapest transportation costs, in line with the objective function of minimising unsatisfied demand in the shortest amount of time and at minimum cost. When the $VA_{kvt} = 10$ helicopters available on day t at node k have been used, the model has to look for the next quickest mode of transport available that will still minimise unsatisfied demand as quickly as possible, namely trucks. The model then considers which recipient has the shortest lead time and cheapest transportation cost. If this recipient cannot be reached, then the model looks at the next shortest lead times and cheapest routes, and so on.

Planners may wish to restrict the use of helicopters to serve those recipients where there is no road access or introduce a new mode of transport, such as an airlift, to drop items directly to recipients.

When the availability of helicopters is limited, then all helicopters at the initial point of entry are used. The remaining helicopters at other heliports are not used which is a waste of a valuable resource which would not occur in the real world. The model needs to be adapted so that better use is made of this valuable resource.

11.5.5 *Pooling Vehicles*

Instead of allocating vehicles equally amongst all nodes, they can be pooled to allow a more effective use of resources. An additional constraint (11.10) is needed.

$$\sum_{kj} V_{kjvt} \leqslant VP_{vt} \quad \text{for all vehicles } v\text{, and days } t \tag{11.10}$$

where the new parameter VP vt specifies the number of vehicles of type v in the pool on day t. Again, indexing the vehicle pool parameter over t allows planners to add additional vehicles to the pool should they become available. Note that this still does not model the movement of vehicles among nodes as in [9].

11.5.5.1 *Pooling Helicopters*

Pooling resources actually increases transportation costs, due to the greater use of helicopters than when not pooled. This is due to the fact that helicopters journeys cost twice as much as trucks, an increase that has a great effect on transportation costs.

Pooling helicopters allows them to be allocated where they are best used, i.e., at the initial point of entry to deal with the incoming supplies. In a similar way to the previous model, the items are sent to those recipients with short lead times and cheaper transportation routes and therefore satisfies the objective function which states that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs.

When all helicopters in the pool are used, items are sent by road to the recipient with shortest lead times and cheapest trucking rates. Items could be stored in inventory for delivery next day but there is a component in the objective function that states that inventory should be minimised. In addition, storing items in inventory would not reduce the time taken to minimise unsatisfied demand nor minimise transportation costs, therefore increasing the objective function.

Pooling helicopters allows a greater number of items to be delivered and therefore unsatisfied demand is minimised more quickly, compared to when vehicles are not pooled.

11.5.5.2 *Pooling Trucks*

The pooling of trucks allows the model to allocate them to where they are most needed. Once again, items are sent to recipients with the cheapest transportation costs and shortest lead times. The model solution shows that items are initially transported by helicopter to recipients with cheaper transportation costs. However, transportation then switches to road which, initially, appears quite surprising as there are an unlimited amount of helicopters available to transport these items with a lead time of zero. However, if items were transferred by helicopter, then there are not enough vehicles available to transfer items from the heliport to the warehouse and then onto recipient. At this point, items would need to be stored in the inventory. But this does not happen because the minimisation of inventory in the objective function causes items to be then sent to the recipient with the next cheapest trucking route, therefore minimising the transportation costs component of the objective function.

There is a difference in the time taken to deliver items due to the fact that initial delivery to the disaster zone is delayed so as to minimise the inventory component of the objective function.

11.5.6 *Emergency Contingency Stocks*

The models examined so far have assumed that there is no inventory in any of the warehouses. We now assumed that there are emergency contingency stocks held in warehouses within the disaster zone to examine the effect that this has.

Even with the use of emergency contingency stocks, the number of aeroplanes arriving each day does not differ from the uncapacitated model. This is not surprising as the objective function states that unsatisfied demand should be minimised in the shortest amount of time and so all items are sent as quickly as possible to the airport closest to the disaster zone. There are an unlimited number of helicopters and trucks available to transport items to warehouses, so inventory will be minimised.

The addition of emergency contingency stocks into the supply chain causes an increase in the transportation costs (due to the large increase in the number of trucks used to transport the emergency stocks from warehouses to recipients). In addition, unsatisfied demand initially decreases sharply, but then follows a similar pattern to the uncapacitated model as more items enter the disaster zone from external suppliers.

The initial unsatisfied demand decreases because all emergency contingency stocks are sent to the closest recipient on day 1. This is because the objective function states that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs. This journey has zero lead time and, as items are delivered by truck, transportation costs are relatively cheap.

Items from external suppliers are sent to those recipients that have short lead times and cheap transportation costs, as in the uncapacitated model. This is to satisfy the objective function which states that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs.

Once again, there are recipients who do not receive any items. These recipients are at a considerable disadvantage to other recipients for a number of reasons. Firstly, they are furthest way from the initial point of entry and so have larger transportation costs. Secondly, they do not have a heliport nearby so they have larger lead times as items have to be delivered by truck. Finally, they do not have a warehouse nearby and so initial demand is not minimised. The combination of all these factors leads to these recipients not receiving items.

In all the models examined so far, the decision of where items are delivered is based on shortest lead times and cheapest transportation costs. However, delivering items based on speed and cost may violate the NGO's Code of Conduct [19] which states that humanitarian aid should be delivered based on need. Thus the model should be adapted to include a parameter identifying relative need and then prioritise aid to where it is most needed.

11.5.7 *Prioritising Greatest Need*

Prioritising need ensures that those in greatest need receive items first. The objective function (11.11) includes a weighted average of unsatisfied demand so those recipients with a greater priority weighting P_k will have a less unsatisfied demand than those deemed to be of lower priority.

$$\text{Minimise} \sum_{kit} P_k U_{kit} + 0.001 \sum_{kjvt} F_{kjv} V_{kjvt} + 0.01 \sum_{kit} I_{kit} + \sum_{kjvt} V_{kjvt} \tag{11.11}$$

The weightings for P_k range from 10 (for the location of the greatest need) down to 1 (indicating the lowest need).

The number of aeroplanes landing is the same as in the unprioritised uncapacitated model. This is to be expected as there are no constraints on how many aeroplanes allowed to land at each airport nor on the number of vehicles available to transport items from airports.

However, transportation costs can increase, depending on how the priority weighting P_k has been allocated. If recipients with a higher priority status are further away from the initial point of entry, then they will tend to have higher transportation costs. If they do not have a heliport nearby, then items need to be transported by road. The model solution in this situation shows an increase in the usage of all forms of transport in order to reach recipients, contributing to increased transportation costs.

11.5.8 *Minimum Delivery to each Recipient*

Another way of ensuring a fairer distribution of food is to enforce a distribution policy whereby a minimum amount M_{ij} of each item i is delivered to each node j is incorporated into a new constraint:

$$\sum_{kv} T_{kjvi} \geqslant M_{ji} \quad \text{for all nodes } j \text{ and items } i \tag{11.12}$$

Indexing M_{ij} by end-node j allows planners to set minimum delivery levels for each recipient based on a number of factors such as number of people affected, particular needs of each recipient, and so on.

Again, the number of aeroplanes arriving is the same as in the original uncapacitated model, the reason being that items will arrive as quickly as possible so that unsatisfied demand can be minimised in the shortest amount of time.

When a minimum delivery policy is introduced, transportation costs again increase slightly compared to the original uncapacitated model, as some formerly neglected recipients have larger transportation costs. The number of helicopters is reduced because some of these new recipients do not have a heliport nearby and so their items are delivered by road, for example, Abbottabad. The original helicopter-aided recipients of these items receive less than previously, thus reducing the need for helicopters.

All recipients at node j receive the minimum number M_{ij} of items i, as declared in the data set. The remaining items are sent by helicopter to those recipients with the shortest lead times and cheaper transportation costs, as the objective function requires that unsatisfied demand should be minimised in the shortest amount of time with respect to transportation costs. If demand has been satisfied then any remaining items are sent by helicopter to the recipient with the next cheapest transportation costs. Items are sent to other recipients via heliports, as this is the quickest way of getting items closest to recipients and allows unsatisfied demand to be minimised more quickly.

It is possible to combine the use of a priority weighting P_k and minimum delivery amount M_{ij} so that all recipients receive a minimum number of items but then priority is given to those recipients with a higher priority weighting.

11.5.9 *Reducing Unused Vehicle Capacity*

In all the models examined so far, there have been situations when the number of items transported has been very small, leading to a great deal of unused space in vehicles. This is not a cost-effective way of delivering items which, in addition, may cause upset to those recipients who are in desperate need of goods if only 10 items arrive for over 100,000 people. Even though unsatisfied demand is minimised in the shortest amount of time, it is not a policy that would be endorsed by most organisations who would want resources to be used to maximum effect. One way of overcoming this is to reduce the amount of slack that is left in each vehicle. Thus more items will be put onto each vehicle enabling much more cost effective operations.

Constraint (11.13) calculates the amount VS_{kjvt} of vehicle slack:

$$VS_{kjvt} = V_{kjvt}VC_v - 0.001\sum_i T_{kjvit}W_i \geqslant 0$$

$$\text{for all nodes } k \;\&\; j, \text{ vehicles } v, \text{ and days } t \tag{11.13}$$

Slack is then minimised in the revised objective function (11.14):

$$\text{Minimise} \sum_{kit} U_{kit}P_k + 0.001\sum_{kjvt} F_{kjv}V_{kjvt} + 0.01\sum_{kit} I_{kit} + \sum_{kjvt} V_{kjvt} + \sum_{kjvt} VS_{kjvt} \tag{11.14}$$

When vehicle slack is minimised, there is no effect on the higher priority components of the objective function. The total number of items delivered to each recipient in the amount of time taken to deliver these items remains the same. However, as desired, the number of deliveries of less than 100 items is reduced, as are the number of vehicles used and transportation costs. This further reduces the value of the objective function as transportation costs are reduced, therefore providing a much more cost effective operation.

11.5.10 *Computational times*

With the smaller data set, the models had between 10,500 and 11,600 integer variables. All but two of the model refinements above took less than 10 seconds to optimally solve, with half taking under 1 second. However, the truck pooling model took 57.7 seconds to solve, probably due to the small number of trucks available, resulting in a tightly constrained model. The capacitated landing model, which took 13.1 seconds, was also tightly constrained with few aeroplanes being allowed to land at each airport.

The fast solution times make the model highly suitable for multiple runs during an interactive session with decision-making end-users to explore different policies.

However, under the larger data set, no optimal solution was provably found after 4 hours for capacitated-trucks model. The long solution time is due to the very small number of trucks available to transport all items to recipients, making it tightly constrained. The addition of extra suppliers and recipients has increased the complexity of the model to find an optimal solution. Under these circumstances, computation needs to be stopped after some predetermined amount of time, and the incumbent solution used or some other heuristic method used.

11.6 Recommendations and Conclusions

This paper develops a mathematical transshipment multi-commodity supply-chain network flow model to aid policy makers plan for effective humanitarian relief operations after an earthquake. A small data set, based on real life data from the South Asian Earthquake of October 2005, is used to validate the model solutions compared to the real life situation. The model aids the planning process by allowing policy makers to test a number of scenarios so that a better understanding of the strengths and weaknesses of the supply chain can be developed.

The model can be initially used as an uncapacitated model to provide useful information about budget requirements, numbers and types of vehicles required, capacity limits at initial points of entry and at warehouses, time taken to satisfy demand, whether the number of existing suppliers is satisfactory to meet the needs of a given scenario, etc. Several variants of the model are developed to add realism and flexibility over a number of possible scenarios thus allowing policy makers to examine the consequences of their real-life situation such as limited availability of vehicles, restricted capacity at initial points of entry and warehouses, road closures etc. The multi-criteria nature of the objective function also obliges planners to consider and clarify their priorities - indeed this is one of the most useful purposes of the model.

Based on the analysis above, general guidance on the use of the model can be synthesised. Table 11.1 lists a number of problem scenarios that planners may be faced with, together with recommendations on how to use the model to overcome each problem. The recommendations concern the allocation of resources and the kind of parameters that need to change and in which direction. They are extrapolated from the computational results of the particular case study in this paper, and are intended as helpful guidance for policy makers and strategic planners to consider and act upon before a disaster occurs. However, the quantitative and optimising characteristics of the model also make it very useful for tactical operations, enabling field planners to flexibly redirect transportation and material resources on a daily basis, if reliable and timely data is available. If some of the data is of doubtful quality or needs to be very roughly estimated, then the models' outputs will need to be treated accordingly. Nevertheless, such outputs will help to compare the consequences of different courses of action.

Table 11.1 Recommendations for effective humanitarian relief operations

Scenario	**Recommendation**
Low Budget.	Increase weighting on transportation cost component in objective function. Minimise vehicle slack. Reduce the number of helicopters used.
Limited Storage.	Stagger arrival of supplies from external suppliers. Send items to warehouses by truck to make use of storage in transit.
Recipients neglected.	Introduce a priority status. Introduce a minimum delivery policy. Consider placing emergency contingency stocks close to these areas.
Small number of helicopters and trucks available.	Pool resources to make maximum use of resource.
Need to reduce the amount of time taken to minimise unsatisfied demand.	Increase the number of helicopters available at the initial point of entry. Increase the number of trucks available at heliports and warehouses. Increase the number of aeroplanes allowed to land at airports. Consider the use of suppliers close to the disaster zone.
Limited Road Access.	Restrict the use of helicopters to those recipients that have no road access. Introduce airlifts as a new mode of transport to these recipients.

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Chapter 12

A Travel Behaviour Study through Learning and Clustering of Fuzzy Cognitive Maps

Maikel León [1,2,*], Lusine Mkrtchyan [2,3], Benoît Depaire [2], Da Ruan [2,3] †, Koen Vanhoof [2]

[1] *Center of Studies on Informatics, Central University of Las Villas, Santa Clara, Cuba*
[2] *Transportation Research Institute, Hasselt University, Diepenbeek, Belgium*
[3] *Belgian Nuclear Research Centre (SCK • CEN), Mol, Belgium*

[*] *mle@uclv.edu.cu*

Transport management and behaviour modelling appears in modern societies because of the importance for all social and economic processes. Using in this field advanced computer techniques like the Artificial Intelligence ones is really relevant from the scientific, economic and social point of view. In this paper we deal with Fuzzy Cognitive Maps as an approach in representing the behaviour and operation of such complex systems. We also show how travellers base their decisions on knowledge of different transport mode properties at different levels of abstraction depending on their perception of available information. These levels correspond to the abstraction hierarchy including different scenarios of traveling, different set of benefits while choosing a specific travel mode, and different situations and attributes related with those benefits. We use learning and clustering of Fuzzy Cognitive Maps to describe travellers' behaviour and change trends in different abstraction levels.

12.1 Introduction

Travel behaviour studies are very important for decreasing travel-related energy consumption, depressing high weight on urban infrastructure, and predicting individuals' behaviours, etc. Many attempts have been made to influence individuals' unsustainable travel behaviour towards more sustainable forms, improving the transportation use by reducing travel demand or distributing it in time and space. However, these behaviour studies can be effectively and efficiently implemented if they are developed founded on a profound

† Prof. Da Ruan deceased on 31 of July 2011 while he was actively involved in this study.

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understanding of the basic causes of travel, such as people's reasons and inclinations, and comprehensive information of individuals' behaviours [1].

12.1.1 *Problem presentation*

In the process of transportation planning, travel demand forecast is one of the most important analysis instruments to evaluate various policy measures to influence travel supply and demand. In past decades, increasing environmental awareness and the generally accepted policy paradigm of sustainable development made transportation policy measures to shift from facilitation to reduction and control. Some objectives of those measures are: to alter travel behaviour without necessarily embarking on large-scale infrastructure expansion projects and to encourage better use of available transport resources avoiding the negative consequences of continued unrestrained growth in private mobility.

Individuals' activity travel selections can be considered as real decision problems, producing the generation of a mental representation or Cognitive Map (CM) of the decision situation and alternative action courses in the expert's mind. This CM concept is often referred to, in theoretical frameworks of travel demand models, especially related to the representation of spatial dimensions, but many features can be taken into account (see Figure 12.1).

Fig. 12.1 Abstraction levels of mind related to Travel Behaviour.

However, actual model applications are scarce, mainly due to problems in modelling and measuring the construct. To this end, the development of the mental map concept can benefit from the knowledge provided by individual tracking technologies. Many studies are focusing on that direction, to improve developed models and to produce a better quality of systems. At an individual level it is important to realize that the relationship between travel decisions and the spatial characteristics of the environment is established through the individuals' perception and cognition of environment [2].

