EMERGENCY EVACUATION MANAGEMENT FOR NUCLEAR POWER PLANT ACCIDENTS UNDER MULTIPLE UNCERTAINTIES

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ABSTRACT

Nuclear power accidents are one of the most dangerous disasters posing a lethal threat to human health and have detrimental effects lasting for decades. Therefore, emergency evacuation is important to minimize injuries and prevent lethal consequences resulting from a nuclear power accident. An evacuation management system in response to a nuclear power plant accident, involves a number of processes with a variety of socio-economic and environmental implications. These processes may be influenced by a number of factors, such as availability of traffic vehicles employed, number of evacuees, destinations of evacuees, limitations of evacuation times, budgets for evacuation, shelter and hospital capacities, and environmental regulations of the areas involved. Extensive uncertainties exist in the evacuation process and the associated factors. Hence, innovative inexact optimization approaches may be proposed to account for various uncertainties existing in an evacuation planning system.

In this dissertation, a series of inexact optimization approaches will be proposed to reflect compound uncertainties existing in emergency evacuation planning systems. In detail, (i) an interval-based evacuation management (IBEM) model will be developed in response to a nuclear-power plant accident; (ii) an inexact gradient-based fuzzy chance constrained programming (IGFCCP) method will be proposed to balance a decision maker’s optimistic and pessimistic preferences and applied to the planning of the evacuation scheme for the Qinshan Nuclear Power Site (QNPS); (iii) an inexact fuzzy stochastic chance constrained programming (IFSCCP) approach will be developed to address various uncertainties and optimize the planning of the evacuation scheme for the QNPS; (iv) an inexact mixed-integer
credibility-constrained de Novo programming (IMICDNP) method will be developed to analyze the trade-offs between conflicting objectives under uncertainty.

The major accomplishments of this research are summarized as follows:

(i) A set of inexact optimization approaches are proposed to deal with uncertainties in emergency evacuation planning systems. The uncertainties, expressed in various forms such as interval, fuzzy, fuzz random variables, can be well reflected through the developed IBEM, IGFCPP, IFSCCP, IMCDP methods. Optimal decision alternatives for emergency evacuation planning are obtained through the proposed approached under various uncertain conditions.

(ii) The applicability of the proposed approaches are demonstrated through a real-case study of emergency evacuation management at the Qinshan Nuclear Power Site (QNPS), which is the first nuclear power plant in China. Under consideration of various system complexities and uncertainties, potential.
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Chapter 1 Introduction

Society is confronted by many natural and man-made disasters. Hurricanes, wildfires, floods, large storms, mudflows, terrorist attacks, chemical spills, industrial accidents, and many similar hazards cause massive economic and social damage and loss of life every year (Pel et al., 2012). According to records from the International Federation of Red Cross and Red Crescent Societies (IFRC), 7,184 disasters took place between 2000 and 2009 (Galindo and Batta, 2013). Among them, nuclear power accidents may be one of the most dangerous disasters posing lethal threats to human health which may last for decades. It is reported that there have been 99 accidents at nuclear power plants from 1952 to 2009, resulting in either loss of human life or significant property damage (Sovacool, 2010). For instance, the Chernobyl disaster in 1986 initially resulted in 50 direct fatalities but eventually attributed to more than 4,000 fatalities. Recently, The Fukushima Daiichi nuclear disaster, resulting from a magnitude 9.0 earthquake, was another Level 7 nuclear accident. Emergency evacuation is quite important to prevent injuries and limit consequences resulting from nuclear power accidents. Emergency evacuations take place during the initial response phase until victims and/or their property can be protected from further threats of disaster. Once an accident occurs, a large number of people at one or several predetermined locations require evacuation. An emergency-related evacuation involves the mass movement of persons from an accident site to several destinations with various vehicles. For example, there were no direct fatalities in the Fukushima nuclear disaster but more than 300,000 people had to be evacuated from the area to
avoid radioactive effects from the nuclear meltdown of three of the plant’s six nuclear reactors. However, evacuation of large crowds in a safe and timely manner is an extremely difficult task (Chiu et al., 2007). Evacuation management for large crowds after a nuclear power accident involves a number of processes and factors with socioeconomic and environmental implications, posing challenges for decision makers (Strupczewski, 2003; Li and Huang, 2012). Therefore, development of an evacuation management model would be a useful tool to aid effective decision making, enhance disaster response capability, and reduce adverse impacts on human beings and the surroundings (Lv et al., 2013).

An evacuation management system in response to nuclear power plant accidents, involves a number of processes with a variety of socio-economic and environmental implications. For instance, a typical evacuation system considers the organization of salvage, gathering of the population, grouping of evacuees, allocation of transportation resources, provision of services, and planning of evacuation routes. The processes are influenced by a number of factors; the number of traffic vehicles employed, number of evacuees, destinations of evacuees, limitations of evacuation times, budgets for the evacuation, capacities of shelters and hospitals, and environmental regulations of the areas involved. Extensive uncertainties exist in the evacuation process and associated factors. For instance, due to the temporal-spatial variation, the number of evacuees around the nuclear plant area would be uncertain. The vehicle capacity for different evacuation routes may be uncertain due to road design standards, evacuation time periods (rush hours or normal hours) and other
factors. The uncertainties are correlated with each other, multiplying the complexities in the evacuation management system. The uncertainties normally result from unforeseeable incidents and deviations in subjective judgments. Ignoring the uncertainties is undesirable since they may result in inferior or wrong decisions (Fan and Huang, 2012). Therefore, innovative inexact optimization approaches are proposed to account for various uncertainties existing in an evacuation planning system.

The objective of this study is to develop a series of inexact optimization approaches to reflect the uncertainty and dual-uncertainty existing in an emergency evacuation planning system. The detailed objectives of this dissertation involve the following:

(i) A series of inexact optimization approaches will be developed for evacuation management in response to nuclear-power plant accidents. These approaches aim to provide decision support emergency evacuation schedule under various uncertainties, which include interval-based evacuation management (IBEM), inexact gradient-based fuzzy chance constrained programming (IGFCCP), inexact fuzzy stochastic chance constrained programming (IFSCCP), inexact mixed-integer credibility-constrained de Novo programming (IMCDP) approaches.

(ii) The proposed approaches will be applied to evacuation strategy identification in the Qinshan Nuclear Power Site (QNPS) under various uncertain conditions. In detail, the IBEM will address uncertainties existing in the system components and parameters as interval values. The IGFCCP approach is to provide decision
alternatives by balancing decision makers’ optimism and pessimism preference for planning of evacuation schemes at QNPS. Uncertainties described as fuzzy, interval and fuzzy random variables in the QNPS evacuation system is to be reflected by the IFSCCP approach. The IMCDP method will be able to provide trade-offs for conflicting objectives between maximizing the number of evacuees during the disaster and minimizing system costs.

The structure of this study is outlined as follows: Chapter 2 provides a comprehensive literature review related to the inexact optimization techniques used in environmental management problems. Chapter 3 introduces the interval-based evacuation management (IBEM) model in response to nuclear-power plant accidents. Chapter 4 proposes the development of the inexact gradient-based fuzzy chance constrained programming (IGFCCP) method for addressing uncertainties presented as interval and fuzzy numbers in the emergency evacuation problem of the QNPS. Chapter 5 introduces the development of inexact fuzzy stochastic chance constrained programming (IFSCCP) to reflect multiple uncertainties expressed as fuzzy, interval and fuzzy random variables that may exist in the emergency evacuation system of the QNPS. Chapter 6 provides the inexact mixed-integer credibility-constrained de Novo programming (IMCDP) method for emergency evacuation management for the the QNPS to reveal impacts of the conflicting objectives between maximizing the number of evacuees during the disaster and minimizing system costs. Chapter 7 gives concluding remarks for the proposed methods and their applications, and recommendations for future research.
Chapter 2   Literature Review

2.1. Emergency Evacuation Planning

Over the past few decades, evacuation activities have been increasingly common due to frequent occurrences of large-scale public events for political, social, economic, cultural, and recreational purposes, such as the Olympic Games, world expositions, and political rallies (Tan et al., 2011). Emergency evacuation planning, in response to natural disasters (e.g. hurricanes, floods, etc.) and man-made accidents (e.g. nuclear power accidents, and terrorist attacks) has attracted a great deal of attention. Mass movement of evacuees is a central concern for academic researchers and community stakeholders. For instance, the Fukushima Daiichi nuclear disaster began on 11 March 2011 and forced more than 300,000 people to be evacuated. Evacuation of large crowds is an extremely complex and difficult task (Chiu et al., 2007). Intensive transportation demands (in terms of space and time) generated by evacuation activities, combined with normal traffic in urban areas which is probably subject to serious congestion problems, cause immense difficulties for proper decision making for evacuation operations (Tan et al., 2011). Evacuation management of large crowds after a natural or man-made (nuclear accidents) accident involves a number of processes and factors with socioeconomic and environmental implications, which poses challenges for decision makers (Strupczewski, 2003; Li and Huang, 2012). For example, emergency evacuation systems often require identification of the evacuation zone, shelter for refugees, the population at the risk, the predicted time of evacuation, safe routes of evacuation for adoption, and the levels of logistics to be offered. Many
related processes and/or factors are complex with multi-period, multi-layer, and multi-objective features. Therefore, development of science-based tools to facilitate accident-related evacuation management is imperative.

Research related to evacuation management is scant and largely relies on qualitative methods before 1979 (Urbanik, 2000). Since then, research has been conducted with a variety of mathematical programming methods being proposed for systematically analyzing evacuation management problems. For example, Yamada (1996) studied a city emergency evacuation planning problem using two network flow models, where the first model sought the shortest paths on an undirected graph and assigned each evacuee a corresponding shelter. The shortest path network was transformed into a minimum cost flow problem by adding capacities to each shelter. Hamacher and Tjandra (2001) gave an overview of mathematical modeling for evacuation problems. They presented variations of discrete time dynamic network flow problems to model evacuation problems (e.g. maximum dynamic flows, earliest arrival flows, quickest paths and flows, and continuous time dynamic flows). Cova and Johnson (2003) presented a mixed-integer linear programming model to identify optimal lane-based evacuation routing plans and prevent traffic crossing conflicts at intersections. Liu et al. (2006) presented a two-level integrated optimization system for identifying optimal evacuation plans. High-level optimization maximized the throughput during a given evacuation duration, while the low-level optimization minimized the total time of the operation, including transportation and waiting times. Han et al. (2006) proposed a framework for simultaneous optimization of
evacuation-traffic distribution and assignment, in which the optimal destination and route assignment were obtained by solving a one-destination traffic assignment problem on a modified transportation network. Yi and Ozdamar (2007) developed a dynamic logistics coordination model for evacuation and support for disaster response activities. Saadatseresht et al. (2009) combined multi-objective evolutionary algorithms and geographical information systems for evacuation planning, proposing a three-step approach for determining the distribution of evacuees into the safe areas (i.e. deciding where and from which road each evacuee should go). Stepanov and Smith (2009) proposed an integer programs model to determine the routes for emergency evacuation planning, where M/G/c/c state dependent queuing models were used to cope with congestion and time delays on road links.

Most previous studies focused on optimization of evacuation routes with model parameters and components being considered as deterministic values. However, in many real-world cases, results obtained through deterministic approaches could be rendered highly questionable due to several shortcomings such as neglecting imprecise information and relying on unstable assumptions about prices (Yeomans and Huang, 2003; Yeomans et al., 2003; Zhu, 2014). A variety of uncertainties inevitably exist in practical emergency evacuation planning problems, due to random characteristics of natural events, estimation errors of modeling parameters, imprecision of input data, variations of system conditions, and vagueness of management objectives (Zhu, 2014). There was a lack of direct communication for uncertainties in the modeling efforts, particularly for evacuation management of
nuclear power plant accidents. Innovative inexact mathematical programming methods are needed to reflect extensive uncertainties in emergency evacuation planning and identify appropriate evacuation schemes under multiple uncertainties.

2.2. Optimization Modelling under Uncertainty

2.2.1. Interval Mathematical Programming

Interval mathematical programming (IMP) was developed based on the interval analysis method proposed by Moore (1979). The parameters and decision variables can be expressed as interval numbers. An interval number is expressed by the lower and upper bounds, but without distributional information between the lower and upper bounds. It is used to approximate uncertainties when the data are insufficient for generating probability distributions or membership functions (Zhu, 2014). A great number of IMP approaches have been proposed to account for uncertainties in environmental management problems. Nakahara et al. investigated the interval coefficient LP problem and proposed methods for feasible solution regions (Nakahara et al., 1992). Huang (1994) proposed a series of interval-parameter mathematical programming methods, consisting of interval linear, interval mixed-integer linear, interval dynamic, and interval quadratic programming, to account for uncertainties in water resources and environmental management problems (Huang and Moore, 1993; Huang et al., 1992, 1994, 1995a, b, 1997; Huang, 1996). The approaches could allow uncertainties to be directly communicated in the optimization process and solutions. Aharon et al. presented optimal solutions for LP when the nominal data are perturbed
and applied to robust optimization approaches to produce “robust” solutions (Ben-Tal & Nemirovski, 2000).

Several methods have been proposed to solve IMP problems. For instance, Huang et al. (1992) proposed a two-step method (TSM), in which an ILP problem is converted into two subproblems corresponding to the lower and upper bounds of the objective function. The TSM is effective for solving ILP problems with less computational requirements. It may experience constraint violations in its solution space (Fan and Huang, 2012; Fan et al., 2012a). Recently, the TSM has been improved to enhance its applicability and avoid violation conditions in applications. Zhou et al. (2008) developed a modified interval linear programming (MILP) method with additional constraints in the submodels to avoid potential violation conditions. Huang and Cao (2011a, b) proposed a three-step method (ThSM) employing a constricting process after the TSM to eliminate infeasible solutions. Fan and Huang (2012) developed a robust two-step method (RTSM) to solve ILP problems, guaranteeing solutions under the best-case constraints.