Records regarding individuals' decision making processes can be used as input to generate mental models. Such models treat each individual as an agent with mental qualities, such as viewpoints, objectives, predilections, inclinations, etc. For modelling, several Artificial Intelligence techniques can be used, in this case Fuzzy Cognitive Maps (FCMs) will be applied; through them we will try to simulate individuals' decision making processes. Consequently, FCMs can be used not only to understand people's travel behaviours, but also to pretend the changes in their actions due to some factors in their decision atmosphere. This technique is very well known by its self-explicability.

From a computational point of view, FCMs are a mixture of several aspects from Fuzzy Logic and Neural Networks; combining the heuristic and common sense rules of Fuzzy Logic with the learning heuristics of the Neural Networks. They were introduced by B. Kosko, who enhanced CMs with fuzzy reasoning, that had been previously used in the field of socio-economic and political sciences to analyse problems such as social decision-making problems, etc. The use of FCMs for many applications in different scientific fields had been proposed.

12.1.2 *Contribution in Disaster Management studies*

Disaster event monitoring as one of the steps in risk and crisis management is a very complex system with uncertain input parameters. Fuzzified inputs, the fuzzy rule base, which is constructed using objective and subjective definitional, causal, statistical, and heuristic knowledge, is able to present the problem in a user-friendly form. The complexity of the system can be managed by hierarchically-structured reasoning models, and if necessary, gained risk factor structure. Crisis or disaster event monitoring provides basic information for many decisions in today's social life.

The disaster recovery strategies of countries, the financial investments plans of investors, or the level of the tourism activities all depend on disaster different groups or crisis factors [3]. Transport problems constitute medullar in disaster management, especially in humanitarian logistic in which most of the problems involved could be addressed as transportation or travel problems. Disaster behaviour or travel behaviour after a disaster is an interesting topic less considered and that certainly contributes with society and environment.

On the other hand, cognitive mapping is an extraordinarily revealing window on a person's ability to cope with these problems. It also probes the subject's expertise and potential as a front-line emergency manager. As an exercise, it instructs trainee emergency managers and students of crisis management in the process of assessing the absolutely fundamental spatial dimension of disasters. An overall reasoning in this study presents that an extraordinary variety of spatial perceptions comes to the fore when many emergency managers are asked to assess the same situation.

This has implications for management strategies, as these will be influenced strongly by distance, space and place, by the time taken to assemble and deploy resources, and by the relative nearness or remoteness of critical sites, all of which are geographical problems. The results also have implications for emergency management training, in particular, that spatial cognition is a vital skill that should be developed along with others such as communication and decision-making.

12.1.3 *Case study*

In this work, FCMs constitute a good alternative to study individuals during their decision making process. A decision maker activates a temporary mental representation in his working memory based on his previous experiences or existing knowledge. Therefore, constructing a mental representation requires a decision maker to recall, reorder and summarize relevant information in his long-term memory. It may involve translating and representing this information into other forms, such as a scheme or diagram, supporting coherent reasoning in a connected structure.

When only taking into account real situations and the benefits people want to gain in certain decision, analysis will be only done in a non-depth mind level, results constitute useful, but more exploitation could certainly be done (see Figure 12.2). It is known that people are able to have deeper levels of reasoning, correlating their actions and goals, and to explore this as real as possible will guide us to a better representation of decision making process, specifically in Travel Behaviour research.

A study related to Travel Behaviour has been made in the city of Hasselt, capital of the Flemish province of Limburg, Belgium. The city has around 73 000 habitants, with a traffic junction of important circulation arteries from all directions. Hasselt made public transport by bus zero-fare from 1 July 1997 and bus use was said to be as much as "13 times higher" by 2010, being the first city in the world that had entirely zero-fare bus services on the whole of its territory.

Fig. 12.2 Human mind level abstraction.

The aim of this study is three fold: in one hand we used learning of FCMs as a predictive tool to explore the possible preferences of users giving certain circumstances, on the other hand, we used clustering algorithms as a descriptive tool to analyse different groups of users and understand the main features of choosing a transport mode. The results of learning will serve as a guide for transportation policy decision makers for future plans if, for example, one of the circumstances is changing, what are the most expected actions to be taken. Consequently, the results of FCMs clustering will help decision makers to program activities considering the specific needs of different groups of users. In addition, we explore how travellers' preferences are changing through different levels of information processing abstraction.

12.2 Modelling with Fuzzy Cognitive Maps

Firstly, in this section we introduce the main concepts and definitions of CMs/FCMs that we need as a theoretical base for the next chapters, then we detail the current approaches of using FCMs/CMs in transportation related topics. We summarize the application domains that use cognitive mapping in decision making process. Next, we briefly explain the main advantages of using CMs/FCMs as a modelling tool and we compare it with some other wide used techniques.

12.2.1 *Knowledge Representation with Fuzzy Cognitive Maps*

Cognitive Maps were first introduced by Axelrod [4] who focused on the policy domain. Since then many researchers have used CMs applying them in various fields where the problems are ill structured or not well-defined. The application areas of CMs or FCMs are very broad and diverse, and, in general, they can be used in different decision making problems such as failure system modelling, network security, electrical circuits, environmental management, information management, data mining, web mining, risk analysis and management, social sciences, health care and medical decisions, human reliability analysis, industry applications, etc. The reader can refer to [5] for the short description and references of mentioned fields in which FCMs have been applied.

Cognitive Maps have two types of elements: *concepts* and *causal beliefs*. The former are variables while the latter are relationships between variables. Causal relationships can be either positive or negative, as specified by a '$+$', respectively a '$-$', sign on the arrow connecting two variables. The variable that causes a change is called *cause variable* and the one that undergoes the effect of the change is called an *effect variable*. If the relationship is positive, an increase or decrease of the cause variable causes the effect variable to change in the same direction (e.g., an increase in the cause variable causes increase of the effect variable). In the case of a negative relationship, the change of the effect variable is in the opposite direction (e.g., an increase in the cause variable causes decrease of the effect variable).

Figure 12.3(a) shows a simple CM for the travel behaviour problem described previously. This example shows some of the concepts to decide which transportation mode is more comfortable: taking a bike or a car. Here only the change directions are shown; for example the increase/decrease of number of bags causes the decrease/increase of bike comfort: therefore the sign is negative. On the other hand, if we consider the causal relationship between bike infrastructure and bike comfort, the link is positive as the change in cause node changes the effect node in the same direction.

In his work Axelrod introduces also *Weighted* CMs and *Functional* CMs. In weighted CMs the sign in the map is replaced with a positive or a negative number, which shows the direction of the effect as well as its *magnitude*. In functional CMs a function is associated with each causal relationship showing more precisely the direction and the magnitude of the effect. These two types of CMs give more flexibility as they can handle and provide more detailed information.

However, CMs, whatever their type, are not easy to define and the magnitude of the effect is difficult to express in numbers. Usually CMs are constructed by gathering information from experts/users and generally, they are more likely to express themselves in qualitative rather than quantitative terms.

To this end, it may be more appropriate to use FCMs, suggested by Kosko [6]. Actually, FCMs are weighted CMs with fuzzy weights. The degree of relationship between concepts in an FCM is either a number in $[-1;1]$, or a linguistic term, such as *often*, *extremely*, *some*, etc. Figure 12.3(b) shows a simple example of FCM for the same problem where the causal relationships are expressed by using fuzzy linguistic terms.

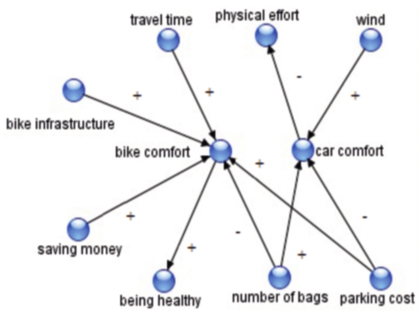

Fig. 12.3 (a) An example of a CM.

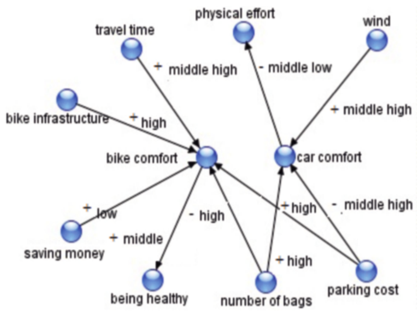

Fig. 12.3 (b) An example of an FCM.

For example, if we consider again the relationship between *bike infrastructure* and *bike comfort*, the increase/decrease of cause variable will cause high increase/decrease in effect variable. It is useful to mention that the nature of our data allowed us to model maps so that all links have only positive sign.

Note that each concept represents a characteristic of the system; in general it stands for events, actions, goals, values, trends of the modelled system, etc. In addition, each concept is characterized by a number that represents its value and it results from the renovation of the real value of the system variable [7].

Beyond the graphical representation of the FCM there is its mathematical model. It consists of a $1 \times n$ state vector A which includes the values of the n concepts and a $n \times n$ weight matrix (adjacency matrix) W which gathers the weights W_{ij} of the interconnections between the n concepts. The value of each concept is influenced by the values of the connected concepts with the appropriate weights and by its previous value. So the value A_i for each concept C_i can be calculated, among other possibilities, by the following rule (12.1):

$$A_i = f\left(\sum_{\substack{j=1 \\ j\neq i}} \left[A_j \times W_{ji}\right]\right) \tag{12.1}$$

where A_i is the activation level of concept C_i, A_j is the activation level of concept C_j and W_{ji} is the weight of the interconnection between C_j and C_i, it is to say, the value of A_i depends of the weighted sum of its input concepts, and f is a threshold or normalization function. The nonlinear function, f, can be a simple thresholding operation with a threshold value T resulting for example binary concept values.

To produce continuous concept values, a continuous-output transformation function may be used. The most widely used function is the sigmoid function. As for our application the links of FCMs have only positive signs, we choose the normalization function given below that fits our task the best (see (12.2) and Figure 12.4).

$$f(x) = \frac{1}{1+e^{-9(x-0.5)}} \tag{12.2}$$

Binary FCMs are suitable for highly qualitative problems where only representation of increase or stability of a concept is required, Trivalent FCMs are suitable for qualitative problems where representation of increase, decrease or stability of a concept is required, but Sigmoid FCMs are suitable for qualitative and quantitative problems where representation of a degree of increase, a degree of decrease or stability of a concept is required and strategic planning scenarios are going to be introduced.

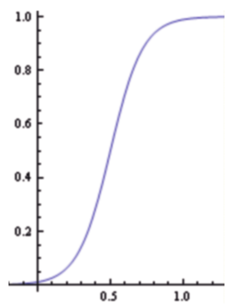

Fig. 12.4 The normalization function and its graphical representation.

So, the new state vector A_{new} is computed by multiplying the previous state vector A_{old} by the weight matrix W. The new vector shows (12.3) the effect of the change in the value of one concept in the whole FCM [8].

$$A_{\text{new}} = f(A_{\text{old}} \times W) \tag{12.3}$$

Some other notions that we use in the next chapters are introduced below.

The *conceptual centrality* of a node C_i is denoted by $CEN(Ci)$ and is

$$\begin{gathered}\text{CEN}(C_i) = \text{IN}(C_i) + \text{OUT}(C_i),\\ \text{where } \text{IN}(C_i) = \sum_{k=1}^{n} w_{ki} \text{ and } \text{OUT}(C_i) = \sum_{k=1}^{n} w_{ik}\end{gathered} \tag{12.4}$$

The *conceptual centrality* represents the importance of the node for the causal flow on the CM. A node C_i is called *transmitter* if $\text{IN}(C_i) = 0$ and $\text{OUT}(C_i) > 0$, and is called *receiver* if $\text{IN}(C_i) > 0$ and $\text{OUT}(C_i) = 0$. The total number of receiver nodes in a map is considered a *complexity index*. A large number of receiver variables indicate a complex map while a large number of transmitters show a formal hierarchical system where causal nodes do not collaborate with each other [9].

Among several ways of developing CMs and FCMs, the most common methods are:

- extracting knowledge from questionnaires,
- extracting knowledge from written texts,
- conducting interviews, and
- drawing maps from data.

To obtain a CM from questionnaires requires first to identify the most important variables for the given problem, and then to give experts ordered pairs of variables in a questionnaire format. Afterward, experts decide the strength of causal links relying on their knowledge and experience. The second method is a type of content analysis in which the causal relationships are identified by analysing texts. The main problem related to this method is that usually the relationships are not explicitly stated, and the language structure in which texts are written can vary from one language to another.

The detailed description of how to construct a map through interviews is provided in [9]. The methodology is composed by the following steps: to decide the most important variables, to provide experts with a sample map, unrelated with the problem at hand, and finally, to ask them to draw their own maps of the issue under investigation. The automatic construction of CMs (particularly FCMs) based on user provided data is discussed in [10].

This method first finds the degree of similarity between any of the two variables, then decides whether the relation between the two variables is direct or inverse, and with the use of a *fuzzy expert system tool* determines the causality among variables. Note that these methods can be used also in combinations, such as questionnaires with interviews. In the next section we discuss the data gathering approach that we followed in this study.

To have more realistic and reliable results, more than one expert participates in FCMs drawing or in knowledge acquiring process to construct FCMs. The group map can be generated based on individual maps.

This is one advantage of FCMs over other approaches like Petri Nets (PN) or Bayesian Networks (BN). PN are another graphical and mathematical modelling tool consisting of places, transitions, and arcs that connect them, that can be used as a visual-communication aid similar to flow charts, block diagrams, and networks. As a mathematical instrument, it is possible to set up state equations, algebraic equations, and other mathematical models governing the performance of systems.

It is well known that the use of PN has as a disadvantage the drawing process by a non-expert in this technique, that is the reason of having only a limited numbers of tools usable for this purpose, and it is not well established how to combine different PN that describe the same system.

BN is a powerful tool for graphically representing the relationships among a set of variables and for dealing with uncertainties in expert systems, but demanding effort caused by specification of the net (structure and parameters) and an expensive algorithm of propagation of probabilities. Also is not evident for a non-expert in this field how to construct a BN, and even more difficult how to compare or combine different BN that describe the same system.

Another observation that we consider important to mention is the fact that there are only few software tools developed with the intention of drawing FCMs by non-expert users with different backgrounds and technical knowledge, as FCM Modeler [11] and FCM Designer [12]. The first one is a simple incursion, while the second one is a better implementation, but still difficult to interact with and it does not have experimental facilities. In [13] a software tool is described with more functionalities; although it was conceived for general purposes, we have included special options and developed specific method to deal with data requirement used in the travel behaviour study.

12.2.2 *Cognitive Maps and Transportation*

In the previous sections we briefly mentioned the application fields of FCMs. Obviously, the application areas are diverse covering very broad range of domains. However, as far as we found, the links between CMs and travel behaviour is less well-developed. Specifically, research on CMs and travel focuses primarily, in fact almost exclusively on route choice. In contrast, the other steps such as trip generation (how many trips?), trip distribution (where to go?) have been given far less attention by cognitive mapping researchers [14].

So it is to the potential role of CMs in trip generation, trip distribution, and mode split we now turn. In [15] it is explained CM modelling to extract the mental representation of individuals in the decision making and planning of trips, related to daily travels.

Current opinion appears to indicate that, because factors such as CM ability, knowledge of feasible alternatives, navigation and way finding strategies, and preferences for path selection criteria all are presumed to have a substantial impact on travel choices, there is a growing need to include spatial cognition explicitly in models.

Cognitive mapping and travel behaviour research have centred on what is known about the location, possible destinations, and feasible alternatives for any choice affecting the network over which the traveling must take place [16]. The literature on household activity modelling, as a conceptually sound and robust way to predict travel behaviour than traditional travel demand modelling is large and increasing. Activity modelling could be enhanced significantly with better information on how modal experience shapes individuals' CMs.

In other words, the CMs of people who mostly walk and use public transit may vary systematically from those who are mostly chauffeured in private vehicles, and from those who usually drive [17]. This line of reasoning is consistent with research on job search behaviour among low wage workers. Those with regular access to private vehicles tend not only to search larger geographic areas work for work, but tend to perceive job opportunities in less spatially constrained ways.

In order to get rid of such cognitive barriers to job opportunities experienced by those without regular access to cars, compensatory solutions such as trip planning services, guaranteed ride home services, and overall improvements to transit service could be implemented.

Another means to compensate for limitations in individuals' CMs could be the dissemination of *Intelligent Transportation Systems* (ITS). Such systems reduce individuals' overall reliance on their own CMs potentially increasing access to known destinations. ITS would not influence necessarily how prior spatial knowledge informs the initial portions of travel behaviour sequence, trip generation and trip distribution [14].

Individuals would still rely on their CMs when choosing to make a trip and selecting a particular destination for that trip. Public transit planning could potentially benefit from CMs researches [2].

While researchers have recognized the connection between travel and spatial learning, little is known yet about how the existing transportation infrastructure itself shapes CMs and, in turn, affects route selection as well as other aspects of travel including trip frequency, trip purpose and destinations, and mode choice. However, the limited available research suggests that transportation infrastructure and, in particular, way finding on overlapping, yet distinct, modal networks, sidewalks, bike lanes, transit routes, local streets and roads, and freeway networks, affects the development of CMs and, in turn, travel behaviour.

12.3 Capturing individuals' mental representation: Automatic knowledge engineering and FCM modelling

Formalizing knowledge for Artificial Intelligence processing is of vital importance. In the *knowledge engineering process* after the variables selection that better describe the problem, and the interaction among them, it is necessary to construct abstract structures that facilitates the organization of the stored information, such a way that they can be interpreted by a computational technique [18], allowing the extraction of useful information, and even more: *knowledge*.

A cognitive model is an abstract structure containing all information related with visualization ideas that takes place in the decision making process [19], the following design is used in our approach:

- Personal information about individual: Useful for demographic processing and analyses, etc.
- Cognitive subsets: The variable interaction that takes place in the decision making process conduces the construction of related variables, such as "*situation-benefit-attribute*".
- Expert criteria: After defining all cognitive subsets the criteria of the individual is captured using artificial scenario. Situational variables are assigned with random states,

and the respondent specifies how much utility reports in that conditions, the use of *bus*, *car* or *bike*.

- Causal influences among variables: It is considered a causal relation among the variables that participate in the modelling of a cognitive subset, and the experts must express their opinions.
- Benefits importance: To all the benefit variables participating in the modelling it is assigned an importance level, experts give their criteria.

Definitely the informatics software products success depends on its architecture design and user interface flexibility, especially when the software product is an *Automatic Knowledge Engineer* [19], in this case generating individual mental representation for after forward processing. In order to achieve effective knowledge acquisition, a dynamically appearance according to the behaviour of the experts is required. This enables, among other things, to capture and formalize in the knowledge bases the relationships among the variables involved in their decisions, and the degree of causal influence. Thus, there is a mitigation of "*bottlenecks*" problem, typically in the *knowledge based systems* creation [20].

We have taken into consideration some features that are practically indispensable in the successful performance of the proposed application:

- wizard with non-fixed pages number generated taking into account previous expert elections (ensuring the dynamism of the application),
- randomly ordered variables lists (in case the users use to select the same variables according to their position in the lists),
- explanatory pages with detailed instructions that will guide the users with some flexibility (these messages and instructions are considered "sophisticated" as it is generated according to the individual respondent behaviour, using the natural language obvious advantages),
- detailed description of each variable when receiving the mouse focus.

In an imaginary case where an expert considers modelling his considerations, according to his own experience, the situational variable *Precipitation* will be the cornerstone of his decisions, the benefit variable *Physical comfort* describes the benefit that reports to the expert the selection of *Precipitation* variable and *Stay dry* characterizes the relationship between the two variables. Later, a list of imaginary scenarios (involving the chosen variables by an expert) is constructed to know the expert criteria under specific circumstances.

For a *No rain* state of the *Precipitation* variable, the respondent preferred *bike* for transportation, with less preference considers taking *bus* and finally private transport (*car*), because the benefit that brings his selection is the *physical comfort* and aims to *stay dry*.

Generally, a cognitive model contains instructions that define individual's mental representations in situations relating to travel behaviour, which the software generates to knowledge bases and can be summarized in four aspects:

- construction of the cognitive subsets,
- expert assessment by building scenarios,
- causal influence among the various categories of variables, and
- importance of the benefits involved in the model.

In the referred knowledge acquiring process, the developed Automated Knowledge Engineer codes in knowledge bases all information concerning the mental maps that take place in the experts who are in situations relevant to travel behaviour. However, the stored knowledge is worthless if it cannot be represented in terms of computational structures that enable further analysis, automated or not, but basically for simulations or predictions purposes that are useful to science and application area. The construction of FCMs from the knowledge bases generated by the Automated Knowledge Engineer helps to solve this problem.

To express the stored knowledge in terms of components that allow automatically building FCMs we identify three primary structures as part of cognitive models contained in the knowledge bases related to FCMs:

- Cognitive subsets: represent triplet concepts namely: situational-benefit-attribute, defining the structure of the map. The concepts for the decisions (Car, Bus, Bike) and for the final utility (Utility) are implicit concepts and mandatory for every cognitive subset. For example, for the cognitive subset Precipitation-Stay dry-Physical comfort, the topology of the resulting map is shown in Figure 12.5.
- Concept causal influences: values in the interval $[0,1]$ representing the causal influences among the variables of the cognitive subsets.
- Weights of the benefit variables involved in the problem (Ratings): represent a list of all weighted benefits with a value in the interval $[0,1]$. This value represents the impact of a benefit concept in the map.

One of the most important features of this topology is the fact that the concepts C_6 and C_7 are considered vectors variables and not linear ones, thus, allowing when running

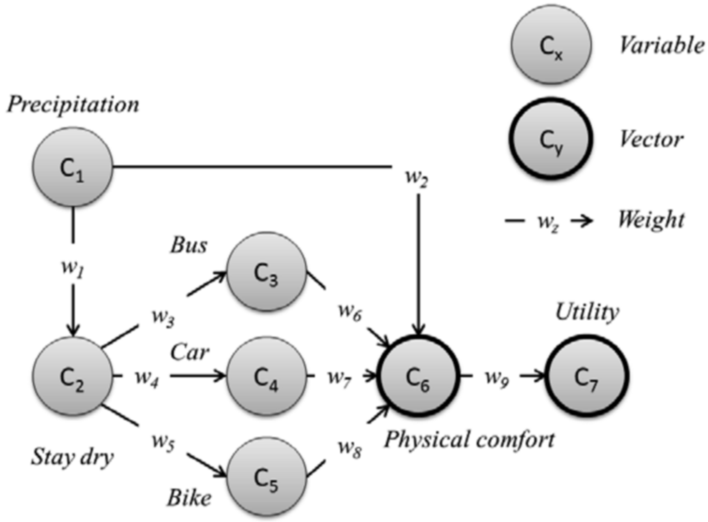

Fig. 12.5 General topology of a minimum FCM.

the inference process that only one of three decisions was active (property exclusivity in the decision node), so the final result of these concepts will be a three-dimensional vector (making an inference for each decision). This philosophy allows the utility calculation of each decision under specific circumstances.

12.4 A learning method for FCMs inspired on Particle Swarm Optimization

Problems associated with development of FCMs encourage researchers to work on automated or semi-automated computational methods for learning of FCM structures using mainly historical data. Semi-automated methods still require a relatively limited human intervention, whereas fully automated approaches are able to compute an FCMs model solely based on historical data. Researches on learning of FCMs models from data have resulted in a number of alternative approaches. One group of methods is aimed at providing a supplement tool that would help experts to develop an accurate model based on their knowledge about a modelled system. Algorithms from the other group are oriented toward eliminating human factor from the entire development process, only historical data are necessary to establish FCMs models. A number of algorithms for learning of FCM structure from data have been proposed. They can be categorized into two groups based on the learning paradigm used, i.e., Hebbian-based learners and methods based on evolutionary algorithms [21].

12.4.1 *Conception of the learning method using Particle Swarm Optimization*

Particle Swarm Optimization (PSO) method, which belongs to the class of Swarm Intelligence algorithms, can be used to learn FCMs structure based on historical data, consisting of a sequence of state vectors that leads to a desired fixed-point attractor state. PSO is a population based algorithm, which performs a search by maintaining and transforming a population of individuals [22]. This method improves the quality of resulting FCMs models by minimizing an *objective* or *heuristic function*. The function incorporates human knowledge by adequate constraints, which guarantee that relationships within the model will retain the physical meaning defined by experts. Figure 12.6 shows the main idea of the proposal.

Fig. 12.6 Using PSO for readjusting an FCM.

The flow chart illustrates the application of PSO in the readjusting of the weight matrix that characterized an FCM, trying to find a better configuration that guaranty a convergence or expected results. PSO is applied straight forwardly using an objective function defined by the user. Each particle of the swarm is a weight matrix, encoded as a vector.

First the concepts and relation are defined, and the construction of an FCM is made, and then is possible to make simulations and obtain outputs due to the inference process. If the new values are not adequate, known by the execution of the heuristic function, then it is necessary a learning process (in this case through the use of PSO metaheuristic) having as results new values for the weight matrix.

The heuristic function $h(x)$ will guide the search (12.5); the optimal case is when the new found causal matrix offers the expected output:

$$h(x) = \sum_{i=1}^{n} r_i(x) \tag{12.5}$$

where

$$r_i(x) = \begin{cases} A, & \text{ExpDecision}_i(x) = \text{InfDecision}_i(x) \\ c > 0, & \text{in other case} \end{cases}$$

$$A = \sum_{k=1}^{m} \left| \text{ExpDecision}_i(x) - \text{InfDecision}_i(x) \right|$$

where n is the number scenarios, m is the number of transport mode decisions, $h(x)$ means that the k^{th} decision of i^{th} scenario from map x according to the expert criteria (*ExpDecision*) is compared with the homolog k^{th} decision that is inferred by the map x (*InfDecision*) and its correspondent causal matrix w. We used $c = 30$ as this value was best fitting our data.

The pseudocode in Figure 12.7 displays the general philosophy of the proposed method. In this case genetic algorithm operators are used at initialization steps. Mixed approaches, like using Genetic Algorithm and PSO have been performed so far. Some results in the related literature are really promising and encouraging further researches and applications in this area. Using this approach, new zones of the search space are explored in a particular way, through the crossover of good initial particles and the mutation of some others, just to mention two possible alternatives.

As it is known, the optimization capability of PSO algorithm is quite sensitive to parameters, through experimentation some of them were deducted to best perform the task, but in general the tactic itself offered a good solution in finding a satisfactory solution, this according to the very complex explored search space.

12.4.2 *Implementing the learning method based on PSO for the FCMs readjustment*

A tool based on FCMs for the modelling of complex systems was developed, supporting facilities for the creation, definition of parameters and options to make the inference process more comprehensible, understanding and used for simulations experiments [23]. In the

```
Generate initial population using W_ij as initial approximation
Calculate initial evaluation
Cross over good particles
Mutation of selected particles
Initialize X_pbest with best solutions found by each particle
Initialize X_gbest as the best global found
Initialize W_max = 1.4, W_min = 0.4, c_1 = 2.05, c_2 = 2.05, k = 0.381966011
For t = 0 to N_generations
   w_k = (W_max − W_min) * ((N_cmax − t)/(N_cmax + W_min))
   For each X_i
      Calculate V_i(t+1) and limit to [−V_max, +V_max] using w_k
      Calculate X_i(t+1) = X_i(t) + k * V_i(t+1) and normalize
      Analyse the Swarm with X_i(t+1) and Speed with V_i(t+1)
      Evaluate the particle X_i(t+1)
      Analyse the vector X_pbest with the best solutions
      Update X_gbest with the best global particle
   endFor
endFor
```

Fig. 12.7 Pseudocode of the proposed method.

learning package, the necessary initialization of parameters is done through the window shown in Figure 12.8.

In simulation and experimenting in general, the visualization process is a fundamental aspect (that is why a panel was conceived where the learning progression can be observed, Figure 12.9 shows an example). It is possible to see how the FCM is updated with a new weight matrix that better satisfies the expected results.

12.4.3 *Validating learned structures against other approaches*

In Table 12.1 we detail the data organization for the statistic experiment, through a population comparison, to validate the performance of an FCM against other classical approaches such as Multilayer Perceptron (MLP), ID3 Decision Tree, or Naive Bayes (NB) classifier. The same knowledge had been modelled with these techniques. The idea is

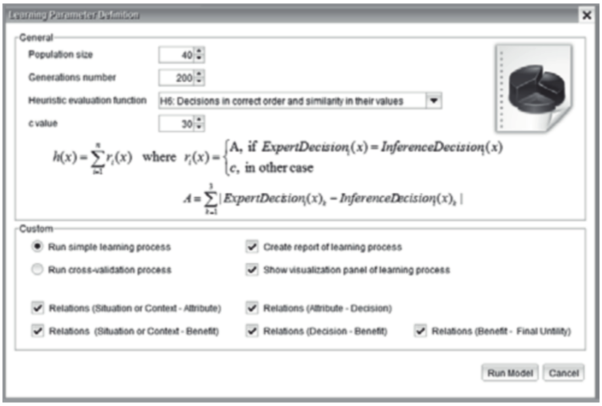

Fig. 12.8 Window for the PSO parameter specificatio12.

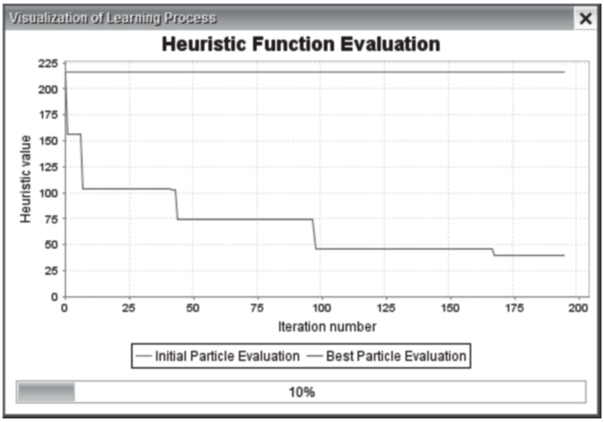

Fig. 12.9 Learning visualization panel.

to analyse the difference among their classification percentage (CP) obtained in a cross-validation process with 10-folds.

After applying Kolmogorov-Smirnov test and having a non-normal distribution in our data, we apply non parametric Friedman test, where a signification less than 0.05 suggests to reject main hypothesis, therefor we can conclude that it exists a significant difference among groups. Looking to the mean ranks, the best value is given to FCM, however, it is not possible yet to affirm that our technique performs better than the others.

Table 12.1 Data organization for processing.

	FCM	**MLP**	**ID3**	**NB**
Expert 1	CP_{FCM1}	$CP_{MLP\ 1}$	$CP_{ID3\ 1}$	$CP_{NB\ 1}$
Expert 2	$CP_{FCM\ 2}$	$CP_{MLP\ 2}$	$CP_{ID3\ 2}$	$CP_{NB\ 2}$
...	...	...	...	...
Expert 221	$CP_{FCM\ n}$	$CP_{MLP\ n}$	$CP_{ID3\ n}$	$CP_{NB\ n}$

It is important to mention that as the data reflects classification percentage, a higher value in the mean rank corresponds to a better performance. Using a Wilcoxon test for related samples it is possible to analyse per pairs, and in all cases the main hypothesis of the test is rejected and it is confirmed that there exists a significant difference between pairs. Summing up, FCMs offer better results than the other approaches.

Table 12.2 contains the average percentages. First the learning scenarios serve for training, then for calculating optimistic estimation (resubstitution technique, empirical error) of the convergence. The resubstitution test is absolutely necessary because it reflects the self-consistency of the method, a prediction algorithm certainly cannot be deemed as a good one if its self-consistency is poor.

Later, the testing scenarios were used to obtain a pessimist estimation (cross-validation, real error) of the convergence through a cross-validation process with 10-folds. A cross-validation test for an independent testing data set is needed because it can reflect the effectiveness of the method in future practical application. The prediction capability had been measured in the forecast of the first possible decision and in three decisions given by the experts.

A recent study in [24] reports that a pressing issue is that currently the most accurate automated methods for learning cannot scale problems exceeding "several dozens of concepts". In our case we have FCMs composed by more than 120 concepts; forthcoming a study about temporal and spatial complexity in our proposal will be issued.

An analysis about the advantages that our method has over the others is productive, thus we clarify that FCMs had a higher accuracy than other classical well-known techniques when predicting the best decision, in this case the transport mode selection or the whole preferences of a transport mode order. In one hand, the existing knowledge in the elaborated topology definitely provides benefit to the classification structure, together with the effectiveness in the learning method based on PSO, which also contributes in this task, consequently the learned FCMs gained in the performed comparison.

Table 12.2 Classification percentage per technique, experiment and model.

FCM	**MLP**	**ID3**	**NB**
FIRST DECISION			
Optimistic Model			
99.47	97.38	94.26	95.63
Pessimistic Model			
93.74	92.06	89.39	91.37
THREE DECISIONS			
Optimistic Model			
96.27	94.38	87.29	93.12
Pessimistic Model			
88.72	82.40	77.59	80.25

On the other hand, FCMs not only performed better, but also the most important is its capacity of presenting visual understanding information, combined with the classification skills, makes them seems a good approach for these kinds of tasks.