A number of IMP-based approaches are proposed for addressing uncertainties in environmental management problems such as municipal solid waste, water resources, air quality, water quality and energy-environmental management. For instance, Kong et al. (2015) proposed an inexact quadratic programming method for solid waste management under uncertainty. Zhang and Li (2014) advanced an inexact two-stage water resources allocation model for sustainable development and management under uncertainty. Fan et al. (2012b) extended the solution methods for IMP to fuzzy

Only limited studies have been reported to analyze the inherent uncertainties in an emergency evacuation management system in terms of emergency evacuation planning in response to nuclear power accidents. For example, Guo et al. (2012) initially introduced the IMP approach into emergency evacuation management problems, in which the parameters were considered discrete intervals. Lv et al. (2013) developed a scenario-based modeling approach for emergency evacuation management and risk analysis under multiple uncertainties. However, a variety of uncertainties may exist due to the complexities in an emergency evacuation system, which may not be expressed by interval mathematical programming methods. The two aforementioned studies only focused on the uncertainty in hypothetical cases, which may be oversimplified when compared with an actual evacuation system. Further research is needed to advanced innovative methods for uncertainties involved in practical evacuation management systems in response to nuclear power plant accidents.
2.2.2. Fuzzy Mathematical Programming

Fuzzy programming (FP) was proposed as an alternative to the stochastic programming method, to account for cases where the probability distribution information of random events is not available. FP was developed based on the possibility theory of fuzzy events, which has been widely used in environmental systems management (Zadeh, 1968; Zimmermann, 1978; Liu and Iwamura, 1998; Pal et al., 2003; Mula et al., 2006; Li et al., 2013; Li et al., 2014; Toksarı and Bilim, 2015).

The probability measure of fuzzy events (i.e. possibility) was first proposed by Zaden (1968). Based on the possibility theory, Zimmermann (1978) proposed the fuzzy programming method with several objective functions. Liu and Iwamura (1998) proposed a fuzzy chance constrained programming method to address the fuzzy parameters in optimization problems. Pal et al. (2003) developed a goal programming (GP) procedure for fuzzy multi-objective linear fractional programming (FMOLFP) problems. Mula et al. (2006) applied a fuzzy mathematical programming approach for manufacturing environments with complex product structures and multiple production stages, to support production planning and material supply decision making. Toksarı and Bilim (2015) studied the issue of solving decentralized bi-level multi-objective fractional programming problems (DBL-MOFPP) with a single decision maker at the first level and multiple decision makers at the second level, and proposed a fuzzy goal programming (FGP) based on a Jacobian matrix for DBL-MOFPP.
Fuzzy credibility chance-constrained programming (FCCCP) was proposed to balance possibility and necessity (Huang, 2006; Zhang et al., 2012). Huang (2006) proposed credibility-based, chance-constrained integer programming models for capital budgeting with fuzzy parameters. Zhang et al. (2012) proposed integer fuzzy credibility constrained programming for power system management. Li et al. (2013) developed an inexact two-stage stochastic credibility constrained programming model for water quality management in the Xiangxi River Watershed in China. FCCCP can effectively generate decision supports when a decision maker’s attitude is totally neutral with regard to fuzzy constraints. An improved measure, namely $m_\lambda$-measure, was proposed to further reflect a decision maker’s optimistic or pessimistic preference regarding the fuzzy constraints (Yang and Iwamura, 2008). The $m_\lambda$-measure is a linear combination of the possibility and necessity measures. A parameter $\lambda$, which can be considered a gradient of the fuzzy constraints, was introduced to represent decision makers’ predetermined preferences (Yang and Iwamura, 2008). The $m_\lambda$-measure concept has been adopted in several environmental management applications (Yang et al., 2011; Dai et al., 2014). For instance, Yang et al. (2011) proposed a weighted min–max model based on the $m_\lambda$-measure to solve a freight train routing problem. Dai et al. (2014) incorporated the $m_\lambda$-measure with fuzzy chance-constrained programming and interval mathematical programming to develop an interval parameter $m_\lambda$-measure based fuzzy chance-constrained programming optimization model. Dai et al. (2014) developed an inexact $m_\lambda$-measure fuzzy chance-constrained programming model to generate optimal strategies for carbon
capture, utilization and storage. The gradient-based fuzzy chance-constrained programming method was proposed based on the $m_k$-measure. It has the advantage of self-duality and can effectively balance a decision-maker’s optimism and pessimism. It can be incorporated into an optimization framework to address complicated environmental systems management problems under multiple uncertainties.

2.2.3. Chance Constrained Programming

Chance constrained programming (CCP) was proposed to assess uncertainties in the format of probability distribution in the 1950s. It can be used when the constraints are required to be satisfied under given probabilities, which means there is an admissible risk of violating the uncertain capacity constraint (Li et al., 2006). CCP can set a reliability level (i.e., minimum or maximum level) of probability for the constraints. It is a well developed stochastic programming method, and is effective for reflecting randomness in the right-hand side values of optimization models (Li et al., 2007; Sun et al., 2010).

In recent years, many programming methods have been incorporated into the optimization framework along with CCP to account for more complex problems (Morgan et al., 1993; Huang, 1998; Liu and Iwamura, 1998a; Talluri et al., 2006; Guo and Huang, 2009; Bilsel and Ravindran, 2011; Chen et al., 2014). For instance, Morgan et al. (1993) developed a mixed-integer-chance-constrained programming technique for maximum reliability versus a minimum pumping objective. Liu and Iwamura (1998) presented a nonlinear chance constrained programming method with fuzzy coefficients occurring for constraints and objectives. Huang (1998) improved the IPP and CCP approaches, and proposed an inexact chance-constrained programming (ICCP) method to effectively incorporate uncertainties in the formats of intervals and stochastic events within the optimization process. Talluri et al. (2006)
dealt with the CCP problems where the objective was to minimize a convex objective, and developed a simulation-based CCP approach. Guo and Huang (2009) incorporated the dynamic programming, fuzzy programming and CCP techniques into an optimization framework. Bilsel and Ravindran (2011) introduced CCP into a multi-objective problem and developed a stochastic multi-objective model to mitigate operational and disruption risks in supplier selection. Chen et al. (2014) introduced the inventory theory model into a general inexact chance-constrained programming framework, to reflect the influence of inventory problems in decision-making problems. The development of hybrid approaches has demonstrated CCP’s flexibility in terms of solution algorithms.

The abovementioned CCP-based approached has been applied to many environmental systems management problems (Ozturk et al., 2004; Yang and Wen, 2005; Wu et al., 2008; Cai et al., 2009; van Ackooij et al., 2014). For example, Ozturk et al. (2004) took into consideration the stochasticity of the hourly load of a power-generating system and its correlation structure and proposed a solution for the stochastic unit commitment problem using CCP. Yang and Wen (2005) proposed a CCP-based method for optimal transmission system expansion planning to account for uncertainties existing in the locations and capacities of new power plants and growing demand. Wu et al. (2008) used CCP to reflect uncertainties in water inflows, electricity prices and unit status, and proposed a new model to optimize the management of short-term electric power generation of cascading hydroelectric plants. Cai et al. (2009) developed an inexact community-scale energy model (ICS-EM) based on IPP and CCP to support the planning of renewable energy management systems. van Ackooij et al. (2014) applied the joint CCP approach to solve a cascading reservoir optimization problem with inflow uncertainties. The wide
applications have illustrated CCP’s effectiveness in generating reliable decision support for system optimization and management.

2.3. Literature Review Summary

A number of inexact programming methods have been developed to address a variety of uncertainties, meaning the study of uncertainty in an optimization process has attracted increasing attention. Generally, there are three major types of inexact mathematical programming, including interval (IMP), fuzzy (FMP) and stochastic (SMP) mathematical approaches. The uncertainties expressed in the three mathematical programming approaches could be expressed as interval variables, fuzzy sets or probability distributions. Many approaches integrate three kinds of inexact programming to solve multiple uncertainties existing in system management problems in many areas, such as resource, environmental, and systems management.

Although vast research efforts have been made in mathematical programming under uncertainty, there are still many challenging concerns. Most of the previous studies solely took uncertainty into account, ignoring the multiple types of uncertainty existing under different parameters. Thus, the analyses cannot comprehensively reflect the interactive relationships and synergy in systems management. Existing methods cannot provide a sufficient trade-off analysis between system reliability and optimality in the decision-making process. Nuclear-accident evacuation management systems involve extensive complexities correlated with social, economic and environmental implications. A number of uncertainties exist in system components and associated parameters. The uncertainties may benefit from research to develop effective optimization methodologies that can characterize inherent uncertainties in the emergency evacuation system and further provide decision support and risk
analysis for population evacuation schemes under various uncertainties. However, few studies in the literature efficiently account for the complexities.

A series of inexact optimization approaches are assessed to reflect uncertainty and dual-uncertainty existing in an emergency evacuation planning system. They will be further applied to support emergency evacuation at the Qinshan Nuclear Power Site in Zhejiang Province, China.
Chapter 3  Development of an Interval-based Evacuation Management Model in Response to Nuclear Power Plant Accidents

3.1. Background

Energy is crucial for supporting daily life and human development (Amin & Gellings, 2006). Over the past few decades, energy supply and demand has been steadily increasing in response to population growth, economic development and improvement of living standards throughout the world. World energy demand is growing at a rate of approximately 1.6% per year, and is expected to reach approximately $700 \times 10^{18} \text{ J/year}$ by 2030 (Pękala et al., 2010). At the same time, fossil-fuel reserves are continuously shrinking, and prices are gradually rising, posing challenges for decision makers when deciding whether new electric-power utilities (e.g. nuclear power facilities) should be established to satisfy the increasing energy demand (Cai et al., 2009; Li et al., 2011; Birant, 2011). However, accidents at the nuclear power plants initiated by equipment malfunctions, operator error or external initiators (e.g., earthquakes, floods and tornadoes) are great obstacles to sustainable development using nuclear energy. They can significantly affect the long-term viability of society and the economy and lead to serious adverse impacts on people and the environment. Therefore, the safety of nuclear power plants is an important issue in the discussion regarding future scenarios for power generation.
A number of studies have been undertaken to analyze accident risks at nuclear power plants (Ravindra, 1990; MacGregor-Smith, 1991; Slaper and Blaauboer, 1998; Hayns, 1999; Davies, 2002; Strupczewski, 2003; Zhou et al., 2011). The studies estimated the frequency and consequences of various accidents at power plants and identified significant equipment and system failures leading to various accidents. The failures could be initiated by internal events such as equipment malfunctions, unavailable equipment, or operator error. They could also be initiated by external events such as an earthquake, flood, fire or tornado. For example, Ravindra (1990) examined the frequency and consequences of severe core damage, serious radiological releases, and consequences in terms of early fatalities, long-term adverse health effects and property damage. Ravindra identified significant contributors to nuclear power plant risks due to seismic disasters. Slaper and Blaauboer (1998) conducted an integrated assessment of probabilistic cancer mortality risks due to possible accidental releases from European nuclear power plants. The results provided a probabilistic view of the risks involved and the major areas at risk. Strupczewski (2003) estimated nuclear-power plant safety based on probabilistic safety analyses and discussed the methods used to decrease core damage factors, high frequency release and cancer deaths due to nuclear accidents. Generally, the studies focused on the evaluation of accident probabilities and subsequent release risks for nuclear power plants. It is not possible to eliminate the nuclear disasters, however, strengthening the disaster response and emergency management can largely mitigate their negative effects.
Disaster response is important in accident preparation for earthquakes, tidal waves, destructive fires, and nuclear power accidents (Sorensen et al., 1992; Drabek, 1999; Cova and Justin, 2003). Emergency evacuation and logistics support are two major disaster response activities (Yi and Ozdamar, 2007). Emergency evacuation activities take place during the initial response phase until the lives and property of victims can be given protection and be protected from further threats. Once accidents occur, a large number of people at one or several predetermined locations need to be evacuated. Emergency-related evacuations involve mass movement of persons from accident sites to destinations with various vehicles. However, evacuation of large crowds in a safe and timely manner is an extremely difficult task (Chiu et al., 2007).

Evacuation management for large crowds after a nuclear power accident involves a number of processes and factors with socioeconomic and environmental implications, which pose challenges for decision makers (Strupczewski, 2003; Li and Huang, 2012). For example, emergency evacuation systems often need to determine the zone for evacuation, shelter for refugees, safe routes for evacuation, predicted time for evacuation, the population at the risk, and levels of logistics to be offered. Many related processes and/or factors are complex with multi-period, multi-layer, and multi-objective features. Therefore, development of science-based tools to facilitate accident-related evacuation management is imperative.

Research related to evacuation management is scant and relies largely on qualitative methods created before 1979 (Urbanik, 2000). Since then, a variety of mathematical programming methods have been proposed to systematically analyze
evacuation management problems. For example, Yamada (1996) studied a city emergency evacuation planning problem using two network flow models, where the first model sought the shortest path on an undirected graph and assigned each evacuee to a corresponding shelter. The shortest path network was transformed to a minimum cost flow problem by adding capacity in each shelter. Hamacher and Tjandra (2001) gave an overview of mathematical modeling of evacuation problems. They presented variations of discrete time dynamic network flow problems to model evacuation problems (e.g. maximum dynamic flows, earliest arrival flows, quickest paths and flows, or continuous time dynamic flows). Cova and Johnson (2003) presented a mixed-integer linear programming model to identify optimal lane-based evacuation routing plans and prevent traffic crossing conflicts at intersections. Liu et al. (2006) presented a two-level integrated optimization system for identifying optimal evacuation plans. The high-level optimization maximized the throughput during a given evacuation duration, while the low-level optimization minimized the total time of the operation, including transportation and waiting times. Saadatseresht et al. (2009) combined multi-objective evolutionary algorithms and geographical information systems for evacuation planning, where a three-step approach was proposed to determine the distribution of evacuees into safe areas. It determined where and from which road each evacuee should travel. Stepanov and Smith (2009) proposed an integer program model to determine routes in emergency evacuation planning, where M/G/c/c state dependent queuing models were used to cope with congestion and time delays on road links. Tan et al. (2009) developed an inexact fuzzy robust
programming model for evacuation management to support management of event-related evacuation. Parameters presented as interval numbers and/or fuzzy boundary intervals were acceptable as uncertainty inputs, so the uncertainties could be communicated directly into the optimization process.

Although much research has been dedicated to evacuation management, little has been concerned with evacuation management for nuclear power plant. Most of the previous studies regarding uncertainty examination in evacuation management have been limited to sensitivity analyses (Urbanik, 2000; Chu et al. 2007). There is a lack of direct communication for uncertainties in modeling, particularly for evacuation management of nuclear power plants. Nuclear power plants pose severe threats to people and the environment, including health risks and environmental damage from uranium mining, processing and transport, the risk of nuclear weapons proliferation or sabotage, and the unsolved problem of radioactive nuclear waste (Giugni 2004; GIEREC. 2007; NENC. 2010). Nuclear reactors are enormously complex machines where many things can and do go wrong. There have been many serious nuclear accidents in terms of human injury and property damage (Sovacool 2008; Stephanie, 2009). Uncertainties are attributed to the randomness that is inherent in nature and due to a lack of probability data and information about potential consequences. Uncertainties exist with respect to the associated crowds, evacuation times, traffic vehicles, economic costs, and other impact factors affecting the optimization processes and decision schemes. Transportation resources and services must be efficiently used without significant disturbances for existing municipal traffic and
environmental quality to obtain timely, safe, and efficient evacuation schemes with uncertainties and complexities.

The objective of this study is to develop an interval-based evacuation management (IBEM) model to plan movement of persons from dangerous to safe areas when nuclear-power plant accident occurs. The IBEM model is based on an interval-parameter linear programming (ILP) technique for tackling uncertainties that cannot be quantified as distribution or membership functions. Interval values are acceptable as uncertainties. Interval solutions are analyzed and interpreted to generate multiple decision alternatives under various system conditions, assisting decision makers to identify crowd-evacuation plans under uncertainty.

3.2. Model Development

3.2.1. Statement of Problem

Human populations are at risk from many hazards, some man-made and others from natural causes. The former includes risks such as the release of hazardous substances such as chemicals, accidents in nuclear power plants and collapse of large scale civil engineering projects such as dam walls. The latter include hazards such as floods, earthquakes and hurricanes (Pidd et al., 1996; Bretschneider and Kimms, 2011). As opposed to natural disasters that can be anticipated, nuclear-power plant accidents are often sudden and unexpected. Even if information is available about a potential accident, it is not certain when, where and how the accident will occur. This lack of information poses great challenges for those responsible for security, in
particular on their ability to respond quickly whenever necessary with flexibility, efficiency and coordination (Hamza-Lup et al., 2007). Techniques for nuclear accident responses after they occur are of great interest and critical importance. Nuclear accidents can lead to large scale environmental emissions if, in addition to severe damage to the reactor core, a security system failure occurs. Accident scenarios such as these are related to the construction and maintenance of the plant and its safety systems, relative to external activities (e.g. earthquake, flood, fire and tornado) in the area, materials used, and operational and safety procedures adopted. Nuclear emergency management is very important to avoid nuclear and radiation leak accidents and to swiftly take action beyond normal work procedures to mitigate consequences. Evacuation has to be conducted to displace people from danger to safety, and it needs to be done in a hurry. It is necessary to prepare evacuation plans to offer an effective response in an emergency situation. One of biggest challenges in developing an evacuation plan is to determine the distribution of evacuees into the safe areas (i.e. deciding where and from which road each evacuee should go, and how many transfer vehicles should be prepared to evacuate a threatened population) (Saadatseresht et al., 2009). Evacuations require thorough analysis because of the substantial logistical complexities involved in their implementation. Emergency planning zones of one nuclear power plant cover a very large area (e.g., over 300 square miles or 900 km\(^2\)), and contain hundreds of thousands of people (Urbanik, 2000).
A nuclear-accident evacuation management system involves a multitude of processes with social, economic, and environmental implications, such as organization of salvage, gathering of population, grouping of evacuees, allocation of transportation resources, provision of services, and planning of evacuation routes. The processes are associated with several factors; the number of traffic vehicles employed, people to be evacuated, destinations of evacuees, limitations of evacuation times, budgets of the evacuation, capacities of shelters and hospitals, and environmental regulations. There are complex interactions between the processes and factors. Accident evacuation practices for large crowds are subject to extensive uncertainties, which further complicate the problem. The uncertainties normally result from unforeseeable incidents and deviations in subjective judgments. They are ubiquitous in many system components and may affect processes of data investigation, modeling computation, and the presentation of results. In fact, deterministic information is limited in evacuation efforts. For example, accident scale and evacuated population cannot be predictable because it is unexpected (i.e. caused by equipment malfunctions, operator error, or natural disasters), which makes it impossible to conduct proactive planning and analysis at the pre-evacuation stage. Hence, evacuation schemes are highly uncertain (e.g., locations, scales, and schedules) and evacuees are evacuated from multiple threatened areas to different destinations (shelters or hospitals).

It is difficult to plan the emergency evacuation because (i) there are a variety of reasons for nuclear accidents, (ii) the disasters are often too difficult to predict or cannot be effectively identified, (iii) there are a lack of sufficient data; (iv) there are
deficiencies in the scientific knowledge of the accidents and (v) there are a number of complexities and uncertainties associated with the accidents and modeling efforts. The complexities embedded within evacuation management systems are far beyond the capabilities of conventional optimization techniques. There is also a demand for studies that incorporate various isolated system components within a general framework to generate robust decision supports for nuclear-accident evacuation management.

3.2.2. Interval-parameter linear programming

Interval-parameter linear programming (ILP) is suitable for tackling uncertainties that cannot be quantified as membership or distribution functions, since interval numbers are acceptable as uncertainties for the ILP (Huang et al., 1992; Fan and Huang, 2012). ILP allows uncertainties to be directly communicated into the optimization process and resulting solutions. Feasible decision alternatives can be generated through interpretation of the interval solutions according to projected applicable conditions. An ILP model can be defined as follows (Huang et al., 1992):

Min \( f^\pm = C^\pm X^\pm \), \hspace{1cm} (3-1a)

subject to:

\[ A^\pm X^\pm \leq B^\pm, \] \hspace{1cm} (3-1b)

\[ X^\pm \geq 0, \] \hspace{1cm} (3-1c)

where \( A^\pm \in \{R^\pm\}^{m\times n}, B^\pm \in \{R^\pm\}^{m\times 1}, C^\pm \in \{R^\pm\}^{1\times n}, X^\pm \in \{R^\pm\}^{n\times 1}, \) and \( R^\pm \) denotes a set of interval numbers. The ‘-’ and ‘+’ superscripts represent lower and upper bounds.
for an interval parameter/variable, respectively. According to Huang et al. (1992), ILP
can be directly transformed into two deterministic submodels, which correspond to
the lower and upper bounds of the objective-function value. By solving the two
submodels, interval solutions can be obtained and used to generate a range of decision
options. The first submodel corresponding to \( f^- \) (when the objective function is
minimized) can be formulated as (assume \( b_i^+ > 0 \) and \( f_i^+ > 0 \)):

\[
\text{Min } f^- = \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^{n} c_j^+ x_j^+ 
\]

subject to:

\[
\sum_{j=1}^{k_1} \lvert a_{ij} \rvert \text{ Sign}(a_{ij}^-) x_j^- + \sum_{j=k_1+1}^{n} \lvert a_{ij} \rvert \text{ Sign}(a_{ij}^+) x_j^+ \leq b_i^- , \ \forall i 
\]

\[ x_j^+ \geq 0, \ \forall j \]  

\[
 x_j^+ \geq x_{j_{\text{opt}}}^-, \ j = 1, 2, \ldots, k_1 
\]

\[
 0 \leq x_j^- \leq x_{j_{\text{opt}}}^+, \ j = k_1 + 1, k_1 + 2, \ldots, n
\]

where \( x_j^+ \ (j = 1, 2, \ldots, k_1) \) are interval variables with positive coefficients in the
objective function. \( x_j^+ \ (j = k_1 + 1, k_1 + 2, \ldots, n) \) are interval variables with negative
coefficients. Solutions for \( x_{j_{\text{opt}}}^- \ (j = 1, 2, \ldots, k_1) \), \( x_{j_{\text{opt}}}^+ \ (j = k_1 + 1, k_1 + 2, \ldots, n) \) and \( f_{\text{opt}}^- \)
can be obtained from submodel (3-2). The second submodel for \( f^+ \) can be formulated
as:

\[
\text{Min } f^+ = \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^{n} c_j^- x_j^- 
\]

subject to:

\[
\sum_{j=1}^{k_1} \lvert a_{ij} \rvert \text{ Sign}(a_{ij}^+) x_j^+ + \sum_{j=k_1+1}^{n} \lvert a_{ij} \rvert \text{ Sign}(a_{ij}^-) x_j^- \leq b_i^+ , \ \forall i 
\]

\[ x_j^+ \geq x_{j_{\text{opt}}}^-, \ j = 1, 2, \ldots, k_1 
\]

\[
 0 \leq x_j^- \leq x_{j_{\text{opt}}}^+, \ j = k_1 + 1, k_1 + 2, \ldots, n
\]
Solutions of $x_{j_{\text{opt}}}^+ (j = 1, 2, \ldots, k_1)$, $x_{j_{\text{opt}}}^- (j = k_1 + 1, k_1 + 2, \ldots, n)$ and $f_{\text{opt}}^+$ can be obtained from submodel (3-3). By integrating the solutions of the two submodels, interval solutions for the ILP model can be expressed as:

$$x_{j_{\text{opt}}}^\pm = [x_{j_{\text{opt}}}^-, x_{j_{\text{opt}}}^+], \forall j$$

$$f_{\text{opt}}^\pm = [f_{\text{opt}}^-, f_{\text{opt}}^+]$$

(3-4a)

(3-4b)

### 3.2.3. Interval-based evacuation management (IBEM) model

Four main components are considered in a typical nuclear-power-plant emergency evacuation system (shown in Figure 3.1). They are: (i) victim flow section, released into the shelters, (ii) makeshift refuge point (MRP) section where residents are advised to evacuate themselves to their respective MRPs for emergence relief and wait to be delivered to long-term settlements, (iii) transfer station section, which can accept the victim flow from the MRPs and transport victim flow into long-term settlements, (iv) long-term settlement (LSP) section, which is the termination point.

An interval-based evacuation management (IBEM) model for nuclear power plant accidents can be formulated as:

$$\text{Max } f^\pm = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{i,j,k}^\pm$$

(3-5a)

subject to:

$$x_{i,j,k}^\pm / \alpha \leq FAS_{i,j}^\pm, \forall i, j, k$$

(3-5b)

$$y_k^\pm / \alpha \leq VFT^\pm, \forall k$$

(3-5c)
\[
\sum_{i=1}^{l} x_{i,2,k} = y_{k}, \quad \forall k
\]  
(3-5d)

\[
\sum_{j=1}^{l} x_{i,j,k} \geq \beta_{i,k}^{+} PA_{i,k}^{+}, \quad \forall i, k
\]  
(3-5e)

\[
\sum_{i=1}^{l} x_{i,2,k} \leq CT^{+}, \quad \forall k
\]  
(3-5f)

\[
\sum_{k=1}^{K} L_{k} (\sum_{i=1}^{l} x_{i,1,k} + y_{k}^{+}) \leq CS^{+}
\]  
(3-5g)

\[
\sum_{k=1}^{K} L_{k} C_{k} \left( y_{k}^{+} DTS + (\sum_{i=1}^{l} x_{i,2,k} - y_{k}^{+}) \times DTC + \sum_{j=1}^{l} \sum_{j=1}^{j} x_{i,j,k} D_{i,j} \right) \leq TC^{+}
\]  
(3-5h)

\[
x_{i,j,k} \in N, \quad \forall i, j, k
\]  
(3-5i)

\[
y_{k}^{+} \in N, \quad \forall k
\]  
(3-5j)

where:

- \( f^{+} \) = total population flow (person);
- \( i \) = the type of emergency assembly point, \( i = 1, 2, 3 \);
- \( j \) = the type of settlement, \( j = 1, 2 \), where \( j = 1 \) for settlement 1, \( j = 2 \) for settlement 2;
- \( L_{k} \) = the length of time period \( k \) (hour);
- \( k \) = planning time period, and \( k = 1, 2, 3 \);
- \( x_{i,j,k}^{+} \) = population flow from emergency assembly point \( i \) to settlement \( j \) during period \( k \) (person/hour);
- \( y_{k}^{+} \) = the patient population flow from transfer station to settlement 1 during period \( k \) (person/hour);
- \( FAS_{ij} \) = the maximum vehicle flux in the road from emergency assembly point \( i \) to settlement \( j \) (vehicle/hour);
\( VFT \) = the maximum vehicle flux in the road from transfer station to settlement 1 (vehicle/hour), where only settlement 1 has hospital; \( a \) is conversion coefficient;
\( \gamma_k^\pm \) = the proportion of patient population in the evacuation process to settlement 2;
\( PA_{i,k}^\pm \) = the population aggregation velocity to emergency assembly point \( i \) in period \( k \) (person/hour);
\( \beta_{i,k}^\pm \) = the evacuation capability of emergency assembly point \( i \) in period \( k \);
\( CT^k \) = the capacity of transfer station (person/hour);
\( CS^k \) = the capacity of settlement 1 (person);
\( C_k \) = the transport cost ($/person/km);
\( DTS \) = the distance from transfer station to settlement 1 (km);
\( DTC \) = the distance from transfer station to settlement 2 (km);
\( Di \) = the distance from emergency assembly point \( i \) to transfer station (km);
\( TC^k \) = the total capital ($).