12.5 Clustering of Fuzzy Cognitive Maps

The aim of this section is threefold: first we refer to the existing approaches of similarity measurement algorithms of FCMs, second we detail the clustering method details, particularly we explain our approach to find the optimum number of clusters by using FCMs, and finally we analyse our results in the last subsection.

12.5.1 *The distance matrix of FCMs*

While there are many cases to use CMs or FCMs in different application fields, there are only few attempts to develop algorithms to compare CMs. Similar studies of finding the similarity between CMs are done in [25] and in [26]. First study is restricted only on similarity algorithm without further use of it for cluster analysis. Second study extends the similarity measurement of the first approach and, in addition, cluster analysis is provided. However there are some drawbacks of this study.

For cluster analysis *Ward linkage* method is applied which commonly uses *squared Euclidean distance* for similarity matrix calculation. In addition, the number of optimum clusters is not discussed; neither any validation method is applied for cluster analysis. An study of FCMs clustering is done in [27].

However, while the clustering based on map *structure* is comprehensive enough to be used for different application domains, the clustering based on map *content* is rather case specific and is restricted by principal component analysis.

Moreover, neither the weights of the links nor the links signs are not considered: thus the functionalities of CMs are not discussed fully in cluster analysis. Another study of clustering is done in [28]. This approach differs from previous ones as it clusters not FCMs into different groups but the nodes of an FCM. Similar approach of clustering the nodes into hierarchical structure is proposed in [29]. These last two studies are less relevant for us because of two reasons: first we already have structured representation of the nodes in our dataset, and, secondly, we are interested in FCMs clustering (not nodes clustering).

In general CMs/FCMs can be compared in two dimensions: comparing the content and the structure of each map. The content difference is associated with the differences in elements in both maps and the differences of the relationships between those elements. The structural difference, on the other hand, is associated with the varying complexity degrees of the maps structure. In our application we have hierarchical maps for all users therefore we will focus only on the content difference analysis.

In [25] three types of differences between two individuals (maps) are proposed:

- Existence or non-existence of elements: thus one expert considers certain element as important for the given domain; the other has the opposite opinion. In this case the adjacency matrix for the CM of the first expert contains the element/elements while the other matrix does not contain.
- Existence or non-existence of beliefs: thus one expert considers that there is a casual relationship between two concepts, while the other has the opposite opinion. In this case two experts should agree upon the fact that the nodes are important for the given domain, but have opposite opinions towards the causal link.
- Different values for identical beliefs: thus two experts agree that there is a relationship between two nodes, but one expert holds the belief more strongly than the other. In adjacency matrices this difference is expressed by non-identical nonzero values for the cell showing the causal link between two nodes.

In [26] the authors suggest an improvement of FCMs similarity measurement algorithm described in [25] mentioning that the algorithm does not consider the missing values properly as well as it lacks of *generalizability*. We will take into account only the comment about *generalizability*, and will adjust the algorithm to be applicable in our study.

Notice that by *generalizability*, we mean that in [25] the number of linguistic terms is fixed and the comparison formula cannot handle different number of linguistic terms. More specifically, the study fixed the number of linguistic terms to 7, assigning maximum strength to 3, minimum strength to −3, and consequently the similarity measurement algorithm cannot be applied for the cases with more/less linguistic terms. Therefore, for our task, we use the following (12.6) distance ratio (*DR*):

$$DR(u_A, u_B) = \frac{\sum_{i=1}^{p}\sum_{j=1}^{p}(a_{ij}^{*} - b_{ij}^{*})}{2p_c^2 + 2p_c(p_{u_A} + p_{u_B}) + p_{u_A}^2 + p_{u_B}^2 - (2p_c + p_{u_A} + p_{u_B})} \tag{12.6}$$

where

$$m_{ij}^{*} = \begin{cases} 1, & \text{if } m_{ij} \neq 0, \text{ and } i \text{ or } j \notin P_c \\ m_{ij}, & \text{otherwise} \end{cases} \tag{12.7}$$

In (12.6), a_{ij} and b_{ij} are the adjacency matrices of the first and second map respectively, p is the total number of possible nodes, p_c is the set of common nodes for both maps, p_c is the number of such nodes, is the number of nodes unique to user u_a/u_b respectively. In (12.7) m_{ij} is the value of the i^{th} row and j^{th} column in the zero augmented adjacency matrix of any of two maps.

12.5.2 *Hierarchical clustering of FCMs*

The aim of this section is to use cluster analysis as a descriptive tool to group travellers and analyse each group finding similarity in people thinking in making a decision about some transport mode. The understanding of travellers' behaviour tendencies will help policy makers in more realistic assessment when some concepts are changing over the time.

As we have already mentioned in the previous chapters, we have 221 users from the city of hasselt who were asked to choose the most important variables of some transport mode choice. In addition different scenarios have been developed and asked users to provide their choice according to the circumstances in a scenario. The nodes in FCMs are divided into three groups: *benefit* nodes, *situation* nodes and *attribute* nodes. A traveller chooses the main benefits of choosing a particular transport mode depending on the situation and the attributes related with that situation.

For example, consider the set {*situation, attribute, travel mode, benefit*} with the following nodes in each set respectively {*car availability*}, {*flexibility, independency, travel time, speed*}, {*car, bike, bus*}, {*convenient, freedom*}. Here the *car availability* is a node showing the situation which is related with attributes such as *flexibility, independency, travel time, speed*. The main benefits of choosing one out of three transport modes are *convenient, freedom*. The expected results of cluster analysis will help the transportation policy decision makers to understand which group of people has the inclination of which benefits, and what the situations leading to the chosen benefit are.

In general cluster analysis is an unsupervised learning method to examine the dataset by dividing it into the groups so that the similarity within the clusters and dissimilarity between different clusters are maximized. Cluster analysis methods have been applied in different fields such as engineering, social science, medical sciences, economics etc. The detailed description of all clustering techniques is out of scope of this paper. The interested reader can refer to [30] and [31].

In the previous subsection we presented the distance ratio algorithm to find the distance between two FCMs. There are two wide used clustering techniques based on similarity or distance measurements: the hierarchical approach and the partitional approach (e.g. K-means). Hierarchical clustering algorithms produce a nested series of partitions based on a criterion for merging or splitting clusters based on similarity. Partitional clustering algorithms identify the partition that optimizes a clustering criterion.

The preference of one approach over another depends on the task on hand and on the main goal of the study. As in our case we do not know the number of clusters in advance and we do not have time complexity issue for the maps in our dataset we prefer using hierarchical clustering.

The most wide used linkage methods are single, complete and ward linkage methods [30]. Ward method is not efficient for our study as we do not use euclidian distance for similarity measurement. To cluster FCMs the single-linkage method takes the distance between two clusters as the minimum of the distances between all pairs of maps from the two clusters. On the other hand, the complete-linkage algorithm calculates the distance between two clusters as the maximum of all pairwise distances between maps in the two clusters.

Single linkage suffers from a chaining effect producing elongated clusters. The study in [30] shows that complete linkage produces more compact and more useful hierarchies in many applications than the single-linkage algorithm. Besides to decide which algorithm best suits our data, we calculated the *Cophenetic Coefficient* (CC) for single, complete, weighted, average, ward and centroid methods.

Note that the CC shows how strong the linking of maps in the cluster tree has a correlation with the distances between maps in the distance vector. This coefficient usually is used to compare different linkage methods. The closer the CC to one the more accurately the clustering solution reflects the data. For our dataset, the results of CC calculation show that complete and centroid methods are the best for our data as they gave maximum values for CC. However, the centroid method also suffers from chaining effect, and the best option that we used for our cluster analysis is complete linkage.

12.5.3 *Finding the optimum number of FCMs clusters*

After clustering of FCMs there are several important questions to be considered: How good is the clustering? What is the optimum number of clusters? Or what are the main patterns to be explored in the clusters? In this section we discuss the optimum number of the clusters and we propose the adjustment of well-known *Davies-Bouldin Index* (DBI). The results are twofold: first we find the optimum number of clusters; second, we use the *concept of central map* to analyse the clusters separately.

There are several cluster validity indexes that lead to the decision of the optimum number of clusters. We will explore two of them only, namely the *Silhouette index* (SI) and DBI [32], [33]. We compare the results of SI and the proposed extension of DBI index.

For each sample in a cluster the SI assigns a confidence value showing how good the sample has been classified. The SI for i^{th} sample in cluster X_j ($j = 1,\ldots,c$) where c is the number of clusters is defined as follow in (12.8).

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \tag{12.8}$$

where $a(i)$ is the average distance between i^{th} sample and all other samples included in X_j, $b(i)$ is the minimum average distance between and all samples in cluster X_k ($k = 1,\ldots,c$; $k \neq j$). The closer $s(i)$ to 1 the better the i^{th} sample assigned to its cluster. The cluster Silhouette index which shows the heterogeneity and isolation properties is defined as follows in (12.9).

$$S(j) = \frac{1}{m}\sum_{i=1}^{m} s(i) \tag{12.9}$$

To find the optimum number of clusters the average value of $S(j)$ is calculated for different number of clusters, and the one with maximum value is taken as the optimum number. As SI, DBI also aims to find the optimum number of clusters. DBI is defined as follows in (12.10).

$$DBI = \frac{1}{c}\sum_{i=1}^{c}\max_{i\neq j}\left\{\frac{\Delta(X_i)+\Delta(X_j)}{\delta(X_i,X_j)}\right\} \tag{12.10}$$

where $\Delta X_i/\Delta X_j$ is the average distance of the samples in $i^{\text{th}}/j^{\text{th}}$ cluster to centre of the cluster, $\delta(X_i,X_j)$ is the distance between the centres of the i^{th} and j^{th} clusters. The cluster configuration minimizing DBI is takes as an optimum number of clusters. As we are clustering FCMs, we adjust DBI to be applied for FCMs. We first derive a central map for each cluster, then calculate the distance of each map in a cluster from its central map, the distance between the central maps of different clusters and derive BDI index defined above.

To find the central map first we do some observations about the structure of the maps that we have for our task. As all the maps in our dataset have the same hierarchical structure, some nodes are only transmitters (situation nodes), some are only receivers, and some others are both transmitters and receivers. For each node we compute the conceptual centrality as in explained before.

A node is included in the central map if it exists in more than half on maps of a cluster. The weights of the links are calculated as the average value of the weights from all maps that contain both nodes that comprise the link. Once we have all central maps of all clusters we calculate BDI for different number of clusters to find the optimum number of clusters. Note that once we identify the number of clusters, we use central maps for further analysis of each cluster.

In the next section we show the results explained here and above sections about clustering of FCMs.

12.5.4 *Cluster estimation and validation*

In this section we explain the results of cluster analysis implemented in Matlab environment. The dendrogram in Figure 12.10 illustrates the arrangement of the clusters produced by Equations (12.6) and (12.7) for distance matrix and complete linkage for inter-cluster distance. Note that we also tested other linkage methods on our data set. However, the results were not satisfactory as the resulted clusters were not compact as some of the clusters had only few maps while the others were with very big size.

To find the optimum number of clusters we calculated the SI for ten clusters as shown in Table 12.3. Moreover, we derived also DBI for ten clusters first finding the central maps for each cluster configuration. The optimum number of clusters with both SI and DBI is found equal to six (see Figure 12.11) with 15, 53, 33, 23, 59 and 38 maps in each cluster

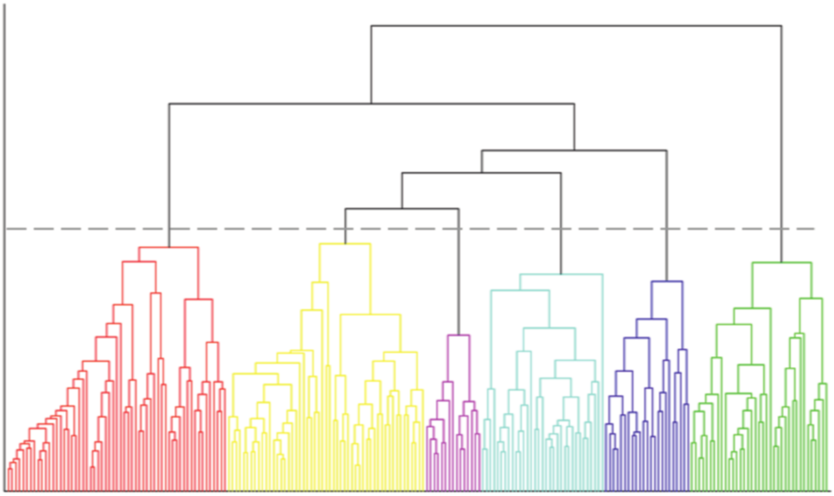

Fig. 12.10 The clustering results' interpretation with a dendrogram.

respectively. After finding the optimum number of clusters, we first analyse "situation-benefit-attribute" sets for each cluster, afterwards, we analyse the demographic features of the clusters.

Due to that we use central maps that we derived for DBI: thus, we have six maps representing each cluster. For demographic analysis we take into consideration the users' age, gender, income, household size, education level, occupation, parking type (paid or free), bike ownership, number of owned cars and having a bus card. The results of chi-square test indicate that some of these variables namely the income, occupation, bus card, parking availability and number of cars are dependent variables.

In the next section we explain each of six clusters in more details in terms of maps structure, nodes, links as well as demographic features of the users in each cluster.

12.6 Clustering and learning: digging deeper into individuals mental maps

As we have already mentioned in the previous chapters, we used learning and clustering of FCMs as predictive and descriptive tools to analyse the preferences of travellers, different travellers groups under certain situations corresponding to different scenarios. In addition we can use clustering and learning results to analyse the users decision making preferences in the different levels of abstraction. Particularly if we analyse clustering with

Table 12.3 SI for different clustering configurations.

Cluster Number	S	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
2	0.354	0.342	0.367								
3	0.389	0.449	0.376	0.342							
4	0.555	0.535	0.392	0.449	0.472						
5	0.612	0.768	0.659	0.435	0.648	0.552					
6	0.829	0.848	0.734	0.868	0.735	0.948	0.842				
7	0.707	0.789	0.633	0.748	0.634	0.868	0.535	0.742			
8	0.524	0.652	0.518	0.489	0.473	0.571	0.456	0.678	0.357		
9	0.529	0.491	0.632	0.352	0.418	0.691	0.548	0.468	0.435	0.342	
10	0.419	0.461	0.515	0.591	0.422	0.252	0.318	0.389	0.448	0.368	0.435

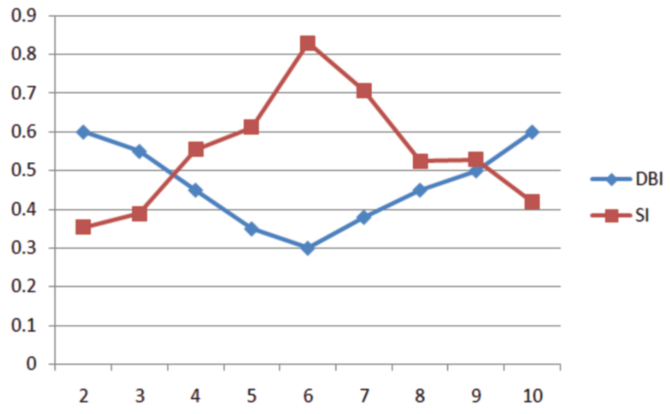

Fig. 12.11 SI and DBI values for different number of clusters.

maps before learning, we will obtain the groups of people that are similar to each other in their initial mental representation of transport mode choice. Figure 12.12 shows the general overview of our approach of using clustering and learning of FCMs to analyse users' preferences in different stages of reasoning.

If we go further and provide more information to the users about different scenarios and ask them to evaluate their behaviour in different circumstances, we will acquire deeper knowledge representation. In this section we analyse the results of clustering of user provided FCMs before learning and after learning: thus we investigate their preferences and similarities when they choose only the nodes and the weighted links (first case) and when in addition they evaluate also different scenarios (second case).

Fig. 12.12 Decision making analysis procedure.

As we have already stated in the previous section, we obtained six different clusters when we take the user provided maps, while after learning the maps and clustering them, we get only four clusters. Figure 12.13 (the width of the relations corresponds to the frequency of links evaluation by group members) shows two central maps of two clusters out of six clusters while Figure 12.14 shows two central maps of clusters out of four learnt maps clusters. For simplicity of the map visualization we omit the three decision nodes and the final utility node.