The objective of the IBEM model is to obtain a preferred plan for maximizing the number of evacuees in a finite time. Constraints can define the interrelationships among the decision variables and the vehicle flux, capacity, and economic conditions. Constraints (3-5b) and (3-5c) dictate the population flow from emergency assembly point to settlement must not exceed the maximum vehicle flux in the road. Constraint (3-5d) states the patients in the evacuating population fluctuate in a range. Constraint (3-5e) states a certain percentage of the population at the emergency assembly point should be evacuated during each period. Constraint (3-5f) states the population
Figure 3.1. The study system (note: PR denotes places of refuge)
transported to transfer stations must not exceed the capacity of the transfer stations. Constraint (3-5g) denotes that the population evacuated to settlements must not exceed the capacity of the settlements. Constraint (3-5h) states the total system cost must not exceed the financial budget. Constraints (3-5i) and (3-5j) define the evacuating population as an integer.

3.3. Case Study

Consider an emergency evacuation system wherein decision makers are responsible for evacuating a large number of people after a nuclear accident event from an original location to multiple pre-specified destinations through public transit. Planning for vehicle allocation and routing strategies is a major concern, which primarily relies on efficient utilization of transportation resources and services. The problem is concerned with how to quickly transfer threatened people from dangerous places to safe places to reduce the health and life vulnerability of affected people. Nuclear power accidents are often associated with a radiological release and the shelter facilities (i.e. MRPs, LSPs and transfer station sections) are polluted by the radioactive material because of atmospheric dispersion. During a disaster response, evacuation should be conducted accurately and quickly. Evacuation planning is a very complex problem involving many behavioral and management facets (Saadatseresht et al., 2009).

The planning time is three hours and divided into three time periods (each period has a time interval of one hour). The planning periods are less than the time for radioactive material to arrive at sheltered facilities. The emergency evacuation system
includes three MRPs, two LSPs and one transfer station, where three MRPs can deliver the victim flow to LSP2 by the transfer station. The LSP1 has an existing capacity of 14,500 to 15,000 persons, and the transfer station has a capacity of 280 to 300 vehicles/hour. LSP1 has an affiliated hospital offering the professional therapy for the patients infected by radioactive material. It would be received approximately [4, 8]% of victim flow from LSP2. Table 3.1 shows the velocity of victim flow gathering into the MRPs. The gather velocities vary between different MRPs and time periods. Table 3.2 shows the distance and maximum traffic flow of each thoroughfare. The problem under consideration is how to effectively allocate the victim flow from the three MRPs to the two LSPs to achieve maximum outflow within a limited time. To enable a fast and safe evacuation, the IBEM model will be applied to reorganize traffic routing through a given area.

### 3.4. Result Analysis

#### 3.4.1 Solutions under Scenario 1

Two scenarios are analyzed based on different policies of total investment (capital) considerations since tradeoffs between economic and safety arguments exist in the management of a nuclear power plant. Scenario 1 represents emergency evacuation management planning without a total investment limit. Table 3.3 shows the solutions obtained under this scenario. Point 1 \((i = 1)\) would have the highest evacuation rate over three time periods. The population from emergency assembly point 1 to settlement 1 would be \([3570, 3740]\) persons/hour in three periods, and to settlement 2
is [3390, 3570], [3340, 3550], [3400, 3570] persons/hour in three periods, respectively. The road conditions from emergency assembly point 1 to settlements 1 and 2 are better than other roads. The maximum vehicle flux in the two roads would be [210, 220] and [200, 210] vehicles/hour, while vehicle flux on the other roads would be less than 170 vehicles/hour. The evacuation rate of the emergency assembly point 1 is mainly subjected to the vehicle flux constraint. The person evacuated from emergency assembly point 1 are too close to the accident, making it necessary to evacuate people by emergency assembly points1 and 2. The evacuated population rate from emergency assembly point 2 to settlement 1 would be [2890, 3060] persons/hour in three periods, and to settlement 2 would be [18, 167], [377, 433], [364, 378] person/hour in the three periods, respectively. The evacuation rate from emergency assembly point 3 to settlement 1 would be [2380, 2550] person/hour in planning periods, and to settlement 2 would be [1342, 1363], [927, 1153], [982, 1166] person/hour in the three periods, respectively. Figure 3.2 presents the patient population flow from transfer station to settlement 1 in three periods. From the figure, the patient population flow increases from [190, 255] person/hour in period 1 to [329, 381] person/hour in period 2, and finally reach up to [357, 408] person/hour in period 3. This is due to the fact that unforeseen circumstance would be occurred owing to people’s nervousness.
Table 3.1. Velocity of victim flow into the MRPs

<table>
<thead>
<tr>
<th>PA (person/hour)</th>
<th>$k = 1$</th>
<th>$k = 2$</th>
<th>$k = 3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRP 1 ($i = 1$)</td>
<td>[2450, 2500]</td>
<td>[2700, 2750]</td>
<td>[2550, 2600]</td>
</tr>
<tr>
<td>MRP 2 ($i = 2$)</td>
<td>[2450, 3500]</td>
<td>[3600, 3650]</td>
<td>[3500, 3600]</td>
</tr>
<tr>
<td>MRP 3 ($i = 3$)</td>
<td>[3200, 3250]</td>
<td>[3400, 3500]</td>
<td>[3100, 3200]</td>
</tr>
</tbody>
</table>
Table 3.2. Distance and maximum traffic flow of each thoroughfare

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Distance (km)</th>
<th>Traffic flow (pcu/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRP 1 ($i = 1$)</td>
<td>TS ($j = 1$)</td>
<td>35</td>
<td>210</td>
</tr>
<tr>
<td>MRP 2 ($i = 2$)</td>
<td>TS ($j = 1$)</td>
<td>25</td>
<td>160</td>
</tr>
<tr>
<td>MRP 3 ($i = 3$)</td>
<td>TS ($j = 1$)</td>
<td>30</td>
<td>120</td>
</tr>
<tr>
<td>MRP 1 ($i = 1$)</td>
<td>LSP 1 ($j = 2$)</td>
<td>20</td>
<td>220</td>
</tr>
<tr>
<td>MRP 2 ($i = 2$)</td>
<td>LSP 1 ($j = 2$)</td>
<td>30</td>
<td>180</td>
</tr>
<tr>
<td>MRP 3 ($i = 3$)</td>
<td>LSP 1 ($j = 2$)</td>
<td>36</td>
<td>150</td>
</tr>
<tr>
<td>TS ($j = 1$)</td>
<td>LSP 1 ($j = 2$)</td>
<td>24</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: MRP is makeshift refuge point; TS is transfer station; LSP is long-term settlement place
Table 3.3. Results of evacuation scheme without capital limit

<table>
<thead>
<tr>
<th>X (person/hour)</th>
<th>k = 1</th>
<th>k = 2</th>
<th>k = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>i = 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j = 1</td>
<td>[3570, 3740]</td>
<td>[3570, 3740]</td>
<td>[3570, 3740]</td>
</tr>
<tr>
<td>j = 2</td>
<td>[3390, 3570]</td>
<td>[3340, 3550]</td>
<td>[3400, 3570]</td>
</tr>
<tr>
<td>i = 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j = 1</td>
<td>[2890, 3060]</td>
<td>[2890, 3060]</td>
<td>[2890, 3060]</td>
</tr>
<tr>
<td>j = 2</td>
<td>[18, 167]</td>
<td>[377, 433]</td>
<td>[364, 378]</td>
</tr>
<tr>
<td>i = 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j = 1</td>
<td>[2380, 2550]</td>
<td>[2380, 2550]</td>
<td>[2380, 2550]</td>
</tr>
<tr>
<td>j = 2</td>
<td>[1342, 1363]</td>
<td>[927, 1153]</td>
<td>[982, 1166]</td>
</tr>
</tbody>
</table>

Note: symbol i denotes emergency assembly point; j denotes settlement; k denotes time period
3.4.2. Solutions under scenario 2

A total capital (investment) limit was considered for the evacuation management system under scenario 2. Table 3.4 presents solutions for the emergency evacuation pattern under this scenario. Emergency assembly point 1 is the largest source for settlement 1. Road conditions from assembly point 1 to settlement 1 are better than others and their distance (from point 1 to settlement 1) is the shortest. However, due to the limited capacity of settlement 1, there is a population flow being transferred to settlement 2. Emergency assembly point 2 is the largest source for settlement 2, although the road conditions from assembly point 2 to settlement 2 are worse than point 1 to settlement 2. The distance from assembly point 2 to settlement 2 is the shortest. Comparing the results from scenario 1, the evacuated population to settlement 2 is smaller under scenario 2. The distances from emergency assembly points to settlement 2 are much longer than that to settlement 1. The long distance could cost more money and time.

Figure 3.3 shows the patient population flow from the transfer station to settlement 1 during the planning horizon, the patient population would increase from [185, 245] persons/hour in period 1 to [305, 340] persons/hour in period 2, and achieve [351, 388] persons/hour in period 3. The patient population is less than under scenario 1. Transporting patients would require special establishments, additional capital, and excess time, resulting in increased cost. The decision makers would conduct a series of publicity activities to decrease the patient population.
Figure 3.2. Results of patient population from transfer station to hospital (scenario 1)
Table 3.4. Results of evacuation scheme with capital limit

<table>
<thead>
<tr>
<th>X (person/hour)</th>
<th>k = 1</th>
<th>k = 2</th>
<th>k = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>i = 1</td>
<td>j = 1</td>
<td>[3570, 3740]</td>
<td>[3570, 3740]</td>
</tr>
<tr>
<td></td>
<td>j = 2</td>
<td>[350, 3570]</td>
<td>[0, 979]</td>
</tr>
<tr>
<td>i = 2</td>
<td>j = 1</td>
<td>[1890, 3060]</td>
<td>[2890, 3060]</td>
</tr>
<tr>
<td></td>
<td>j = 2</td>
<td>[1057, 2550]</td>
<td>[371, 1518]</td>
</tr>
<tr>
<td>i = 3</td>
<td>j = 1</td>
<td>[2380, 2550]</td>
<td>[2380, 2550]</td>
</tr>
<tr>
<td></td>
<td>j = 2</td>
<td>[473, 1870]</td>
<td>[782, 810]</td>
</tr>
</tbody>
</table>
3.4.3. Total evacuated populations

Figure 3.4 shows the total evacuated population (objective function values) under scenarios 1 and 2. The solutions to the objective function values are \([20365, 21665]\) persons under scenario 1 and \([19125, 20205]\) persons under scenario 2, which represent the range of expected people needed for evacuation. When the actual value of each variable varies within its lower and upper bounds, the expected evacuees would change within the solution interval. Specifically, lower decision variable values within their solution intervals (e.g., less population from emergency assembly to settlement) should be potentially used under advantageous conditions. Comparatively, higher decision variable values (i.e., more people transferred to destinations) would correspond to more demanding conditions. A willingness to transfer less people to reach the destinations would guarantee a high system stability (i.e. low risk of violating system constraints). A desire to transfer more people will run into the risk of potential instability of the system (i.e. a high risk of violating system constraints).

The total evacuated population under scenario 1 would be higher than under scenario 2. The capital limit would lead to a decreasing evacuated population transferred to settlement 2. Since the distance (from assembly points) to settlement 2 is larger than to settlement 1, the transportation cost would increase with transportation distance leading to increased system cost. Vehicle flux is the major impact factor under scenario 1 and capital limit is the major impact factor under scenario 2. The solutions obtained from the proposed model support emergency evacuation management decisions. The interval solutions generate decision
Figure 3.3. Results of patient population from transfer station to hospital (scenario 2)
Figure 3.4. Results of total evacuation populations under two scenarios
alternatives, where a spectrum of options can be analyzed based on a decision maker’s preferences.

3.5. Summary

An interval-based evacuation management (IBEM) model has been developed in response to nuclear power plant accidents under uncertainty. The IBEM model is based on the interval-parameter linear programming (ILP) technique for tackling uncertainties that cannot be quantified as distribution or membership functions, since interval values are acceptable as its uncertain inputs. The number of evacuees, vehicle allocation plans and corresponding routing strategies can be generated with the IBEM model to evacuate large crowds after a nuclear power plant accident. Parameters for emergency evacuation systems are integrated into a general modeling formulation, without overemphasizing one issue at the expense others. These include the zone for evacuation, the population at the risk, the predicted time for evacuation, the shelter of refugees, the safe routes for evacuation, and the levels of logistics to be offered. A variety of uncertainties can be directly communicated into the optimization process.

The case study produced useful solutions. A number of decision alternatives can be obtained from the solutions by adjusting different combinations of the population shipped within the solution intervals according to projected conditions. They reflect a compromise between optimality and stability, and are realistic reflections of the system complexities. Since tradeoffs between economic and safety arguments exist in the management of nuclear power plants, two scenarios are analyzed based on
different policies for total capital considerations. Willingness to spend more capital for evacuation would guarantee the system stability (transfer more population). Conversely, a desire to shorten the investment will run into potential system-failure risk.