Before learning of FCMs the travellers are grouped as follows (for simplicity we do not show all six central maps):

- In the first group are young travellers (less than 30 years old), with medium income (from 2 000 to 4 000 Euros) having more than two cars and a small household size (living alone or in two). This group is the most homogenous in terms of their preferred nodes and evaluated links: thus there are not links or nodes that are chosen only by few members of the group. The main benefits combining the travellers in this group is normally their desire to be free while traveling, to have convenience, paying attention on the required time and effort of a specific travel mode. The attributes that they consider

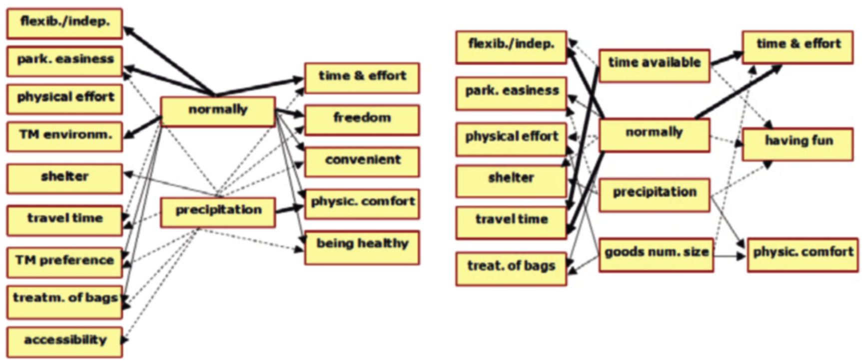

Fig. 12.13 Central maps of two different clusters before maps learning.

as very important for chosen benefits are the travel time as well as the flexibility and independence. In addition they take into account also the travel time, the treatment of bags; mental effort needed and direct traveling possibility.

- In the second group are older-retired people (more than 60 years old), having only one car, with household more than two persons and who mainly use paid parking. This group has most of the preferences as the previous one, in addition users in this group pay more attention on physical comfort, easiness of parking, physical effort, and the situation precipitation taking into account the shelter availability as well as the reliability of a transport mode under the chosen situation variables.
- In the third cluster are grouped the travellers having more than 40 years old who are either employed or retired, with high income (more than 4000 Euros), using mainly the paid parking. The preferences of this group are very similar to the second group with the difference of choosing a benefit being healthy, convenience and paying no attention on reliability. Actually, this group and the previous one are in the same cluster after learning of maps (shown in left of Figure 12.13).
- The fourth group is different from previous ones (shown in right of Figure 12.13). In this group mainly are students and young employers with medium or high income, and they mainly use free parking. There is one benefit variable unique to this group: having fun. Another difference with respect to the other groups is the set of situation variables that the group chooses in making a decision of a transport mode. Namely the group considers the situations related with precipitation, number and size of the goods purchased, as well as the available time.

- The fifth group clusters the travellers with low education, high income preferring not to provide information about their income and declaring themselves as unemployed. This group has a unique benefit variable that is the assurance and certainty related with their decision. The unique situation that the group considers and other groups do not, is the availability of parking and some attributes that the group considers as important are the reliability, accessibility, travel time, transport mode preference, etc.
- The last group is the only group that gives importance to safety and security, saving money, and the traveling cost Here travellers have low education, low income (less than 2 000 Euros), mainly students and unemployed or retired with small household.

These were the preferences of users when they choose the variables and the links between variables that they consider important for travel decisions. However, these preferences are changing when users are provided more information in terms of different possible scenarios. Indeed, in different levels of information, knowledge and experience people tend to act differently, in the beginning it is more reactive response, than with deeper understanding and analysing gives more situational awareness leading to more rational decisions.

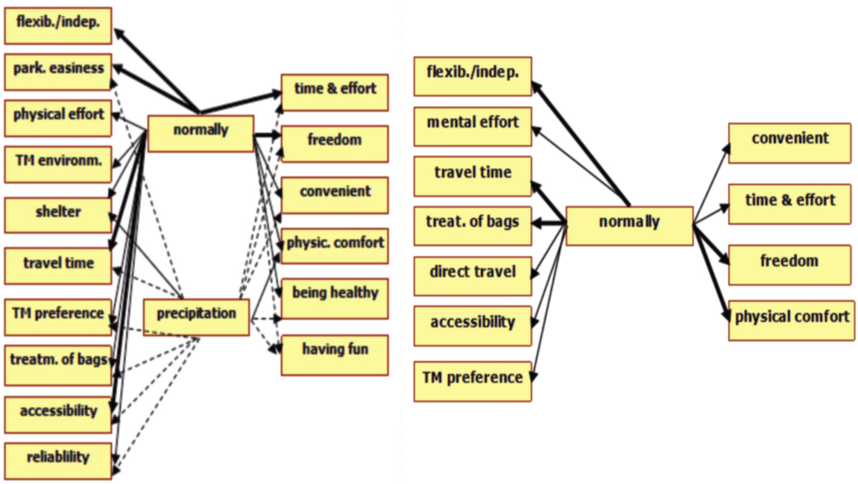

Fig. 12.14 Central maps of two different clusters after learning of maps.

For example, in our case study we found that in the beginning a group of travellers consider the cost and saving money as important factors for traveling decision. However, with awareness of different circumstances and scenarios, their preferences towards the mentioned factors are decreasing. Therefore, the travellers with these preferences (the sixth cluster described above) are distributed among other clusters: thus only four cluster groups have been identified with adjusted maps after applying PSO learning algorithm.

As a concluding remark, one should notice that for policymakers it is important to distinguish in which case they have to refer to the initial clusters and when to the clustering of the adjusted maps. Clustering of learnt maps takes into account different scenarios; therefore it gives more comprehensive view of traveller's subconscious decision making preferences. Consequently, policymakers can refer to these clustering results when the task is related with a complex policy testing.

On the other hand, the clustering of non-learnt maps can be used when testing new policies related with simpler measures.

12.7 Conclusions

In this study we proposed FCMs as a modelling tool to analyse the behaviour of complex systems, where it is very difficult to describe the entire system by an accurate mathematical model. Consequently, it is easier and practical to represent it in a graphical way showing the causal relationships between concepts. Since this symbolic method of modelling and control of a system is easily adaptable and relies on human expert experience and knowledge, it can be considered intelligent.

As a case study we discussed the travel behaviour and we analysed the main concepts that affect on the travellers choice of a specific transport mode such as car, bike or bus. We explored the learning and clustering algorithms for FCMs to offer policymakers a framework and real data to play with, in order to study and simulate individual behaviour and produce important knowledge to use in the development of city infrastructure and demographic planning. We used clustering and learning of FCMs to give deeper inside of travellers mind while taking a decision of a transport mode.

We showed the benefits of the application of a learning method inspired in the PSO metaheuristic, obtaining an improvement on the knowledge structures originally modelled. It is an unsupervised weight adaptation methodology that have been introduced to fine-tune FCM causal links and accompanied with the good knowledge of a given system or process can contribute towards establishment of FCMs as a robust technique. Experimental results based on simulations verify the effectiveness, validity and advantageous behaviour of the proposed algorithm. The area related to the learning of FCMs is very promising because the FCMs obtained are directly interpretable by humans, representing useful tool to extract information from data about the relations among the concepts or variables inside a domain.

The clustering results can be used by policy decision makers to analyse the preferences of different groups of travellers in terms of their preferred benefits, situation and attribute variables. We use the concept of a central map as a representative for each group and obtained central maps with both initial maps and maps after applying the PSO learning algorithm. The comparison of two clustering results shows that travellers change their preferences while providing more information of different scenarios.In keeping with a more rigorous approach, future work should attempt to probe the backgrounds, experience and knowledge of participants rather than merely to analyse the resulting maps. This would also require the investigator to monitor participants' general performance in emergency management courses more closely and to relate this quantitatively to the attributes of their emergency maps. Moreover, there are unresolved issues about how much prior experience and knowledge the emergency manager would normally have of the geographical area in which the disaster takes place. In this respect the present exercise is merely a pilot study: the paper therefore serves as a preliminary attack of an interesting problem about which there is much more to learn.

As a future extension of this study, it could be interesting to explore an approach where first clustering is executed and one map represents each cluster (the central one or an aggregation of all maps), so the learning process can be done for this structure but considering all scenarios of the maps included in the cluster. A current work dealing with this approach is in progress, and results of different approaches will be reported to community.

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Chapter 13

Fire and explosion safety assessment in container line supply chain

Yu-wang Chen [1], Dong-Ling Xu [1], Jian-Bo Yang [1], and Dawei Tang [2,*]

[1] *Manchester Business School, the University of Manchester, Manchester, UK, M15 6PB*
[2] *Safety and Environment Assurance Center, Unilever Colworth, Colworth Science Park, Sharnbrook, Bedfordshire, UK, MK44 1LQ*

[*] *dawei.tang.wh@gmail.com*

Safety assessment is an important part of maritime safety analysis and management as it can provide decision support to safety-based operations. In this chapter, we first review fire and explosion safety related regulations and assessment approaches, and then present a hierarchical assessment framework for evaluating safety against fire and explosion hazards in container line supply chain (CLSC). Main criteria and factors influencing fire and explosion safety on containerships are investigated, and a safety modeling and synthesis method using the Evidential Reasoning (ER) approach is briefly discussed. The outcomes generated by the proposed safety assessment method are highly consistent with "goal-setting" safety regulations.

13.1 Introduction

Container line supply chain (CLSC), which transports cargo efficiently across seas and into ports throughout the world, has contributed significantly in facilitating global economic development and prosperity. Approximately 90 percent of world trade moves in shipping containers, and over 250 million containers are transported annually (RAND, 2003). However, due to its characteristics of having complex physical and information flows, CLSC is also highly vulnerable to many possible undesirable accidents such as machinery failure, contact, collision, fire and explosion, grounding, etc. (EMSA, 2008; MAIB, 2008). Among these "major accidents hazards", fire and explosion may be one of the most dangerous hazards with the potential to cause disastrous consequences (Wang, 2002). For example, on March 21, 2006, M.V. Hyundai Fortune, a 64,054 gt. Panama flag contain-

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ership, was severely damaged in an accidental fire and explosion in aft on-deck container stacks and eventually abandoned after efforts to contain the fire failed. Besides the potential disastrous consequences, MAIB (Marine Accident Investigation Branch) statistics indicate that about 12% accidents of UK merchant vessels ($\geqslant 100\,\text{gt}$) from 1997 to 2009 were caused by fire and explosion hazards as shown in the following Fig. 13.1 (MAIB, 2008).

[redacted]

Fig. 13.1 Statistics on accidents of UK merchant vessels

In response to the fact that CLSC is a dominant way to transport cargo but highly vulnerable to fire and explosion hazards, in past decades a set of regulations were issued by ISO (International Standard Organisation), IMO (International Maritime Organisation), UK HSE (Health & Safety Executive), etc. Meanwhile, a number of safety assessment approaches, such as Quantitative Risk Analysis (QRA) and Formal Safety Analysis (FSA), have been widely used to assess the safety levels corresponding to various hazards in maritime transportation (Wang, 2001). However, limited work has been carried out specifically on the fire and explosion safety assessment in CLSC. In this chapter, a well-structured assessment framework is proposed to assess safety against fire and explosion hazards in CLSC. The rest of this chapter is organised as follows. A brief review of safety-related regulations and assessment approaches is provided in Section 13.2. A hierarchical assessment framework for evaluating safety against fire and explosion hazards in CLSC is presented and a safety modeling and synthesis method using the Evidential Reasoning (ER) approach is briefly discussed in Section 13.3. Conclusions are drawn in Section 13.4.

13.2 Review of safety-related regulations and assessment approaches

Safety is very important in CLSC. Any disruption or damage on CLSC caused by accidents may result in non-availability of goods at the expected time and place, and in the expected conditions. It can further incur economic losses and damage credibility with investors and other stakeholders. Traditionally, the safety strategies of maritime transpiration and offshore installations over hazards are completely relied on ISO, IMO and classification society regulations (HSE, 2001). These regulations are usually guided by expert judgments responding to serious marine accident experience.

Internationally, IMO SOLAS (International Convention for the Safety of Life at Sea) specifies detailed fire safety provisions for all ships and specific measures for cargo ships (IMO, 2000).

In the UK, PFEER (Offshore Installations - Prevention of Fire and Explosion and Emergency Response Regulations) provides general requirements for preventative and protective measures to manage fire and explosion hazards, to secure effective emergency response, and to ensure compliance with regulations (HSE, 1995); UKOOA (Offshore Operators Association) fire and explosion guidance provides an integrated approach to the management of fires and explosions (UKOOA, 2003).

On the basis of safety related regulations, many typical safety assessment approaches have also been widely applied to the evaluation of likelihood and consequences of hazards, such as Fault Tree Analysis (FTA), Failure Modes, Effects and Criticality Analysis (FMECA), QRA and FSA (HSE, 2001). QRA is a complicated technique for risk assessment, and its frequency analysis and consequence modeling methods have been successfully applied to the risk management of fires and explosions (Franks, 2000; Vinnem, 2007). FSA is probably the most formal and comprehensive framework for general risk management in the field of maritime safety (Wang, 2001; HSE, 2002). It was first developed by the UK Maritime and Coastguard Agency (MCA) and later incorporated into the IMO interim guidelines for safety assessment. The approach mainly consists of five steps: (1) hazard identification, (2) risk assessment, (3) risk control options, (4) cost-benefit analysis, and (5) decision making.

Despite the variety of safety assessment approaches, FSA and other conventional assessment techniques only provide an assessment process instead of a well-structured assessment framework. Furthermore, these approaches are not designed to specifically address fire and explosion safety issues in CLSC.

13.3 Fire and explosion safety assessment

To improve safety against fire and explosion hazards in CLSC, safety assessment framework needs to be developed on the whole CLSC level. Generally, CLSC can be characterized by the following physical stages: shipment consolidation, inland transportation, port of loading, maritime transportation, port of unloading, inland transportation, shipment deconsolidation (as shown in Fig. 13.2).

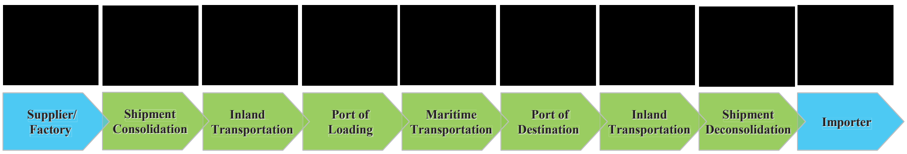

Fig. 13.2 Typical physical stages in CSLC

Internal vulnerability exists at each element of each stage. Thus many factors may influence the safety of CLSC. Basically, we can classify those factors into different categories. Thus, at each stage, a hierarchical structure with all contributing factors can be constructed to assess safety against fire and explosion hazards.

13.3.1 *Assessment Criteria Hierarchy*

In the framework, the safety level against hazard-based risks is modeled by three basic parameters, namely *occurrence likelihood*, *probability of occurrence of potential consequence*, and *potential consequence*. The evaluation of these three parameters can be further decomposed into the assessment of contributing factors as shown in Fig. 13.3. To evaluate *occurrence likelihood* of fire and explosion events, we need assess the inherent features of cargo and a containership and prevention measures. To evaluate *probability of occurrence of potential consequence*, we need assess detection, control, mitigation measures and recovery difficulty. *Potential consequence* can be evaluated by potential losses to people, property, environment and business systems.

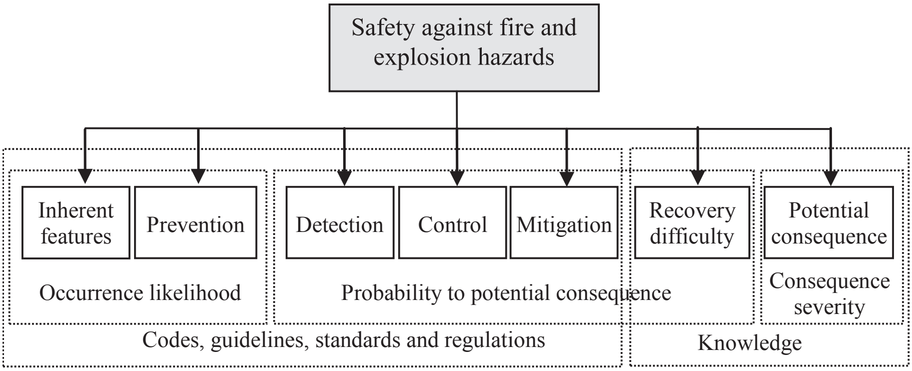

Fig. 13.3 Assessment criteria hierarchy of fire and explosion safety

It is worth noting that the performance standards of inherent features, prevention, detection, control and mitigation measures can be learnt from fire and explosion safety related codes, guidelines, standards and regulations, and recovery difficulty and potential consequence can be assessed by using experts' knowledge and historical accident data. As a case study, in the following we briefly discuss the main factors influencing the safety against fire and explosion hazards on containerships.