The IBEM model is applicable to evacuation problems associated with uncertainties expressed as discrete intervals. This is also the first attempt to strengthen the nuclear-power-plant disaster response and emergency management to mitigate their negative effects. The results suggest the IBEM model can explicitly address complexities and uncertainties in emergency evacuation management systems and is applicable to real-world practical nuclear accidents. The IBEM model could be further enhanced by incorporating methods for fuzzy programming and stochastic analysis into its framework to address more complex uncertainties and dynamics.
Chapter 4  An Inexact Gradient-Based Fuzzy Chance Constrained Programming Model for Nuclear Emergency Management

4.1. Background

Emergency evacuation planning is of great importance for ensuring public health safety when a nuclear power accident occurs. The emergency evacuation is critical for nuclear power plants in China because the coastal areas, where the nuclear power plants are located, are usually the most densely populated regions. As the largest nuclear power site in China, the Qinshan Nuclear Power Site (QNPS) is equipped with seven operating units, and there are four more units under construction or planned. The emergency evacuation management system contains great complexities and uncertainties. For instance, the pressurized water reactors are in three different power plants within the nuclear power site, with various radionuclide release start times and release duration times. There are three different temporary shelters and four nearby cities to accommodate evacuees. There are many evacuation routes that connect the nuclear site and the designed temporary shelters, with various road conditions and capacities. Complexities have posed many challenges for local decision makers. To address the various complexities of the QNPS system, and to minimize the adverse influence of nuclear accidents and ensure public health safety, optimal nuclear emergency evacuation management plans are desired.

An optimization model for nuclear emergency management will be proposed for the QNPS. A large-scale regional inexact gradient-based fuzzy chance constrained
programming (IGFCCP) model will be developed to address various uncertainties and optimize the planning of an evacuation scheme within the study horizon. The proposed model will be capable of addressing uncertainties described as possibility distributions and intervals in the evacuation management system. In addition, the model will balance a decision maker’s optimism and pessimism regarding the capacities of the evacuation routes. The results will be valuable for generating optimized evacuation strategies under multiple uncertainties.

4.2. Emergency Evacuation Management at the QNPS

4.2.1. Overview of the Study Region

QNPS is in the Haiyan County of Zhejiang Province, with an area of $1.3 \times 10^6$ m² (Figure 4.1). It was the first nuclear power site constructed in mainland China. There are three nuclear power plants in the QNPS. The QNPS is approximately 108 km from Shanghai to the northeast, 82 km from Hangzhou to the west, and 43 km from Jiaxing to the north. The QNPS is seated in the Qinshan Town of Haiyan County, and it is 8 km away from the county capital at the southeast. The total population in the Haiyan County is about 370,000, with about 31,000 people in the Qinshan Town.

The construction of the Qinshan I nuclear power plant started in 1984. Qinshan I is the first domestically designed and constructed nuclear power plant in China (Wang, 2009). It has a CNP-300 pressurized water reactor with a light water reactor cooling system and three radiation shields (IAEA). It started operating in April 1991, with a capacity of 300 MWe. The electricity has been supplied from the grid since December
Figure 4.1. Location of the QNPS
1991. The total electricity generated from the station is over 35 trillion kWh (WNA, 2011). The construction of the Qinshan II nuclear power plant began in June, 1996. There are four operational units in Qinshan II, with a total capacity of 2,440 MWe. It is equipped with two-loop CNP-600 pressurized water reactors, which are based on an improved design of the reactor in Qinshan I. The four units first supplied electricity for the grid in February, 2002, March, 2004, August, 2010, and November, 2012, respectively. The Qinshan III nuclear power plant consists of two operational units, with a capacity of 650 MWe from each reactor. The reactors are CANDU-6 pressurized heavy-water reactors, designed by Atomic Energy of Canada Limited. The construction work started June, 1998 and the two units began operating in November, 2002 and June, 2003, respectively.

Emergency planning for the QNPS was conducted according to the national standard “Criteria for emergency planning and preparedness for nuclear power plants” and the local natural and social conditions. The emergency planning zones are classified into two major types: A plume emergency planning zone (PEPZ) and ingestion emergency planning zone (IEPZ). The PEPZ is further divided into the inner and outer zones. Its design is based on the meteorological conditions and the MELCOR Accident Consequence Code System (MACCS) code provided by the US Sandia National Laboratory. The PEPZ is centered around the #2 nuclear power plant, with an inner zone radius of 5 km and an outer zone radius of 7 km. The PEPZ covers Qinshan District, Ganfu Town and Tongyuan Town, including 18 villages and two towns, as presented in Table 4.1. The inner zone contains the villages in the Qinshan District, Gandong, Zhenzhong and Gannan in the Ganfu Town.
Table 4.1. The ranges for the inner and outer zones for the PEPZ

<table>
<thead>
<tr>
<th>Town/District</th>
<th>Inner Zone</th>
<th>Outer Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qinshan</td>
<td>Qinshan, Yangliushan, Qinxing, Changchuanba,</td>
<td>Qinshan, Yangliushan, Qinxing, Changchuanba,</td>
</tr>
<tr>
<td></td>
<td>Fegnshan, Yongxing, Beitoan, Qinshanjizhen</td>
<td>Fegnshan, Yongxing, Beitoan, Qinshanjishzen,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xinlian, Qingfeng</td>
</tr>
<tr>
<td>Ganfu</td>
<td>Gandong, Zhenzhong, Gannan</td>
<td>Gandong, Zhenzhong, Gannan, Baoshan, Yongxin,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ganfu, Ganfujizhen</td>
</tr>
<tr>
<td>Tongyuan</td>
<td></td>
<td>Xueshuigang, Fengyi</td>
</tr>
</tbody>
</table>
4.2.2. Problem Statement

The QNPS’s study for hypothetical severe nuclear accidents was conducted based on “The Reactor Safety Study - WASH-1400” provided by the US Nuclear Regulatory Commission in 1975. According to the studies of hypothetical severe nuclear accidents, as soon as the type and scale of an accident is identified, critical questions can be answered, such as how soon the radioactive substances would be released and how long it would last,. An emergency evacuation plan should be generated, to evacuate as many residents as possible within the maximum allowable evacuation time.

The QNPS’s emergency evacuation system’s evacuation routes are shown in Figure 4.2. Five assembly places (APs), three temporary settlements (TSs), and four nearby settlement cities (CSs) are selected to accommodate evacuees in an accident. The five APs are provided to assemble the population, in which three of them are in the Qinshan Town (Chuangchuanba Village Committee, Qinshan Middle School and Luotang Village Committee) and the other two placed in the Ganfu Town (Zhenzhong Village, the intersection between Nanbeihu Street and Huhang Road). Once a nuclear accident occurs at the QNPS, residents in the inner zone of the PEPZ would be transported from the APs to the TSs. The three TSs are Xitangqiao Area, Baibu Town, and Yuanhua Town in the City of Haining. The evacuees would be transported and accommodated to the four nearby cities, i.e., Haining, Jiaxing, Tongxiang and Pinghu. The four cities are affiliated with facilities for basic medical and radiation injury
treatments. However, the severely injured evacuees would only be sent to Jiaxing City for more advanced treatment.

Even though clear evacuation routes have been identified, the evacuation system is inherent with extensive uncertainties resulting from unforeseeable incidents and deviations in subjective judgments. For example, the evacuees in the inner zone cannot be accurately quantified due to the spatial-temporal variation of the population in the local communities. The vehicle flux and road capacities for evacuation may not be estimated by deterministic values. Uncertainties may be compounded due to the interactions among uncertain parameters and integration of various uncertainties. The uncertainties bring great challenges to the decision makers for an effective emergency evacuation management. Consequently the complex system and its uncertain components must be characterized to generate appropriate evacuation schemes under various uncertainties.

4.2.3. Data collection

Extensive investigations and data collections were conducted to characterize the QNPS’s evacuation management system. According to the Population Census of Haiyan County in 2009, and analysis of Haiyan County’s naturaly increasing population rate between 1992 and 2009, the population in the PEPZ is approximately 52,800, with 46,048 permanent residents. The total population in the inner PEPZ is around 23,400, with about 4,500 migrants. Detailed information regarding the
Figure 4.2. The detailed evacuation routes
evacuation facilities and routes were collected from the Nuclear Power Plant Accident Emergency Committee of Zhengjiang Province (NPPAEC-ZJ). The three TS capacities are presented in Table 4.2. The three TSs, i.e., Xitangqiao Area, Baibu Town, and Yuanhua Town, are denoted as XA, BT and YT, respectively. Table 4.3 provides the lengths of the evacuation routes from the APs to the TSs, and Table 4.4 provides the route lengths from the TSs to the CSs. The five APs, i.e., Chuangchuanba Village Committee, Qinshan Middle School, Luotang Village Committee, Zhenzhong Village, and the intersection between Nanbeihu Street and Huhang Road, are denoted as CVC, QMS, LVC, ZVG and NSHR, respectively. The four CSs, i.e., Jiaxing, Pinghu, Tongxiang and Haining, are denoted as JX, PH, TX, and HN, respectively. The evacuation route vehicle capacities were estimated by the transportation department, and the maximum allowable vehicle fluxes for the routes between the TSs and CSs are given in Table 4.5. The maximum number of available ambulances from CS1 (i.e., Jiaxing) were estimated with a basic investigation of Jiaxing’s medical equipment, as given in Table 4.6. Each ambulance is capable of transporting \([1, 2]\) severely injured evacuees.

The maximum evacuation capacity from the APs to the TSs is affected by various factors, including transportation methods and local road conditions. The uncertainties can be addressed by describing them using intervals. Detailed membership information was collected from an expert assessment, and the maximum evacuation rates are presented as triangular fuzzy sets \((b, \bar{b}, \bar{b})\). The minimum, maximum and most likely values defining the fuzzy sets are tabulated in Table 4.7.
Table 4.2. The capacities of TSs.

<table>
<thead>
<tr>
<th>TS Name</th>
<th>Construction Area (m²)</th>
<th>Education Usage Area (m²)</th>
<th>Population Settlement (person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XA</td>
<td>32,101</td>
<td>13,482</td>
<td>[4400, 4600]</td>
</tr>
<tr>
<td>BT</td>
<td>21,216</td>
<td>8,911</td>
<td>[2900, 3100]</td>
</tr>
<tr>
<td>YT</td>
<td>11,267</td>
<td>14,732</td>
<td>[4700, 4900]</td>
</tr>
</tbody>
</table>

Note: Xitangqiao Area, Baibu Town, and Yuanhua Town, are denoted as XA, BT and YT
### Table 4.3. The lengths of the evacuation routes from APs to TSs (Unit: km).

<table>
<thead>
<tr>
<th></th>
<th>CVC</th>
<th>QMS</th>
<th>LVC</th>
<th>ZVG</th>
<th>CNSHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>XA</td>
<td>19.1</td>
<td>16.7</td>
<td>15.5</td>
<td>24.8</td>
<td>26.5</td>
</tr>
<tr>
<td>BT</td>
<td>25.1</td>
<td>22.7</td>
<td>21.5</td>
<td>28.3</td>
<td>26.7</td>
</tr>
<tr>
<td>YT</td>
<td>22.3</td>
<td>23.2</td>
<td>22.0</td>
<td>18.3</td>
<td>16.6</td>
</tr>
</tbody>
</table>

Note: CVC denotes Chuangchuanba Village Committee; QMS denotes Qinshan Middle School, LVC denotes Luotang Village Committee, ZVG denotes Zhenzhong Village, NSHR denotes the intersection between Nanbei Street and Huhang Road,
Table 4.4. The lengths of the evacuation routes from TSs to CSs (Unit: km).

<table>
<thead>
<tr>
<th></th>
<th>JX</th>
<th>PH</th>
<th>TX</th>
<th>HN</th>
</tr>
</thead>
<tbody>
<tr>
<td>XA</td>
<td>33.4</td>
<td>36.0</td>
<td>28.0</td>
<td>19.0</td>
</tr>
<tr>
<td>BT</td>
<td>29.4</td>
<td>32.6</td>
<td>48.6</td>
<td>26.8</td>
</tr>
<tr>
<td>YT</td>
<td>45.8</td>
<td>23.4</td>
<td>17.8</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Note: JX, PH, TX, and HN denotes Jiaxing, Pinghu, Tongxiang and Haining, respectively.
Table 4.5. The maximum allowable vehicle flux from TSs to CSs (Unit: vehicle/h).

<table>
<thead>
<tr>
<th></th>
<th>JX</th>
<th>PH</th>
<th>TX</th>
<th>HN</th>
</tr>
</thead>
<tbody>
<tr>
<td>XA</td>
<td>[34, 36]</td>
<td>[33, 83]</td>
<td>[34, 36]</td>
<td>[33, 83]</td>
</tr>
<tr>
<td>BT</td>
<td>[34, 36]</td>
<td>[33, 83]</td>
<td>[11, 15]</td>
<td>[11, 15]</td>
</tr>
<tr>
<td>YT</td>
<td>[33, 83]</td>
<td>[33, 83]</td>
<td>[33, 83]</td>
<td>[24, 26]</td>
</tr>
</tbody>
</table>
Table 4.6. The maximum available ambulances from CS1 (Unit: vehicle/h).

<table>
<thead>
<tr>
<th>Number</th>
<th>XA</th>
<th>BT</th>
<th>YT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[30, 32]</td>
<td>[52, 55]</td>
<td>[24, 26]</td>
</tr>
</tbody>
</table>

Table 4.7. The minimum, maximum and the most likely values of the maximum evacuation rates from APs to TSs (Unit: person/h).