(1) Occurrence likelihood

The occurrence likelihood defines the probability that a fire and explosion event occurs onboard a containership.

- Inherent features include flammable and explosive characteristics of cargo (particularly for dangerous goods and hazardous substances, e.g., oils, chemicals, acids, flammable solids, substances liable to spontaneous combustion, substances which can emit flammable gases on contact with water, etc.), and inherent fire and explosion safety of the containership (e.g., basic structure and layout, ventilation system of machinery spaces, etc.).
- Preventative measures, including managerial, operative and technical measure, are the most effective means to minimise the occurrence likelihood of fire and explosion events and its associated risks. The performance of preventative measures can be evaluated by design measures, procedural controls, early warning systems, and prevention and protection systems.

(2) Probability of occurrence of potential consequence

This basic parameter represents the probability that potential consequence happens, given the occurrence of a fire and explosion event. It is affected by detection, control, mitigation measures and recovery difficulty.

- Detection measures can reduce undesired consequences of fire and explosion events by detecting and locating fires and alerting the navigation bridge and fire teams. Generally, the detection system is installed to transmit information to control points. Its performance is determined by automatic sprinklers, fire detection and alarm systems, and fire patrols.
- Control measures can limit the scale, intensity and duration of potential consequence. If a fire or explosion event happens, the containership has the capability of limiting the fire growth within every space by fire-extinguishing systems and fire brigade.
- Mitigation measures are deployed to mitigate the effects of fire and explosion events, including emergency training and drills, life-saving appliances, emergency instructions, and communication systems. For examples, it is required that at least one escape route must remain available during and after a fire and explosion event.
- Recovery difficulty is characterized by those activities that are needed to provide initial recovery and to provide the basis to facilitate long-term recovery activities, e.g., cargo replacement and ship repair, and support the resumption of trade within accident areas (those areas directly impacted by the effects of the accident) and non-accident areas (those areas indirectly affected by the consequences of the accident) (DHS, 2007).

(3) Potential consequence

The potential consequence describes the magnitude of possible consequence. It can be evaluated on the following dimensions:

- Human cost (e.g., physical and psychological harm to people, human death)
- Property damage (e.g., damage on cargo and containership, property losses)
- Environmental damage (e.g., environmental pollution, pollution on ecosystem)
- Losses to business systems (e.g., corporate image cost, economic losses to the community)

To assess the potential consequence of fire and explosion events, a fire and explosion scenario with a specific set of conditions usually needs to be defined.

13.3.2 *Subjective safety modeling and synthesis*

In safety analysis, the assessment of each contributing factor can be described by subjective linguistic variables. For example, one may often use such evaluation grades as "*catastrophic*", "*critical*", "*marginal*", and "*negligible*" to evaluate the parameter of *potential consequence (PC)*. In addition, uncertainties are always associated with maritime safety assessment due to lack of reliable assessment data and lack of confidence. As such, a belief structure (Yang and Singh, 1994) can be applied to model the subjective safety assessment with uncertainty. For example, the subjective safety description $S(PC)$ can be expressed in the following form:

$$S(PC) = \{(\beta_{1,PC}, \text{catastrophic}), (\beta_{2,PC}, \text{critical}), (\beta_{3,PC}, \text{marginal}), (\beta_{4,PC}, \text{negligible})\}$$

where $\beta_{i,PC}$ ($i = 1,\ 2,\ 3$ or 4) represents the extent to which PC is assessed to the ith subjective expression.

In the assessment criteria hierarchy, the safety level on a general or higher level criterion y is usually evaluated on the basis of evidence information collected from the bottom level safety factors. It is therefore important to synthesize the safety assessment information on the bottom level safety factors in a rational way so as to obtain the safety assessment of the whole CLSC. The following Evidential Reasoning (ER) approach can be employed to synthesize the subjective assessment information represented by the belief structures (Wang, 2000; Liu *et al.*, 2008).

Suppose there are L basic safety factors associated with assessing a general safety criterion y in the criteria hierarchy. We can define a set of basic factors as follows:

$$E = \{e_1, e_2, \ldots, e_i, \ldots, e_L\}$$

Suppose the weights of the basic factors are given by $w = \{w_1, w_2, \ldots, w_i, \ldots, w_L\}$, where w_i is the relative weight of the ith factor e_i with $0 \leqslant w_i \leqslant 1$. The weights of the basic factors may be estimated using some existing methods such as simple rating and pairwise comparison methods. Further, suppose N mutually exclusive evaluation grades H_n ($n = 1, \ldots, N$) can be defined as a complete set of standards for assessing a basic safety factor. In the assessment of potential consequence as discussed above, H_n represents a set of four linguistic variables. Therefore the assessment on the safety factor e_i ($i = 1, \ldots, L$) may be represented as the following belief distribution:

$$S(e_i) = \{(H_n, \beta_{n,i}),\ n = 1, \ldots, N\}, \quad i = 1, \ldots, L$$

where $\beta_{n,i} \geqslant 0$, $\sum_{n=1}^{N} \beta_{n,i} \leqslant 1$, and $\beta_{n,i}$ denotes a degree of belief. The above distributed assessment represents that the factor e_i is assessed to the grade H_n with the degree of belief of $\beta_{n,i}$, $n = 1, \ldots, N$.

Let β_n be a degree of belief to which the general safety criterion y is assessed to the grade H_n. Thus β_n $(n = 1,\ldots,N)$ can be generated by aggregating the assessments for all the basic safety factors e_i $(i = 1,\ldots,L)$. Let $m_{n,i}$ be a basic probability mass representing the degree to which the ith basic factor supports the hypothesis that the general criterion y is assessed to H_n. Let $m_{H,i}$ be a remaining probability mass unassigned to any individual grade after all N the grades have been considered for assessing the general criterion y as far as e_i is concerned. $m_{n,i}$ and $m_{H,i}$ can be calculated from $\beta_{n,i}$ as follows:

$$m_{n,i} = w_i \beta_{n,i}\,;\;\; n = 1,\ldots,N;\; i = 1,\ldots,L$$

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - w_i \sum_{n=1}^{N} \beta_{n,i},\;\; i = 1,\ldots,L$$

$m_{H,i}$ can be decomposed into $\overline{m}_{H,i}$ and $\widetilde{m}_{H,i}$ as follows:

$$\overline{m}_{H,i} = 1 - w_i, \quad \widetilde{m}_{H,i} = w_i \left(1 - \sum_{n=1}^{N} \beta_{n,i}\right), \quad i = 1,\ldots,L$$

with $m_{H,i} = \overline{m}_{H,i} + \widetilde{m}_{H,i}$.

Then, the final assessment distribution can be generated using the following analytical ER algorithm (Wang *et al.*, 2006),

$$\{H_n\} \;:\; m_n = \mu \left[\prod_{i=1}^{L} (m_{n,i} + \overline{m}_{H,i} + \widetilde{m}_{H,i}) - \prod_{i=1}^{L} (\overline{m}_{H,i} + \widetilde{m}_{H,i})\right], \quad n = 1,\ldots,N$$

$$\{H\} \;:\; \widetilde{m}_H = \mu \left[\prod_{i=1}^{L} (\overline{m}_{H,i} + \widetilde{m}_{H,i}) - \prod_{i=1}^{L} (\overline{m}_{H,i})\right]$$

$$\{H\} \;:\; \overline{m}_H = \mu \left[\prod_{i=1}^{L} (\overline{m}_{H,i})\right]$$

$$\mu = \left[\sum_{n=1}^{N} \prod_{i=1}^{L} (m_{n,i} + \overline{m}_{H,i} + \widetilde{m}_{H,i}) - (N-1) \prod_{i=1}^{L} (\overline{m}_{H,i} + \widetilde{m}_{H,i})\right]^{-1}$$

$$\{H_n\} \;:\; \beta_n = \frac{m_n}{1 - \overline{m}_H}, \quad n = 1,\ldots,N$$

$$\{H\} \;:\; \beta_H = \frac{\widetilde{m}_H}{1 - \overline{m}_H}, \quad n = 1,\ldots,N$$

Then the aggregated safety assessment for the general criterion y can be described by the following belief distribution:

$$S(y) = \{(H_n, \beta_n),\; n = 1,\ldots,N\}$$

13.3.3 *Implementation of IDS software tool*

The synthesis process of using the ER approach above can be implemented with the support of the IDS (Intelligent Decision System) tool (Xu and Yang, 2003). There are 3 major steps in using the IDS tool for safety assessment: model implementation, information collection and aggregation, and assessment result generation.

(1) Model implementation

Using the IDS tool, the construction of the assessment criteria hierarchy is straightforward. The IDS main window is shown in Fig. 13.4, where there are a tree view window for displaying the criteria hierarchy and a list view window for displaying the alternatives for assessment.

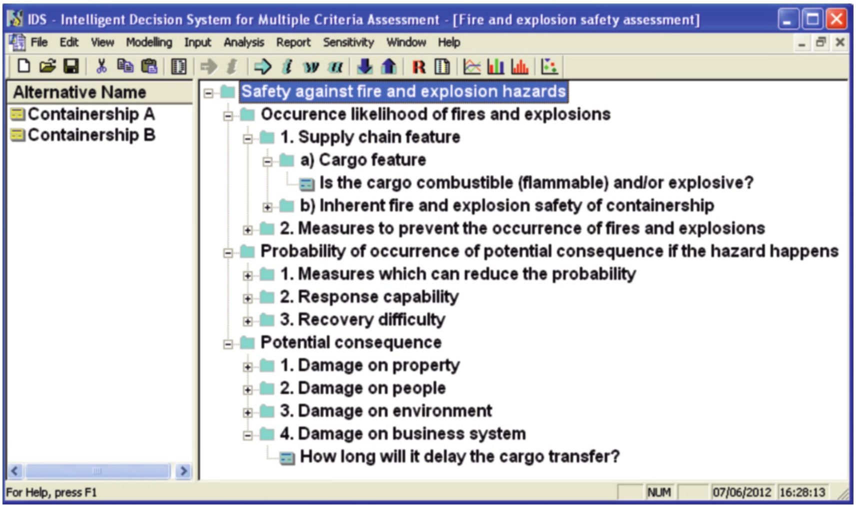

Fig. 13.4 IDS main window and the assessment criteria hierarchy

After the criteria hierarchy is structured, each criterion needs to be further defined. The definition includes an explanation of the criterion, whether it is a quantitative or qualitative type and the number of evaluation grades as described in Section 13.3.2.

(2) Information collection and aggregation

The safety assessment model implemented using the IDS tool as described above can be distributed to safety managers for collecting assessment information. The belief structure and the ER aggregation process can make maximum use of different types of raw information, including probabilistic data, incomplete and missing data (Yang and Xu, 2002). The synthesis of the assessment information from bottom level factors to higher level criteria is through the ER approach (Yang and Singh, 1994; Yang, 2001; Yang and Xu, 2002), which is built into the IDS tool as the kernel aggregation engine. The aggregation process is automatic.

(3) Assessment result generation

The IDS tool can generate different types of assessment results in graphical formats, such as safety distribution and safety ranking. The graphs enable the comparisons among selected alternatives to be carried out on any selected areas in different levels of the criteria hierarchy. Fig. 13.5 presents the overall safety assessment distribution of a containership against fire and explosion hazards.

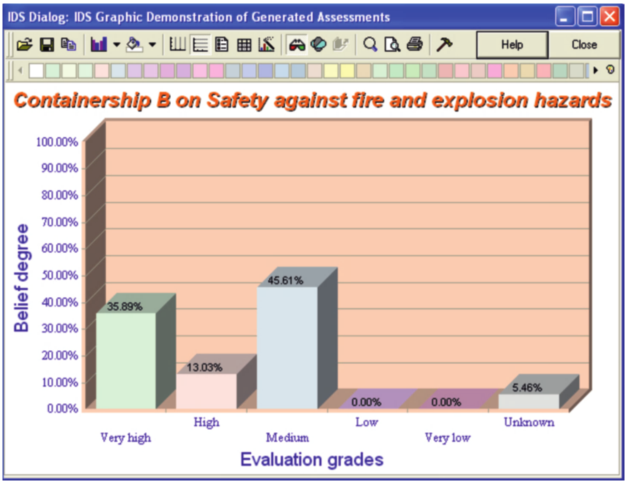

Fig. 13.5 Safety assessment distribution with belief structure

In addition, with the support of the IDS tool, sensitivity analysis can be conducted to identify the "cause and effect" relationship between the safety factors, the criterion weights and the assessment outcomes.

13.4 Conclusion

In this chapter, a hierarchical assessment framework is presented for evaluating safety against fire and explosion hazards in CLSC. The main criteria and factors influencing fire and explosion safety on containerships are investigated, and a safety modeling and synthesis method using the ER approach is briefly discussed. The proposed fire and explosion safety assessment model has been tested using data collected from the Port of Liverpool, and the generated outcomes are highly consistent with the "goal-setting" safety regulations. Sensitivity and tradeoff analysis for supporting fire and explosion safety-related decision making could be considered in the future research.

Acknowledgements

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Chapter 14

A Human Situation Awareness Support System to Avoid Technological Disasters

Mohsen Naderpour and Jie Lu

Decision Systems & e-Service Intelligence Lab, Centre for Quantum Computation & Intelligent Systems, School of Software, Faculty of Engineering and Information Technology, University of Technology Sydney, PO Box 123, Broadway, NSW 2007, Australia

E-mail: Mohsen.Naderpour@student.uts.edu.au, Jie.Lu@uts.edu.au

In many complex technological systems, accidents have primarily been attributed to human error. In the majority of these accidents the human operators were striving against significant challenges. They have to face data overload, the challenge of working with a complex system and the stressful task of understanding what is going on in the situation. Therefore, to design and implement complex technological systems where the information flow is quite high, and poor decisions may lead to serious consequences, Situation Awareness (SA) should be appropriately considered. A level 1 SA is highly supported in these systems through the various heterogeneous sensors and signal-processing methods but, for levels 2 and 3 there is still a need for concepts and methods. This work develops a system called the Human Situation Awareness Support System (HSASS) that supports the safety operators in an ever increasing amount of available risky status and alert information. The proposed system includes a new dynamic situation assessment method based on risk, which has the ability to support the operators' understanding of the current state of the system, predict the near future, and suggest appropriate actions. The proposed system does not control the course of action and allows the human to act at his/her discretion in specific contexts.

14.1 Introduction

A technological disaster is an event caused by the failure of a technological system and/or human error in controlling or handling the technology. Since the beginning of the industrial revolution many serious large-scale technological systems' accidents that had grave consequences, such as those of Three Mile Island, Bhopal and Chernobyl, have primarily been attributed to "operator error". For instance, the release of methyl isocyanate

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from the Union Carbide chemical plant in Bhopal, India, in 1984 caused 2000 human casualties, 10,000 permanent disabilities, and over 200,000 injuries, arguably making it the worst industrial disaster in history where the accident was officially blamed on human error [1]. Human error is the biggest challenge within most industries and on the surface, would seem to imply that people are merely careless, poorly trained, or somehow not very reliable. In fact, in the vast majority of these accidents the human operator was striving against significant challenges. Operators have to face both data overload and the challenge of working with a complex system. They are drilled with long lists of procedures and checklists designed to cope with most of these difficulties, but from time to time they are apt to fail. In fact, the person is not the cause of these errors but so much as the final dumping ground for the inherent problems and difficulties in the technologies that engineers have created [2]. Operators generally have no difficulty in physically performing their tasks, and no difficulty in knowing what is the correct thing to do, but they are stressed by the task of understanding what is going on in the situation. Over the last two decades, great deal of research has been undertaken in the area of Situation Awareness (SA).

Today, in technological systems, operators rely on the principles and design of human computer interaction to observe and comprehend the overwhelming amount of process data that varies rapidly. They have often been moved to a control room far away from the physical process, so that their role becomes more of a monitor or supervisor of the automation system, which is able to pass more and more information to the operator. It is widely accepted that more data does not equate to more information. In many cases automation has only worsened the problem [3], and operators are required to handle more data and more responsibility. For instance, in the 1970s, a typical operator manually controlled approximately 45 control valves in one process unit. Today, an operator controls, on average 175 control valves through an automation system interface. More specifically, the number of observable process variables in the power distribution sector grew from 200,000 to 700,000 between the years 1990 and 2000 [4]. Although experienced users tend to filter through the overabundance of data to generate information and acquire good SA, even the most expert operator can become swamped by the excessive amount of data provided by new technologies. In the presence of all this data, operators are finding that they are even less aware than ever before about the situations they are controlling. This has led to a huge gap between the massive amount of data produced and disseminated and the operator's ability to effectively assimilate the required data and to make a timely, accurate decision [5].