<table>
<thead>
<tr>
<th>Route</th>
<th>$\bar{b}$</th>
<th>$b$</th>
<th>$\tilde{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP1 to TS1</td>
<td>711</td>
<td>1,218</td>
<td>1,725</td>
</tr>
<tr>
<td>AP1 to TS2</td>
<td>837</td>
<td>1,571</td>
<td>2,304</td>
</tr>
<tr>
<td>AP1 to TS3</td>
<td>693</td>
<td>1,271</td>
<td>1,848</td>
</tr>
<tr>
<td>AP2 to TS1</td>
<td>711</td>
<td>1,217</td>
<td>1,722</td>
</tr>
<tr>
<td>AP2 to TS2</td>
<td>837</td>
<td>1,571</td>
<td>2,304</td>
</tr>
<tr>
<td>AP2 to TS3</td>
<td>1,836</td>
<td>2,841</td>
<td>3,846</td>
</tr>
<tr>
<td>AP3 to TS1</td>
<td>711</td>
<td>1,217</td>
<td>1,722</td>
</tr>
<tr>
<td>AP3 to TS2</td>
<td>837</td>
<td>1,571</td>
<td>2,304</td>
</tr>
<tr>
<td>AP4 to TS3</td>
<td>1,836</td>
<td>2,841</td>
<td>3,846</td>
</tr>
<tr>
<td>AP4 to TS1</td>
<td>711</td>
<td>1,217</td>
<td>1,722</td>
</tr>
<tr>
<td>AP4 to TS2</td>
<td>624</td>
<td>963</td>
<td>1,302</td>
</tr>
<tr>
<td>AP5 to TS3</td>
<td>693</td>
<td>1,271</td>
<td>1,848</td>
</tr>
<tr>
<td>AP5 to TS1</td>
<td>711</td>
<td>1,217</td>
<td>1,722</td>
</tr>
<tr>
<td>AP5 to TS2</td>
<td>624</td>
<td>963</td>
<td>1,302</td>
</tr>
<tr>
<td>AP5 to TS3</td>
<td>693</td>
<td>1,271</td>
<td>1,848</td>
</tr>
</tbody>
</table>
4.3. Development of an Emergency Evacuation Management Model

4.3.1. Methodology

The Inexact Gradient-based Fuzzy Chance Constrained Programming (IGFCCP) model was developed based on interval-parameter programming (IPP) and Fuzzy Chance Constrained Programming (FCCP). Uncertainties presented as discrete intervals can be reflected through IPP, and uncertainties in the format of fuzzy sets can be addressed through GFCCP. The model can be solved with a two-step algorithm to provide feasible and reliable solutions for nuclear emergency management under multiple uncertainties.

A general optimization model with interval parameters and fuzzy right-hand-side variables can be formulated as:

\[
\begin{align*}
\text{Max } f &= c^+ x \\
\text{subject to: } A^+ x &\leq \tilde{b} \\
x &\geq 0
\end{align*}
\]

(4-1a, 4-1b, 4-1c)

where \( x^+ \) is a vector of decision variables; \( c^+ \) and \( A^+ \) denotes the interval parameters with crisp lower and upper bounds but unknown distribution information; \( \tilde{b} \) is a vector of fuzzy sets.

Let the fuzzy membership functions of \( \tilde{b} \) be triangular functions given by:

\[
\mu(t) = \begin{cases} 
\frac{t - b}{b - \underline{b}} & \text{if } b \leq t \leq \bar{b}, \\
\frac{t - b}{\bar{b} - \underline{b}} & \text{if } b \leq t \leq \bar{b}, \\
0 & \text{otherwise.}
\end{cases}
\]

(4-2)
Possibility and necessity are the two most widely used functions to describe the likelihood of a fuzzy event occurring. The possibility of the fuzzy event $\tilde{b} > r$ is defined as:

$$\text{Pos}(\tilde{b} > r) = \begin{cases} 
1 & \text{if } r \leq b, \\
\frac{\tilde{b} - r}{\tilde{b} - b} & \text{if } b \leq r \leq \tilde{b}, \\
0 & \text{if } r \geq \tilde{b}.
\end{cases}$$

(4-3)

And the necessity of the fuzzy event wherein $\tilde{b} > r$ is defined as:

$$\text{Nec}(\tilde{b} > r) = \begin{cases} 
1 & \text{if } r \leq \tilde{b}, \\
\frac{b - r}{b - \tilde{b}} & \text{if } \tilde{b} \leq r \leq b, \\
0 & \text{if } r \geq b.
\end{cases}$$

(4-4)

Possibility is an adventurous measure and necessity is a conservative measure. A gradient-based measure (GM) was proposed in this study in order to balance the decision maker’s optimism and pessimism. GM is a combination of possibility and necessity defined as:

$$\text{GM}(\tilde{b} > r) = \lambda \text{Pos}(\tilde{b} > r) + (1 - \lambda) \text{Nec}(\tilde{b} > r)$$

(4-5)

where the gradient is limited as $0 \leq \lambda \leq 1$. The larger the fuzzy gradient $\lambda$, the more optimistic the decision maker. The smaller the fuzzy gradient $\lambda$, the more pessimistic the decision maker.

The fuzzy membership function, and the possibility, necessity, and GM of the fuzzy event $\tilde{b} > r$ are illustrated in Figure 4.3. Given a gradient $\lambda$, the confidence level of the GM can be calculated as:
Figure 4.3. Fuzzy membership, possibility, necessity and GM of the fuzzy event $\tilde{b} > r$. 
Hence, by applying the concept of GM into the optimization framework, model 4-1 can be transformed into an IGFCC model as:

Max \( f = c^* x \) \hspace{1cm} (4-7a)

subject to: \( GM(A^* x \leq b) > \alpha^* \) \hspace{1cm} (4-7b)

\( x \geq 0 \) \hspace{1cm} (4-7c)

\( 0 \leq \lambda \leq 1 \) \hspace{1cm} (4-7d)

\( 0 \leq \alpha^* \leq 1 \) \hspace{1cm} (4-7d)

where \( \alpha^* \) denotes the decision makers’ confidence level of the GM. To mitigate the constraint violation risks, particularly in emergency management, the decision maker is usually slightly conservative, which can be expressed as \( \lambda \leq 0.5 \). Thus, the Constraint (7b) can be re-written as:

\[
GM(A^* x \leq b) = \frac{b - \lambda b - A^* x (1 - \lambda)}{b - b} > \alpha^* \hspace{1cm} (4-8)
\]

Model 4-7 can be transformed as:

Max \( f = c^* x \) \hspace{1cm} (4-9a)

subject to: \( (1 - \lambda)A^* x \leq b - \lambda b - \alpha^* (b - b) \) \hspace{1cm} (4-9b)

\( x \geq 0 \) \hspace{1cm} (4-9c)

\( 0 \leq \lambda \leq 1 \) \hspace{1cm} (4-9d)
The uncertainties, in the form of intervals, can be further addressed by introducing an interval-parameter programming approach developed by Fan and Huang (2012). Interval solutions for the objective function value and the decision variables can be obtained with two deterministic sub-models by applying a two-step interactive solution algorithm. The sub-model corresponding to the upper bound of the objective function value is formulated as:

\[
\text{Max } f^- = \sum_{j=1}^{k_1} c_j^- x_j^- + \sum_{j=k_1+1}^{n} c_j^+ x_j^+ 
\]

subject to:

\[
\sum_{j=1}^{k_1} |a_{ij}^-| \text{ sign}(a_{ij}^-) x_j^- + \sum_{j=k_1+1}^{n} |a_{ij}^+| \text{ sign}(a_{ij}^+) x_j^+ \leq (b - \lambda b - \alpha^+(b-b)) / (1-\lambda), i = 1, 2, ..., m
\]

(4-10a)

\[
x_j^- \geq 0, j = 1, 2, ..., k_1
\]

(4-10b)

\[
x_j^+ \geq 0, j = k_1 + 1, k_1 + 2, ..., n
\]

(4-10c)

where the coefficients \( c_j^- \) (\( j = 1 \) to \( k_1 \)) are positive and the coefficients \( c_j^- \) (\( j = k_1 + 1 \) to \( n \)) are negative. \( \text{sign}(a_{ij}^+) \) denotes -1 when \( a_{ij}^+ < 0 \) and it denotes 1 when \( a_{ij}^+ > 0 \). \( f^- \) is the lower bound of the objective function value.

Model 4-10 can be solved and the optimal solution \( x_{j-opt}^- \) for \( j = 1 \) to \( k_1 \) and \( x_{j-opt}^+ \) for \( j = k_1 \) to \( n \) can be obtained. The sub-model corresponding to the lower bound of the objective function value can be constructed as:

\[
\text{Max } f^+ = \sum_{j=1}^{k_1} c_j^+ x_j^+ + \sum_{j=k_1+1}^{n} c_j^- x_j^-
\]

subject to:
\[ \sum_{j=1}^{k_i} a_{ij}^+ \text{sign}(a_{ij}^+) x_j^+ + \sum_{j=k_i+1}^{n} a_{ij}^+ \text{sign}(a_{ij}^+) x_j^- \leq (b - \lambda b - \alpha^-(b-b)) / (1-\lambda), i = 1, 2, ..., m \]  

(4-11b)

\[ \sum_{j=1}^{k_i} a_{ij}^+ x_j^+ + \sum_{j=k_i+1}^{k_{i+1}} a_{ij}^+ x_j^- + \sum_{j=k_{i+1}+1}^{k_{i+2}} a_{ij}^+ x_j^+ + \sum_{j=k_{i+2}+1}^{n} a_{ij}^- x_j^- \leq (b - \lambda b - \alpha^-(b-b)) / (1-\lambda) \]  

(4-11c)

\[ x_j^+ \geq x_{j-opt}^-, j = j = 1, 2, ..., k_i \]  

(4-11d)

\[ x_j^- \leq x_{j-opt}^+, j = k_i + 1, k_i + 2, ..., n \]  

(4-11e)

\[ x_j^+ \geq 0, j = 1, 2, ..., k_i \]  

(4-11f)

\[ x_j^- \geq 0, j = k_i + 1, k_i + 2, ..., n \]  

(4-11g)

where the coefficients \( a_{ij}^+ (j = 1, 2, ..., k_i; j = k_{i+1} + 1, k_{i+1} + 2, ..., n) \) are positive, and the coefficients \( a_{ij}^- (j = k_i + 1, k_{i+1} + 2, ..., k_{i+2}) \) are negative, \( k_i \leq k_i \leq k_{i+2} \leq n \), and \( f^* \) is the upper bound of the objective function value.

Solutions for the IGFCCCP model can be obtained by solving deterministic models 4-10 and 4-11:

\[ f_{opt}^\pm = [f_{opt}^-, f_{opt}^+] \]  

(4-12)

\[ x_{j-opt}^\pm = [x_{j-opt}^-, x_{j-opt}^+] \]  

(4-13)

4.3.2. Model development

The IGFCC model for emergency evacuation management of the QNPS was developed to optimize evacuation flows from the inner zone of the PEPZ, with five APs and three TSs, to the settlements in the four nearby cities during evacuation. The
maximum allowable evacuation time is 2.5 hours. The total evacuation time is divided into five, 0.5 hour period, denoted as \( t = 1, 2, 3, 4, \) and \( 5 \), respectively. The five APs (i.e., Chuangchuanba Village Committee, Qinshan Middle School, Luotang Village Committee, Zhenzhong Village and Cross of Nanbeihu Street and Huhang Road) are denoted as \( i = 1, 2, 3, 4, \) and \( 5 \), respectively. The three TSs (i.e., Xitangqiao Area, Baibu Town and Yuanhua Town) are denoted as \( j = 1, 2, \) and \( 3 \), respectively, and the four SCs (i.e., Jiaxing, Pinghu, Tongxiang and Haining) are denoted as \( k = 1, 2, 3, \) and \( 4 \), respectively.

The objective of this model is to maximize the total number of evacuees during the maximum allowable evacuation time. It can be formulated as:

\[
Max f^\pm = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{t=1}^{5} x^\pm_{ijt}
\]

(4-14)

where \( x^\pm_{ijt} \) is the evacuee flow from APs \( i \) to \( j \) in the \( k \)th period.

The ambiguous coefficients, including the number of residents in the inner PEPZ, the three TSs’ capacities, the capacities of provincial and national highway, and the maximum available ambulances are expressed as intervals to quantify the multiple uncertainties in the system. The maximum village-level evacuation rates were encoded as fuzzy sets. Constraints for the IGFCC model include:

(1) Evacuation target constraint: The minimum requirement is to evacuate all of the residents in the inner zone of the PEPZ:

\[
\sum_{i=1}^{5} \sum_{j=1}^{2} \sum_{t=1}^{5} x^\pm_{ijt} \geq ET^\pm
\]

(4-15)

where \( ET^\pm \) is the population of the inner PEPZ.
(2) Village-level evacuation flow capacity: The evacuation rate from residents’ homes to ASs is subjected to various factors, transportation methods and local road conditions. The maximum village-level evacuation capacity can be estimated by experts from the local community.

\[ x_{ijt}^\pm \leq VEC_{ijt} \forall i, j, t \]  

(4-16)

where \( VEC_{ijt} \) is the maximum evacuation rate from AP\(_i\) to TS\(_j\).

(3) Vehicle flux constraint: Evacuees at the TSs will be transferred to the SCs using ambulances and buses. The evacuation rate will be limited to the number of available vehicles.

\[ y_{j\mu t}^\pm \leq VAS \cdot VAN_j^{\pm}, \forall j, t \]  

(4-17)

\[ z_{jkt}^\pm \leq VBS \cdot VBN_{jk}^{\pm}, \forall j, k, t \]  

(4-18)

where \( y_{j\mu t}^\pm \) is the number of severely injured evacuees from TS\(_j\) to SC\(_1\) in period \( t \); \( z_{jkt}^\pm \) is the number of evacuees from TS\(_j\) to SC\(_k\) in period \( t \); \( VAS \) and \( VBS \) are the stretcher number for each ambulance and seat number of each bus, respectively. \( VAN_j^{\pm} \) and \( VBN_{jk}^{\pm} \) are the number of available ambulances and buses, respectively.

(4) Medical evacuation demand: The proportion of severely injured evacuees depends on the total radiation dose and the time interval of the radiation dose received (Brown and Rzucidlo, 2011). It can be estimated with a first response assessment.

\[ y_{j\mu t}^\pm \geq MP \cdot \sum_{i=1}^{5} x_{ijt}^\pm, \forall j, t \]  

(4-19)

where \( MP_t \) denotes the proportion of severely injured evacuees in period \( k \).

(5) TS capacity: The three TSs are designed with the following capacities:
\[
\begin{align*}
\sum_{t=1}^{T} \sum_{i=1}^{5} x_{ijt}^+ - \sum_{t=1}^{T} \sum_{k=1}^{5} z_{jkt}^- - \sum_{t=1}^{T} y_{ijt}^+ & \leq TC_j^+, \forall j, T = 1, 2, ..., 5 \\
\end{align*}
\]  

(4-20)

where \( TC_j^+ \) denotes the capacity of TC\(_j\).

(6) Technical constraints:

\[
\begin{align*}
x_{ijt}^+, y_{ijt}^+, z_{jkt}^+ & > 0, \forall i, j, k, t
\end{align*}
\]

(4-21)

According to the aforementioned methods, the model can be transformed into two sub-models. The sub-model that corresponds to the lower bound of the objective function value is formulated as:

\[
\begin{align*}
\text{Max } f^- = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{t=1}^{5} x_{ijt}^- \\
\text{subject to:}
\sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{t=1}^{5} x_{ijt}^- \geq ET^+ \quad (4-22b)
\end{align*}
\]

\[
(1-\lambda_{VEC})x_{ijt}^- \leq VEC_{ij} - \lambda_{VEC} \overline{VEC}_{ij} - \alpha_{VEC}^+ (VEC_{ij} - \overline{VEC}_{ij}), \forall i, j, t \quad (4-22c)
\]

\[
y_{ijt}^- \leq VAS \cdot VAN_j^-, \forall j, t \quad (4-22d)
\]

\[
z_{jkt}^- \leq VBS \cdot VBN_k^-, \forall j, k, t \quad (4-22e)
\]

\[
(1-\lambda_{MP})y_{ijt}^- \geq MP_t \cdot \sum_{i=1}^{5} x_{ijt}^-, \forall j, t \quad (4-22f)
\]

\[
\sum_{t=1}^{T} \sum_{i=1}^{5} x_{ijt}^- - \sum_{t=1}^{T} \sum_{k=1}^{5} z_{jkt}^- - \sum_{t=1}^{T} y_{ijt}^+ \leq TC_j^+, \forall j, T = 1, 2, ..., 5 \\
\]

(4-22g)

\[
x_{ijt}^-, y_{ijt}^-, z_{jkt}^- > 0, \forall i, j, k, t \quad (4-22h)
\]

Integar solutions \( x_{ijt-o}^-, y_{ijt-o}^-, z_{jkt-o}^- \) can be obtained by solving model 4-22, and the sub-model that corresponds to the upper bound of the objective function value can be formulated as:
Max \( f^+ = \sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{t=1}^{4} x_{ijt}^+ \) 

subject to:

\[
\sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{t=1}^{4} x_{ijt}^+ \geq ET^-
\] 

\[(1-\lambda_{\text{VEC}})x_{ijt}^+ \leq VEC_{ij} - \lambda_{\text{VEC}} VEC_{ij} - \alpha_{\text{VEC}^-} (VEC_{ij} - VEC_{ij}), \forall i, j, t\]

\( y_{jt}^+ \leq VAS \cdot \text{VAN}_j^+, \forall j, t\)

\( z_{jkt}^+ \leq VBS \cdot \text{VBN}_{jk}^+, \forall j, k, t\)

\[(1-\lambda_{\text{MP}})y_{jt}^+ \geq MP_j \cdot \sum_{i=1}^{5} x_{ijt}^+, \forall j, t\]

\[
\sum_{i=1}^{5} \sum_{j=1}^{3} \sum_{t=1}^{4} x_{ijt}^+ - \sum_{i=1}^{5} \sum_{t=1}^{4} z_{jkt}^+ - \sum_{t=1}^{4} y_{jt}^+ \leq TC^+_j, \forall j, T = 1, 2, \ldots\]

\( x_{ijt}^{\text{opt}} \leq x_{ijt}^+ \)

\( x_{ijt}^{\text{opt}} \leq x_{ijt}^- \)

\( x_{ijt}^{\text{opt}} \leq x_{ijt}^+ \)

Accordingly, integer solutions for \( x_{ijt}^+, y_{jt}^+ \) and \( z_{jkt}^+ \) can be obtained by solving model 4-23, and the interval solutions for the IGFCPP model can be obtained as:

\( f_{\text{opt}}^\pm = [f_{\text{opt}}^-, f_{\text{opt}}^+] \)

\( x_{j-t}^{\text{opt}} = [x_{j-t}^- \text{opt}, x_{j-t}^+ \text{opt}] \)
4.4. Results analysis

Interval solutions were obtained by solving the IGFCC model under seven scenarios. To reflect the decision makers’ characteristics (i.e., optimistic or pessimistic) for evacuation efficiency, the fuzzy gradients under the five scenarios are 0.1, 0.2, 0.3, 0.4, and 0.5, respectively. The solutions are intervals with lower and upper integer bounds, which indicate the related decision variables are sensitive to modeling inputs.

4.4.1. Solutions under Scenario 4

In no-notice emergencies such as nuclear accidents, decision makers usually prefer less optimistic strategies. The results of Scenario 4 where the fuzzy gradient = 0.4, implying the decision maker is slightly conservative regarding evacuation efficiency, are discussed in detail. In this scenario, the objective function value (i.e. optimized total evacuation amount) would be [28415, 33930]. Beyond the targeted population in the inner PEPZ, another [7481, 10996] people would be evacuated to safe areas outside of the PEPZ. A detailed evacuation scheme under this scenario is discussed as follows.

(1) Evacuation scheme from APs to TSs

The number of evacuees transferred from the five APs to the three TSs are presented in Figure 4.4. In the optimized scheme, the total numbers of residents evacuated from APs 1 ~ 5 are [6,350, 7,651], [3,979, 5,174], [6,776, 8,437], [5,655, 6,334], and [5,655, 6,334], respectively. The busiest AP would be AP3, while AP2 would be the least busy. Significant variation between evacuation rates is expected on the route from AP3 to TS3, while the evacuation numbers from AP1, AP4 and AP5
Figure 4.4. Evacuation schemes from the five APs to the three TSs during the five periods.
would be relatively stable. In the first period, a total number of [1,001, 1101] residents would be evacuated taking the route from AP3 to TS3, while only 217 residents would take the route from AP2 to TS3. The evacuation numbers for the other 13 routes would be close. The lower and upper bounds would fall into the ranges of [340, 479] and [394, 663], respectively. In the second period, the evacuation rates for routes beginning from AP1, AP4 and AP5, and from AP2 and AP3 to TS1 and TS2, are expected to stay unchanged. Decreases are expected for routes from AP2 and AP3 to TS3. In the third period, further decreases in evacuation rates are expected for three routes from AP3, AP4 and AP5 to TS1, where a decrease from [397, 524] to 397 is expected. The evacuation numbers from AP3 to TS3 would drop from [818, 901] to [418, 484], and from AP2 to TS1 would change from [397, 524] to [397, 418]. In the fourth period, the evacuation schemes for AP4 and AP5 will remain the same as they are in the third, and they are expected to stay the same in the last period. A slight decrease in the upper bound of the evacuation numbers from AP1 to TS1 would be found, while a slight increase is expected for the route from AP3 to TS1. The evacuation tasks would drop significantly for the route from AP2 to TS1 and from AP3 to TS3. In the final period, the residents at AP2 would all be evacuated to TS2. The evacuation rate from AP3 to TS3 would reach its lowest at [18, 50]. The difference in the evacuation schemes for the fifteen routes may result from the various transportation capacities of the routes, and the different capacities of the three TSs.

In the optimized scheme, the total evacuees in the first evacuation section are [6,502, 7,959], [6,102, 7,542], [5,702, 6,638], [5,292, 6,191] and [4,817, 5,600]
during periods 1 to 5, respectively. Figure 4.5 shows the evacuation tasks from APs to TSs are allocated relatively evenly over the five periods, even though there would be a slight decrease in the evacuation rate during the evacuation process. The decrease can be explained by the limited capacity of the TSs, which would be empty with the highest capacity at the beginning of the evacuation. The highest proportion of 23% is expected in Period 1 and a lower proportion of 17% is expected in Period 5. The segments of the upper and lower bounds are slightly different in Periods 2 and 4, but they exhibit a similar evenly distributed pattern.

As for the second stage of the evacuation, when the evacuees are transferred from the three TSs to the nearby cities for settlement, the optimized scheme is presented in Table 4.8 and Figure 4.6. A gradual decrease during the evacuation process is expected. The total evacuation numbers would be [5,877, 7,618], [5,362, 7,103], [5,044, 5,938], [4,602, 5,064] and [3,451, 3,913] during the five periods, respectively. The decrease of evacuation rates with time is due to the decrease of evacuation numbers from the APs to TSs, and the limited capacities of the TSs. The evacuees transferred from TS1 to the SCs would be [1,689, 2,112] during all of the periods. The evacuation rate of TS2 would exhibit a significant decrease from [2,522, 2,945] in the first period to [1,247, 1,286] in the last period. The evacuation numbers from TS3 would remain unchanged during the first two periods, and drop within the range of [906, 1,730] during the last three periods.

No particular schemes were developed for the transportation of the minorly and moderately injured evacuees as the four CSs have affiliated hospitals with ambulances and professional medical care for the minor and moderate injuries. However, additional
Figure 4.5. Evacuation segments of the five periods under Scenario 4.
Table 4.8. Results of the evacuation scheme from the TSs to the SCs.

<table>
<thead>
<tr>
<th></th>
<th>SC1</th>
<th>SC2</th>
<th>SC3</th>
<th>SC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Period 1</td>
<td>[856,895]</td>
<td>0</td>
<td>[0,384]</td>
<td>833</td>
</tr>
<tr>
<td>Period 2</td>
<td>[856,895]</td>
<td>0</td>
<td>[0,384]</td>
<td>833</td>
</tr>
<tr>
<td>Period 3</td>
<td>[856,895]</td>
<td>0</td>
<td>[0,384]</td>
<td>833</td>
</tr>
<tr>
<td>Period 4</td>
<td>[856,895]</td>
<td>0</td>
<td>[0,384]</td>
<td>833</td>
</tr>
<tr>
<td>Period 5</td>
<td>[856,895]</td>
<td>0</td>
<td>[0,384]</td>
<td>833</td>
</tr>
<tr>
<td>TS2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Period 1</td>
<td>833</td>
<td>[856,895]</td>
<td>[0,384]</td>
<td>833</td>
</tr>
<tr>
<td>Period 2</td>
<td>[318,318]</td>
<td>[856,895]</td>
<td>[0,384]</td>
<td>833</td>
</tr>
<tr>
<td>Period 3</td>
<td>0</td>
<td>[856,895]</td>
<td>[0,368]</td>
<td>833</td>
</tr>
<tr>
<td>Period 4</td>
<td>0</td>
<td>[856,895]</td>
<td>0</td>
<td>391</td>
</tr>
<tr>
<td>Period 5</td>
<td>0</td>
<td>[856,895]</td>
<td>0</td>
<td>[0,0]</td>
</tr>
<tr>
<td>TS3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Period 1</td>
<td>[0,895]</td>
<td>833</td>
<td>833</td>
<td>[0,0]</td>
</tr>
<tr>
<td>Period 2</td>
<td>[0,895]</td>
<td>833</td>
<td>833</td>
<td>[0,0]</td>
</tr>
<tr>
<td>Period 3</td>
<td>[0,64]</td>
<td>833</td>
<td>833</td>
<td>[0,0]</td>
</tr>
<tr>
<td>Period 4</td>
<td>[0,0]</td>
<td>833</td>
<td>833</td>
<td>[0,0]</td>
</tr>
<tr>
<td>Period 5</td>
<td>[0,0]</td>
<td>73</td>
<td>833</td>
<td>[0,0]</td>
</tr>
</tbody>
</table>
Figure 4.6. Numbers of evacuees transferred from the three TSs during the five periods.
attention is needed for the transportation of severely injured evacuees and only the hospitals in CS1 have adequate medical facilities and equipment for severe radiation injuries. Results of the evacuation scheme for the severely injured people from the TSs to SC1 are given in Table 4.9 and Figure 4.7. The transportation of severely injured would increase from Period 1 to Period 3, and remain stable during Periods 4 and 5. The number of severely injured evacuees transferred from TS2 would gradually increase along the evacuation process, while those from TS3 would be the same during the five periods.

The total number of severely injured evacuees transferred to the nearby cities are [66, 81], [74, 92], [86, 100], [90, 106], and [97, 112] during periods 1 to 5, respectively. According to Figure 4.7, the total number of injured evacuees from the TSs to SC1 would continuously increase from Periods 1 to 5. The highest proportion of 23% is expected in Period 5 and the lowest proportion of 16% is expected in Period 1. The upper and lower proportions of the evacuation numbers in Periods 2 and 3 are slightly different, but the gradual increasing trend can be found in the upper and lower bound solutions. The increasing evacuation numbers are due to an increase in injuries with time after the occurrence of nuclear accidents.
Table 4.9. Results of the evacuation scheme for the severely injured people from the TSs to SC1.