SA can be described as knowing and understanding what is going on around you and predicting how things will change [6]. The problem of poor operator SA continues to worsen as technology advances whether the operator is a pilot, a manufacturing operator, or a manager, and it can be seen through automation-facilitated accidents throughout the world. For example, on March 23, 2005, at Texas City, TX BP Amoco Refinery explosion, 15 workers were killed and 170 injured when a column was overfilled, overheated, and over-pressurized on startup. A key problem identified in this catastrophic event was the difficulty experienced by the operator in maintaining an accurate awareness of the situation while monitoring a complex, fast moving environment [7]. Several other studies of accident throughout many industries have found that loss of, or poor operator SA, was related to accidents classified as human error. For instance, loss of SA has been associated with 88% of major air carrier accidents that involved pilot errors and 58.6% of operational error in air traffic control operations [8]. Due to the severity of the accidents that have occurred over the last ten years, SA has become the focus of research that aims to understand operator performance in critical, dynamic environments [9].

This research considers the applicability of SA concepts to safety in the control of complex systems. Safety supervision continues to increase in degree of automation and complexity as operators are decreasing. As a result, each safety operator must be able to comprehend and respond to an ever increasing amount of available situations with risky status and alert information. This study introduces a new system for SA enhancement called the Human Situation Awareness Support System (HSASS).

This chapter presents the basic concepts of SA, the proposed HSASS system and how it will be implemented, and looks at related areas of research for the future.

14.2 Basic Concepts and Related Works

14.2.1 *Situation Awareness*

One of the widely applicable SA definitions introduced by Endsley in 1995, describes SA as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” [10]. Endsley’s model is arranged into three hierarchical levels of SA, each stage being a necessary precursor to the next higher level (Fig. 14.1). This model follows a chain of information processing, from perception, through interpretation, to prediction. From the lowest to the highest, the levels of SA are [11, 12]:

- *Perception*: Perception involves the sensory detection of significant environmental cues. For example, operators need to be able to see relevant displays or hear an alarm.
- *Comprehension*: Comprehension is understanding the meaning or significance of that information in relation to goals. This process includes developing a comprehensive picture of the world.
- *Prediction*: Projection consists of extrapolating information forward in time to determine how it will affect future states of the operating environment. The higher levels of SA allow operators to function in a timely and effective manner, even with very complex and challenging tasks.

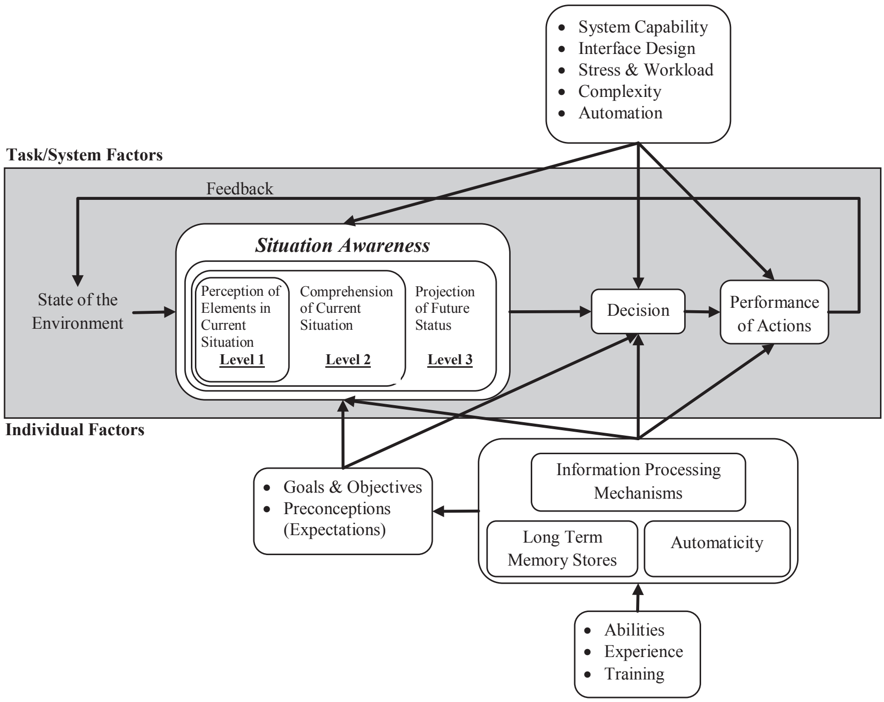

Fig. 14.1 Situations Awareness in Dynamic Decision Making [10].

Endsley’s model has been used in a number of studies as a justification for structuring the computer-supported SA process in a variety of complex positions, such as air traffic controllers, nuclear power plant operations, anesthesiologists, military commanders, electronic warfare tacticians, automobile drivers, power plant operators, and so on [2, 5, 11, 13].

14.2.2 *Situation Assessment*

SA is a state of knowledge that has to be distinguished from the processes underlying the achievement of SA, which should be addressed as situation assessment [10]. The situation assessment models describe basic principles and general features about how people process information or interact with the environment to attain their SA. In fact, awareness information for a situation is derived as the results of situation assessment. Since SA is regarded as a dynamic and collaborative process, assessing a situation is often required data integration or called data fusion with support of computer based intelligent techniques. The enhancement of operators' SA in complex systems is a major design goal in developing operator interfaces, automation concepts and training plans in a wide variety of fields [14–16].

As SA aims to predict the status of a situation in the near future, which is the third level of the SA model, we need proper and effective situation assessment approaches and tools to conduct the prediction. For example many studies have reported that machine learning techniques could be an effective method for intelligent prediction by extracting rules from previous data to generate new assessment results [14], but their use has been limited, possibly because of the lack of rich training data for this problem [17]. In some research, authors developed a quantitative model based on Bayesian inference and information theory, and described the process of knowledge-driven monitoring and the revision of operators' understanding of the environments [15, 18]. Other studies considered computational methods, but these approaches often do not satisfactorily handle all forms of uncertainty, especially when information conflicts. Therefore, human behavior models have been developed from cognitive architectures. The limitations of these systems are that they do not easily incorporate cognitive factors. Consequently, some approaches used the fuzzy logic system to address the limitations of traditional models in producing the full range of human behaviors [19–21].

14.2.3 *Representing Situation Awareness*

Endsley developed a methodology to determine the aspects of a situation that are important for a particular user's SA requirements. This methodology is known as the Goal-Directed Task Analysis (GDTA) and it is a specific form of cognitive task analysis that focuses on identifying the goals and critical information needs for a task context. The GDTA process has been used in many domains to detail SA requirements. As such, it forms an exemplary template for incorporating human cognition into an actionable model by describing in detail not only a user's information data needs (Level 1) , but also how that information needs to be combined to form the comprehension (Level 2), and projection of future events (Level 3) that are critical to SA, thereby providing a critical link between data input and the decisions to be made in a goal-directed environment [22].

In this analysis, the major goals of a particular job class are identified, along with the major sub-goals necessary for meeting each goal. Associated with each sub-goal, the major decisions that need to be made are then identified. The SA needed for making these decisions and carrying out each sub-goal are identified (Fig. 14.2). These requirements focus not only on what data the operator needs, but also on how that information is integrated, or combined, to address each decision.

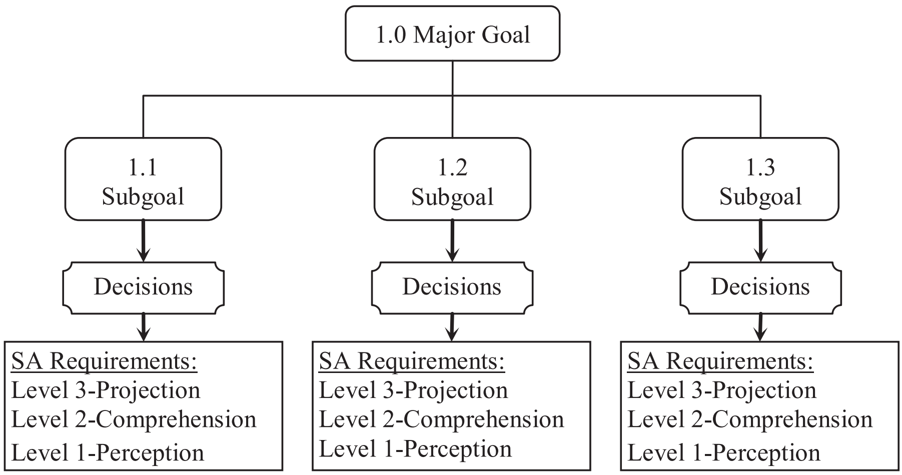

Fig. 14.2 Goal-Directed Task Analysis for Determining SA Requirements [10].

This type of analysis is based on goals or objectives, not tasks. This is because goals form the basis for decision making in many complex environments. Conducting such an analysis is usually carried out using a combination of cognitive engineering procedures such as expert elicitation, observation of operator performance and analysis of documentation [2].

Table 14.1 Safety Goals and Decisions.

1.0	Eliminate or reduce the risks to a level that is as low as reasonably practicable
1.1	Determine the risks
1.1.1	Hazards identification
	• *Past hazards*
1.1.2	Likelihood determination
	• *Prior likelihood*
	• *Posterior likelihood*
1.1.3	Severity determination
	• *Past consequences*
	• *Degree of losses*
1.1.4	Level of Risk
	• *Current level*
1.2	Reduce the risks
1.2.1	Establish the practical options
	• *Available reduction and containment options*
1.2.2	Impact of the options
	• *New level of risk*

14.3 A Human Situation Awareness Support System

14.3.1 *A HSASS General Model*

As discussed earlier, SA involves perceiving critical factors in the environment (SA level 1), understanding what those factors mean, particularly when integrated together in relation to the operator's goals (SA level 2), and at the highest level, an understanding of what will happen with the system in the near future (SA level 3) [2]. To determine the features that are important for an operator's SA, we use GDTA. The SA requirements focus not only on what data the operator needs, but also on how that information is integrated or combined to address each decision. In this analysis process, SA requirements are defined as those dynamic information needs associated with the major goals, or subgoals of, the operator to perform his/her job. The results are showed in Table 14.1 [23].

The information provided for situational awareness must be more than just information gathering. This implies collecting the right multi-domain information across a net-centric environment for shared awareness and presenting the results for the human to understand

and make quick decisions. Any new approach must efficiently bring together the human operator, sensor equipment data, and real world events to provide a subset of actionable information [17]. Fig. 14.3 shows the general model of HSASS.

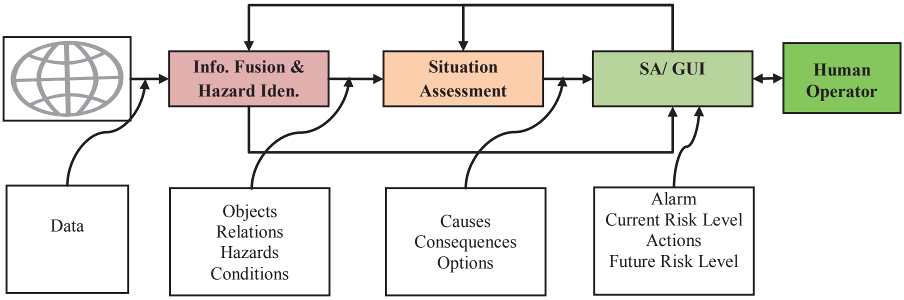

Fig. 14.3 The HSASS General Model.

14.3.2 *Information Fusion and Hazard Identification Component*

Critical factors in the environment (SA level 1) should be collected from various sensors, which are distributed in an intended area. This aims to locate and identify objects, and also provide a global picture of the situation, which is reported by fusing the attributes of an object from multiple sources. Any variety of relations - physical, organizational, informational, and perceptual - can be considered, as appropriate to the given information system's mission. Knowledge and experience of the past can be applied to the determination of the potential hazardous circumstances. The outcome of this step is identification of hazardous entities or relations that have a potential to lead to loss. As can be seen from the Fig. 14.3, this forms what we defined as the information fusion and hazard identification component.

14.3.3 *Situation Assessment Component*

SA level 2 relates to the operator's understanding of the system as a whole, and emergent events (such as alarms or casualties), that arise from hazardous situations. Therefore it is necessary to understand the causality of the current situation. SA level 3 requires that the system and operator should understand the future state so consequences of the current situation should be determined; depending on the consequent losses, the current hazards may subsequently require risk elimination, mitigation, transfer, control or combination thereof, so it is necessary to assist the operators to choose the appropriate actions.

Based on above mentioned points, the situation assessment component involves causal, consequence and option analysis. The causal analysis techniques are predominately applied within reliability engineering and are generally supported by mathematical foundations and a suite of computer based tools. The quantification of causal models entails an objective assessment of the potential frequency or likelihood for the causal factors. These are combined according to the rules of probability calculus and Boolean logic to generate a normalized or absolute measure for the realization of existing hazards. Consequence analysis is concerned with what may potentially follow the occurrence of a hazardous situation. Adverse outcomes associated with the current hazardous situation should be considered, including various degrees of harm to people, commercial detriment to an enterprise, damage to the ecology of the environment, or a combination of these factors. It is useful for all three components to be converted and expressed in a common currency, such as money, for potential comparison and aggregation in order to provide a coherent view of the totality of loss associated with a hazardous situation. Options analysis provides the future necessary actions that should be implemented to eliminate or reduce the risks. On identification and recording, it is essential to estimate the likely effects and potential benefits of each option on the consequent safety, commercial and environmental losses, in order to establish the objective and systematic criteria for selection and implementation. This is a requirement of the statutory legal framework in some countries (e.g. the UK) to ensure that the safety risks are reduced to As Low As Reasonably Practicable (ALARP) levels.

14.4 HSASS Implementation

14.4.1 *Environment Description*

To illustrate how to implement the HSASS into a real world environment, we use the example of a petrochemical plant with expert systems as artificial intelligence tools. An ethylbenzene process plant, involving two reactors and two distillation columns, as shown in Fig. 14.4, is chosen.

An exothermic reaction occurs in Reactor 1 (R1) at 160 °C and 9 bar, in which benzene (B) and ethylene (E) react to produce ethylbenzene (EB). The undesirable reaction of ethylene and ethylbenzene to produce higher-order species, for example, diethylbenzene (DEB) is suppressed by the large excess of benzene in R1. Any DEB produced is separated from ethylbenzene and recycled to R2, which operates adiabatically as DEB reacts with benzene to produce ethylbenzene. Benzene, in the D1 distillate, is recycled to R1. A mixture of EB

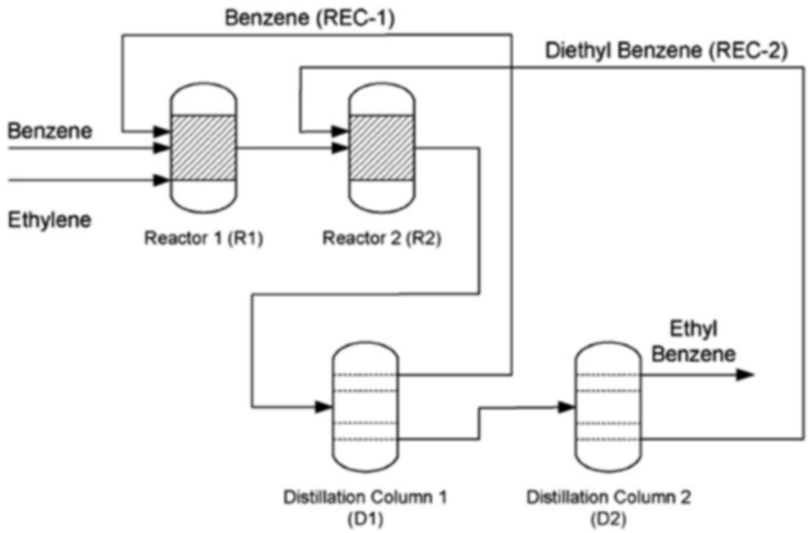

Fig. 14.4 Process Flow Sheet of Ethylbenzene Process.

and DEB in the D1 bottoms product is fed to D2, with EB recovered in the distillate, and DEB recycled to R2 [12].

Chemical processes are characterized by many variables that allow representation of the behaviour, using a set of rules. These factors allow us to use them appropriately for SA. We use three types of rules: fact, intermediate and decision rules. The format of the rule is as follows:

IF *Antecedent*; THEN *Consequent*

Inference direction can be generally divided into three types: (1) backward reasoning: starts with the target, intending to prove the target to be true or false; (2) forward reasoning: starts from the fact, reasoning towards target; (3) mixed reasoning: reasoning in both directions. In our work, the forward reasoning strategy is used.

14.4.2 *Hazard Identification Implementation*

Hazards are often obtained through the design and implementation phase, and various models have been developed to identify them. For example, HAZOP is one of the most powerful hazard identification methods available and has been clearly described in the re-

Table 14.2 Temperature Limits (°C).

Unit	Operating value	Six-sigma quality	High alarm	Automatic shutdown
R1	160	165	170	180
R2	166	170	175	185
D1	186	190	195	200
D2	200	205	210	220

search literature [30]. Fault tree, event tree, bow-tie and experts' knowledge are adopted as the knowledge acquisition techniques.

To show and store the hazardous situations we use fact rules. In a fact rule, 'antecedent' refers to conditions that have potential to harm, while 'consequent' is a name for the current situation. For example:

$$\text{IF } TCR1 > 170^\circ C\text{; THEN } \textit{the temperature of R1 is high}$$

For the ethylbenzene process, hazardous situations include those due to controller failure, loss of cooling, disturbances in the feed temperatures and flow rates, the reboiler heat duty, and flooding in the distillation columns. The safety systems are assigned temperature limits, as shown in Table 14.2, including limits for the six-sigma quality (by definition, when the controller fails to maintain the temperature within the six-sigma quality limit, the controller "Fails"), high alarm and automatic shut-down. For each abnormal event, when these limits are exceeded, time logs for the safety systems are recorded [12]. For example Fig. 14.5 shows a bow-tie diagram for a high-temperature abnormal event associated with reactor R1. The consequences include continued-operation (CO), shut-down (SD), release (REL), and explosion (EXP), based on the performance of six safety systems shown in rectangles across the left. The six safety systems are: S1 (high alarm), S2 (operator observation), S3 (operator correction), S4 (automatic shut-down), S5 (manual shut-down), and S6 (emergency relief system).

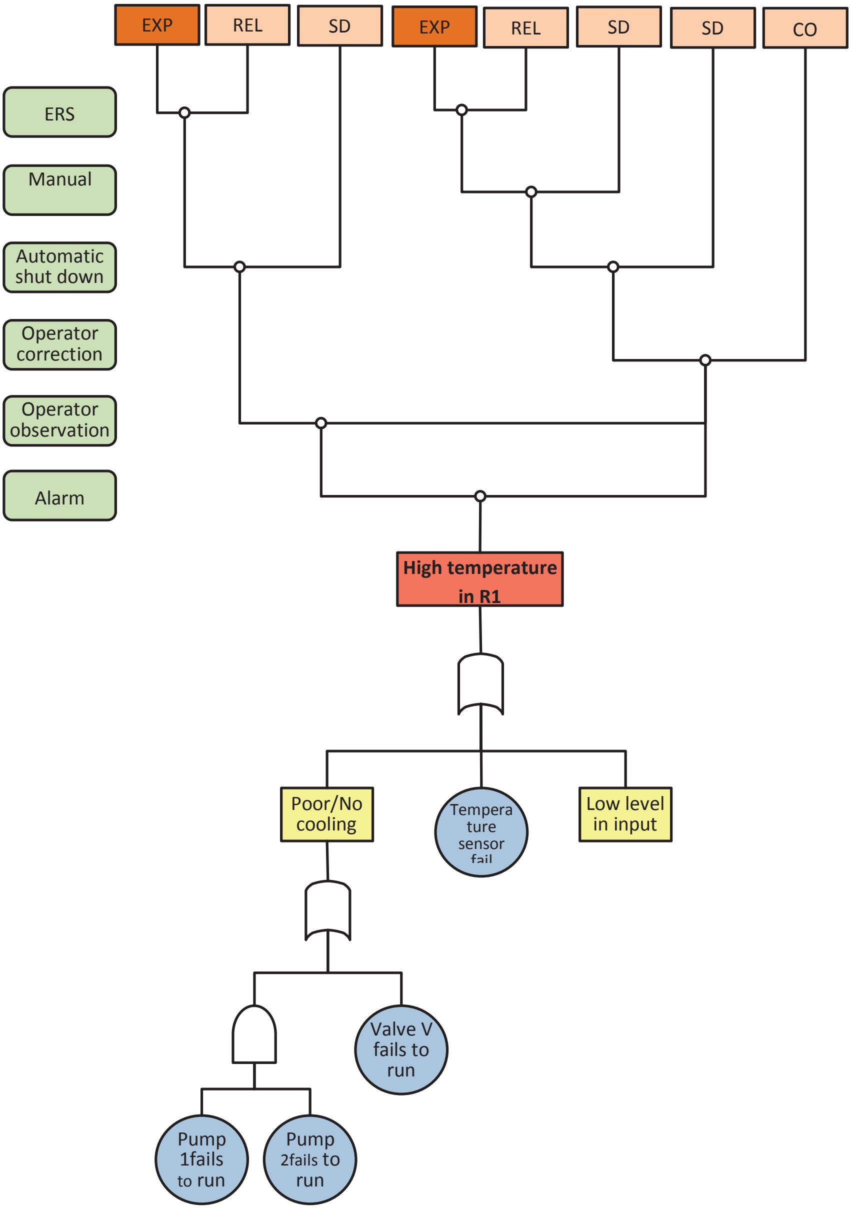

Fig. 14.5 Bow-tie Diagram for High Temperature in R1.

14.4.3 *Situation Assessment Implementation*

The situation assessment component will provide the comprehension and projection levels of the SA. To support these levels, we use intermediate rules. In an intermediate rule, 'antecedent' is a situation, while 'consequent' is a description of causes and consequences.

14.4.3.1 *Likelihood Determination*

To determine the likelihood of a target event, the concept of physical reliability models can be used. Reliability models aim to explain the reliability (or failure) of a component as a multivariate function of operational physical parameters. Among different types of physical reliability models, covariate models and static models can be used to estimate the primary events and consequently the probability of the target event [24].

Operational physical parameters, also called covariates, may be temperature, velocity, pressure, or vibration amplitude. Covariate models explain the failure rate of a component as a function e.g.:

$$F(t) = 1 - \mathrm{Exp}\left(-\left(\frac{t}{\mathrm{Exp}\left(\sum_{i=0}^{n} a_i x_i\right)}\right)^{\beta}\right)$$

where any change in covariate x_i will change the failure probability $F(t)$. Static models do not consider time as an influential parameter and only consider the component's strength and stresses. Both stress and strength can be constant or considered as random variables having probability distribution functions. For example, the failure probability of component Q having a constant strength, k, and being under a random stress, Y, can be defined as the probability of Y being greater than k, e.g.:

$$Pr(Q) = \Pr(Y > k) = \int_{k}^{\infty} f_y(y)\, dy$$

where $f_Y(y)$ is the probability density function (PDF) of stress, Y. Assuming an exponential distribution for $f_Y(y)$, $\Pr(Q)$ can written as:

$$\Pr(Q) = \int_{k}^{\infty} \lambda\, e^{-\lambda y} dy = e^{-\lambda k}$$

Therefore the failure probability of component Q can be reassessed when a new value for k is observed.

Table 14.3 Consequence Severity Matrix.

Severity class	Monetary Value	Human loss	Ass Loss	Environment loss
Very little	<10k	One minor injury	Minorrepairs that can be done immediately by own crew	Around the area, easy recovery
Little	10-100k	One or two minor injury	Repairsthat take several days to carry out	Within plant, short term remediation effort
Medium	100k-1million	Multiple major injuries	Damagethat takes months to repair and cause serious consequences	Minor offsite impact, remediation cost will be less than 1 million
High	1-10 million	One fatality or multiple injuries with disabilities	Very large material damage	Communityadvisory issued, remediation cost remain below 5 million
Very high	>10million	Multiple fatalities	Significant parts of the system destroyed	Communityevacuation for longer period, remediation cost in excess of 5 million

14.4.3.2 *Consequence Determination*

Generally, consequences of an abnormal situation may be categorized into four groups; asset loss, human fatality, environmental loss, and confidence or reputation loss. The severity matrix used in this study is outlined in Table 14.3 including equivalent dollar value of damage associated with each consequence category based on the severity of damage [25].

The failure probability of each safety system can be determined by the probabilistic method and end states are determined by multiplying the related probabilities together.

Previous probabilities are called "Priors", representing our belief about the system before observing the new data. After the initiation of the process, accident precursor data which are the near misses and incidents occurring in the process (defined as events that are not characterized as accidents but indicate the increasing likelihood of an accident occurrence) can be collected from the system. The ASP data can be used to form the likelihood function, which in turn updates the prior knowledge about the occurrence probability of every end state resulting in the formation of the posterior function. Bayesian theory is a probabilistic approach that applies the conditional probability principals to reason with uncertainties. The results obtained by application of this theory in this study will yield the "Posterior" which is the updated knowledge about the end states of the system. Considering

Table 14.4 Risk Matrix.

P. \ S.	Very little	Little	Medium	High	Very high
Very likely	Significant	Significant	High	High	High
Likely	Medium	Significant	Significant	High	High
Even	Low	Medium	Significant	High	High
Unlikely	Low	Low	Medium	Significant	High
Very Unlikely	Low	Low	Medium	Significant	Significant

x as the failure probability of the system and $f(x)$as the probability distribution function (prior distribution), $f(xData)$ will present the posterior distribution that is derived using the following equation:

$$f(x \mid Data) \propto g(Data \mid x) f(x)$$

where $f(x \mid Data)$is the posterior function, $g(Data \mid x)$ is the likelihood function and $f(x)$ is the prior [26].

14.4.3.3 *Current Risk Level*

To obtain the risk level of the target hazard we use a fuzzy risk analysis model. We present probability of hazards with five linguistic values, e.g. very likely, likely, even, unlikely, and very unlikely, and will explain the severity by five linguistic values e.g. very little, little, medium, high and very high. The risks are represented by low, medium, significant and high. Triangular and trapezium membership functions can be used together to increase the sensitivity in some bound points. Fig. 14.6 shows membership functions for probability, severity and risk variables.

To construct the fuzzy risk analysis model, we considered the risk matrix as shown in Table 14.4, which has 25 rules, e.g.:

IF *the probability is likely* AND *the severity is medium*

THEN *the risk is high*

14.4.3.4 *Risk Reduction*

If the estimated risk is unacceptable, it is necessary to identify risk-reducing measures that reduce either the frequency or the consequences of the occurrence of the unwanted event. For each individually considered risk element, a decision must be made whether or not the investment in the risk-reducing measures has the effect of reducing the risk to an acceptable level [33]. A list of available reduction and containment options can be presented as decision rules where ‘antecedent’ is a situation, while ‘consequent’ is suggested actions to remove or eliminate the risk. Based on the operator’s decision, a new level of risk can be calculated.

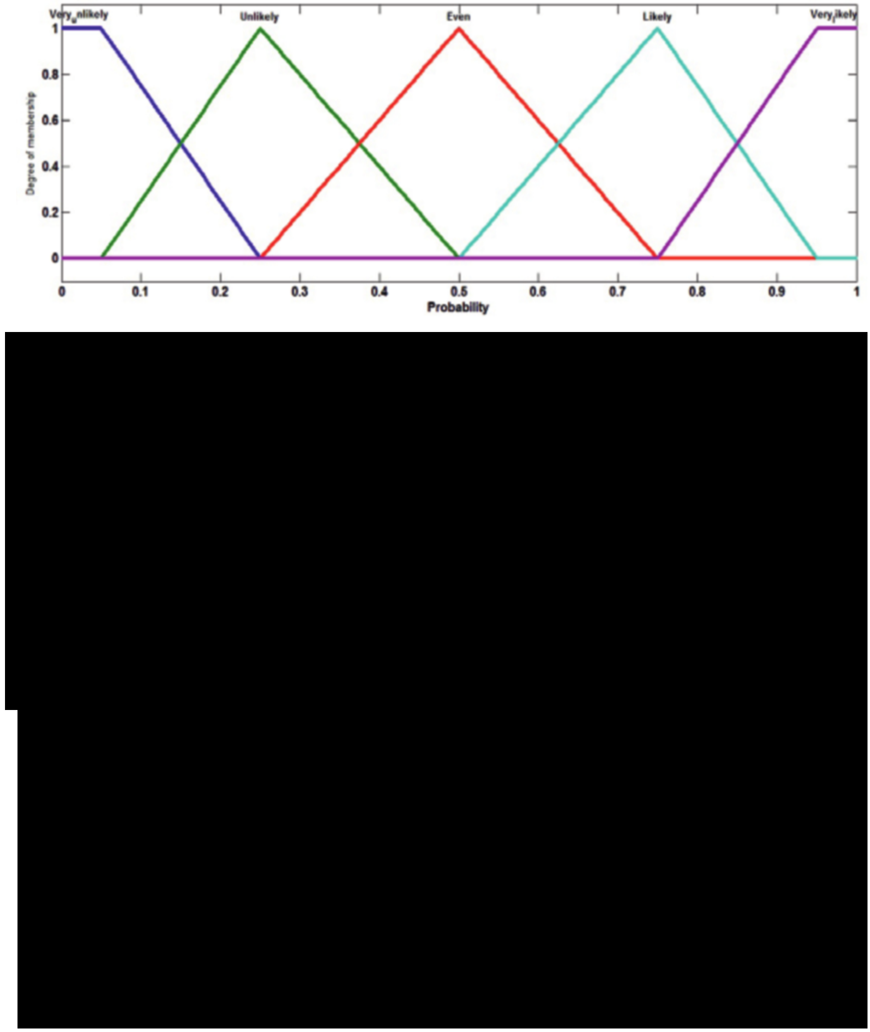

Fig. 14.6 Membership Functions.

Table 14.5 Examples of Knowledge Rules.

Rule 1	IF	$T_{R1} > 170\,^{\circ}C$	Fact
	THEN	Hazard (H1R1) : high temperature in R1	
Rule 2	IF	$T_{R2} > 175\,^{\circ}C$	Fact
	THEN	Hazard (H1R2) : high temperature in R2	
Rule 3	IF	$T_{D1} > 195\,^{\circ}C$	Fact
	THEN	Hazard (H1D1): high temperature in D1	
Rule 4	IF	$T_{D2} > 210\,^{\circ}C$	Fact
	THEN	Hazard (H1D2): high temperature in D2	
...			
Rule 21	IF	(H1R1)	Intermediate
	THEN	Poor cooling or TC_{R1} fail or input low level	
Rule 22	IF	(H1R2)	
	THEN	. . .	
...			
Rule 40	IF	(H1R1)	Decision
	THEN	switch to redundancy pump in cooling system and administrative checks	
...			

Assume the temperature in Reactor1 is increased to 170 °C. The system is initialized an abnormal situation occurred; the results are sent to the inference machine and stored in the integrated database. Rule 1 is selected and returned according to the knowledge rules. The system reports that the hazard (H1R1) occurred and an alarm will be shown on the operator's interface. At the same time, H1R1 characteristics are recalled from the database.

The posterior probability is calculated using Bayesian inference. For this example the abnormal event occurred at interval 20 and the posterior probability is 0.0132. According to the fuzzy risk analysis model the current risk level is 0.65 and the system presents "significant" risk level on the GUI. The causes of hazardous situation are searched by the inference machine and Rule 21 is written to the cause's area of GUI, and Rule 40 is selected. The operating suggestions are displayed in the monitoring windows of the system. Usually, during a short time period when multiple alarms occur, it is not possible to remove all of them. One has to attribute priorities, and our approach has this ability.

14.5 Conclusion and Future Study

During the operation of complex systems that include human decision making, acquiring and interpreting information from the environment forms the basis for the state of knowledge of a decision maker. This state is often referred to as situation awareness (SA). Lacking or inadequate SA has been identified as one of the primary factors in accidents attributed to human error and it is especially important in work domains where the information flow can be quite high, and poor decisions may lead to serious consequences. As technological systems continue to increase in degree of automation and complexity, the task of providing actionable information for SA becomes more difficult and costly to achieve. In this study we proposed a new system to support SA for the safety operators. Initially, our system conducts the complicated task of understanding what is going on in the situation, and it then assesses the current situation by the risk analysis concept through a case study.

The enhancement of SA is a major design goal for developers of operator interfaces, automation concepts, and training programs in a verity of fields. To evaluate the degree to which new technologies or design concepts actually improve operator SA, it is necessary to systematically evaluate them based on a measure of SA, which can determine those ideas that have merit and those that have unforeseen negative consequences [8]. Therefore, developing a SA measuring method and a system prototype evaluation based on the proposed SA measurement will form the basis for future study in this work.

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