<table>
<thead>
<tr>
<th>Period</th>
<th>TS1</th>
<th>TS2</th>
<th>TS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[20, 27]</td>
<td>[22, 29]</td>
<td>[24, 25]</td>
</tr>
<tr>
<td>2</td>
<td>[24, 32]</td>
<td>[26, 35]</td>
<td>[24, 25]</td>
</tr>
<tr>
<td>3</td>
<td>[30, 32]</td>
<td>[32, 43]</td>
<td>[24, 25]</td>
</tr>
<tr>
<td>4</td>
<td>[30, 32]</td>
<td>[36, 49]</td>
<td>[24, 25]</td>
</tr>
<tr>
<td>5</td>
<td>[30, 32]</td>
<td>[43, 55]</td>
<td>[24, 25]</td>
</tr>
</tbody>
</table>
Figure 4.7. Injury evacuation segments of the five periods.
4.4.2. Comparison of Results under Scenarios 1 to 5

Five scenarios with different fuzzy gradients were analyzed to reflect decision makers’ optimistic or pessimistic preferences regarding transportation conditions for evacuation. A decision maker’s attitude under the five scenarios are listed in Table 4.10 in linguistic terms. In the following comparisons, “S1”, “S2”, “S3”, “S4” and “S5” represent Scenarios 1 to 5, respectively.

The total number of evacuees for the seven scenarios are [27,805, 31,841], [27,970, 32,371], [28,150, 33,076], [28,415, 33,930], and [28,750, 34,894], respectively. In Figure 4.8, the more optimistic the decision maker, the larger the maximum number of evacuees. However, the risks of constraint violation are also higher. It is highly possible that blind optimism would lead to the violation of constraints and then the failure of the whole evacuation system.

The upper and lower bounds of the evacuation numbers from APs to TSs for the five scenarios are presented in Figure 4.9 and Figure 4.10, respectively. The upper and lower bounds of the total evacuation numbers increase when the fuzzy gradient increases from 0.1 to 0.5 in the first three periods. The increase is less significant in Periods 4 and 5. It is possible blind optimistic does not bring a considerable increase in the total evacuation numbers under the transportation scheme of the IGFCC model.

The evacuation scheme for the second stage of the evacuation (i.e., the transportation from TSs to SCs) is presented in Figure 4.11. No significant increase in the number of severely injured evacuees transferred from the TSs to SC1 is expected when the fuzzy gradient increases from 0.1 to 0.5. In the lower bound solutions, the number of severely injured evacuees
Table 4.10. Description of the five scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Fuzzy Gradient</th>
<th>Linguistic term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>Practically pessimistic</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>Almost pessimistic</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>Very pessimistic</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>Quite pessimistic</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>Neither pessimistic nor optimistic</td>
</tr>
</tbody>
</table>
Figure 4.8. The total amount of evacuated residents under the five scenarios.
Figure 4.9. Numbers of evacuees transferred from AP to TS under the seven scenarios (Lower bound).
Figure 4.10. Numbers of evacuees transferred from AP to TS under the seven scenarios (Upper bound).
Figure 4.11. Numbers of severely injured evacuees transferred from the TSs to SC1 under the seven scenarios.
transferred from the TSs to SC1 to receive appropriate treatment, rises very slowly (i.e., from 405 to 418) as the transportation constraint is loosened. Similar trends are expected for the total number of evacuees transferred from the TSs to the SCs (Figure 4.12). There is an overall, slow increase of evacuees when the fuzzy gradient rises from 0.1 to 0.5. The change in the lower bound solution is even less significant than in the upper bound solutions. Even when the evacuation capacity constraint is relaxed, the increase in total evacuee numbers would not be significant. Overestimation of the evacuation capacity may lead to greater risks of traffic jams and transportation failure, the decision makers should be very careful when risking violation of transportation capacity constraints with higher evacuation numbers.

4.5. Summary

An Inexact Gradient-based Fuzzy Chance Constrained Programming (IGFCCP) model was developed. This model is based on interval-parameter programming (IPP) and Gradient-based Fuzzy Chance Constrained Programming (GFCCP). The IPP method addresses the uncertainties as intervals defined by crisp lower and upper bounds. The GFCCP method was based on the concept of a fuzzy gradient measure, which is a combination of possibility and necessity and can balance a decision maker’s optimism and pessimism. Uncertainties were expressed as discrete intervals and possibility distributions and addressed within the optimization framework.

The IGFCCP model was applied to aid nuclear emergency evacuation management in the QNPS, which is one of the largest nuclear plants in China. The
Figure 4.12. Numbers of evacuees transferred from the TSs to the SCs under the seven scenarios.
results provided stable intervals for the objective function and decision variables with different levels of a decision maker’s preferences for transportation capacity constraints. The evacuation system consists of five APs, three TSs and four CSs. The objective is to maximize the evacuees from the inner zone within the Plume Emergency Planning Zone (PEPZ). Decision alternatives for the evacuation schemes have been generated, and seven scenarios were analyzed to reflect the impacts of the imprecision (fuzziness) associated with the transportation capacity from the APs to the TSs. The results are valuable for supporting local decision makers when generating effective emergency evacuation strategies.
Chapter 5  Inexact Fuzzy Stochastic Chance Constraint Programming for Emergency Evacuation in the Qinshan Nuclear Power Site (QNPS) under Uncertainty

5.1. Background

Emergency evacuation planning is of great importance in response to some emergency accidents or disasters. Emergency evacuation is essential once a nuclear power accident occurs as radioactive materials may leak, posing lethal effects on human health. China is experiencing a boom from the development of nuclear power sites, and a large number of nuclear power plants have been constructed or are going to be constructed. Among them, the Qinshan Nuclear Power Site (QNPS) was the first nuclear power plant constructed in 1970. It now contains seven operating units, and there are four more units under construction or planned. The QNPS is in the Zhejiang Province, one of the densely inhabited districts in China. Emergency evacuation planning is desired to safely transfer local residents when an accident occurs in the QNPS.

However, extensive complexities and uncertainties may exist in the emergency evacuation management system. For instance, the pressurized water reactors are in three different power plants within the nuclear power site, with various radionuclide release start and release times. The total population living near the QNPS may vary. Evacuation route capacities also exhibit uncertain features due to road and traffic conditions. Uncertainties may be multiplied as a result of the interaction between
system components, leading to a greater challenge for local decision makers to provide appropriate evacuation schemes. The development of nuclear emergency evacuation management plans under consideration of various complexities and uncertainties is needed to provide the most effective evacuation schemes.

An optimization model for nuclear emergency management will be proposed for the QNPS. Inexact fuzzy stochastic chance constrained programming (IFSCCP) will be developed to address various uncertainties and optimize the planning of an evacuation scheme within the study horizon. The proposed model will be capable of addressing uncertainties such as fuzzy, interval and fuzzy random variables in an evacuation management system. In addition, the model will balance a decision maker’s optimism and pessimism regarding evacuees in the QNPS area. The results will be valuable for generating an optimized evacuation strategy under multiple uncertainties.
5.2. Methodology

5.2.1. Interval Linear Programming (ILP)

In ILP, interval values are allowed to be communicated into the optimization process. All parameters and decision variables in a linear programming problem can be intervals (Huang et al., 1992).

Specifically, an ILP model can be defined as:

Max \( f^+ = C^+ X^+ \)  
subject to:

\[
A^\pm X^\pm \leq B^\pm \]  
\[
X^\pm \geq 0 \]

where \( A^\pm \in \{ R^2 \}^{mn} \), \( C^\pm \in \{ R^2 \}^{1n} \), \( B^\pm \in \{ R^2 \}^{m1} \), \( X^\pm \in \{ R^2 \}^{n1} \); \( R^+ \) denotes a set of interval number; \( A^\pm = (a_{ij}^\pm)_{mn} \), \( C^\pm = (c_1^+, c_2^+, \ldots, c_n^+) \), \( B^\pm = (b_1^+, b_2^+, \ldots, b_m^+) \) and \( X^\pm = (x_1^+, x_2^+, \ldots, x_n^+) \). An interval number (\( a^\pm \)) is defined as (Huang et al., 1992):

\[
a^\pm = [a^-, a^+] = \{ t \in a | a^- \leq t \leq a^+ \} .
\]

An interactive solution algorithm named two-step-method (TSM) was proposed to solve this problem (Huang et al., 1992, 1995; Fan and Huang, 2012). Interval solutions can be obtained with analysis of detailed interrelationships between the parameters and variables and between the objective function and constraints. The main idea of the TSM is to convert the original ILP model into two LP submodels corresponding to the lower and upper bounds of the objective-function value, respectively. For \( n \) interval coefficients \( c_j^\pm \) (\( j = 1, 2, \ldots, n \)) in the objective function, the former \( k \) coefficients are assumed to be positive (i.e. \( c_j^+ \geq 0 \), for \( j = 1, 2, \ldots, k \)).
and the latter \((n - k)\) coefficients are negative (i.e. \(c_j^+ \leq 0\), for \(j = k+1, \ldots, n\)). The first submodel of model (5-1) would correspond to \(f^+\). It can be formulated as follows (assuming that \(b_j^+ > 0\) and \(f^+ > 0\)):

\[
\text{Max} \quad f^+ = \sum_{j=1}^{k} c_j^+ x_j^+ + \sum_{j=k+1}^{n} c_j^- x_j^-
\]

Subject to:

\[
\sum_{j=1}^{k} |a_{ij}^+| \text{Sign}(a_{ij}^+) x_j^+ + \sum_{j=k+1}^{n} |a_{ij}^-| \text{Sign}(a_{ij}^-) x_j^- \leq b_i^+, \quad i = 1, 2, \ldots, m.
\]

\(x_j^+ \geq 0, \quad j = 1, 2, \ldots, k\)

\(x_j^- \geq 0, \quad j = k+1, k+2, \ldots, n\)

Solutions of \(x_{j_{opt}}^+ (j = 1, 2, \ldots, k)\) and \(x_{j_{opt}}^- (j = k+1, \ldots, n)\) can be obtained through solving submodel (5-2). Based on solution for submodel (5-2), the submodel corresponding to the lower bound of equation (5-1a) can be formulated as follows:

\[
\text{Max} \quad f^- = \sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^+ x_j^+
\]

Subject to:

\[
\sum_{j=1}^{k} |a_{ij}^-| \text{Sign}(a_{ij}^-) x_j^- + \sum_{j=k+1}^{n} |a_{ij}^+| \text{Sign}(a_{ij}^+) x_j^+ \leq b_i^-, \quad i = 1, 2, \ldots, m.
\]

\(0 \leq x_j^- \leq x_{j_{opt}}^+, \quad j = 1, 2, \ldots, k.\)

\(x_j^+ \geq x_{j_{opt}}^- , \quad j = k+1, k+2, \ldots, n.\)

From submodel (5-3), solutions of \(x_{j_{opt}}^- (j = 1, 2, \ldots, k)\) and \(x_{j_{opt}}^+ (j = k+1, \ldots, n)\) can be obtained. Thus, the final solution of \(f_{opt}^\pm = [f_{opt}^-, f_{opt}^+]\) and \(x_{j_{opt}}^\pm = [x_{j_{opt}}^-, x_{j_{opt}}^+]\) can be obtained for model (5-1).
5.2.2. Fuzzy Stochastic Chance Constraint Programming

5.2.2.1. Fuzzy Random Variable

The fuzzy random variable on the real number set can be defined as follows.

**Definition 5.2.1.** For a probability space $(\Omega, F, P)$, a fuzzy random variable is a function $\xi: \Omega \rightarrow F_r(R)$, if only if for $\forall \alpha \in [0, 1]$, the set value function

$$\xi_\alpha: \Omega \rightarrow K_\alpha(R)$$

$$\xi_\alpha(\omega) := (\xi(\omega))_\alpha := \{x \in R | \mu_{\xi(\omega)}(x) \geq \alpha\}$$

is $F$ measurable, where $R$ denotes the set of all real numbers, $F_r(R)$ denotes the set of all fuzzy numbers, and $K_\alpha(R)$ denotes all non-empty bounded close intervals.

**Remark:** If $\xi$ is a fuzzy random variable, the lower and upper bounds of the $\alpha$-cuts, denoted as $\xi^-_\alpha(\omega)$ and $\xi^+_\alpha(\omega)$, respectively, are real-valued random variables for all $\alpha \in [0, 1]$.

**Definition 5.2.2.** Let $\xi = (\xi_1, \xi_2, ..., \xi_n)$ be a fuzzy random vector in a probability space $(\Omega, F, P)$ and $f_i: R^n \rightarrow R$, $i = 1, 2, ..., m$ be a real-valued continuous function, then the chance measure $Ch$ of the fuzzy random event $f_i(\xi) \leq 0$, $i = 1, 2, ..., m$ is defined as:

$$Ch\{f_i(\xi) \leq 0, i = 1, 2, ..., m\}(\alpha)$$

$$= \sup\{\beta | Pr\{\omega \in \Omega | Ch\{f_i(\xi) \leq 0, i = 1, 2, ..., m\} \geq \beta\} \geq \alpha\}$$

where $\alpha, \beta \in [0, 1]$ are predetermined confidence levels, $Pr$ is the probability of a random event, and $Ch$ is the measure of two fuzzy events.

To compare the preferences between two fuzzy events, the measures of possibility and necessity are introduced to reflect the preferred confidence degrees of
decision makers (Dubois and Prade, 1988; Inuiguchi and Ramik, 2000; Zhang et al., 2009). \( \tilde{a} \) and \( \tilde{b} \) are non-interactive fuzzy numbers with continuous membership function. For a confidence level \( \alpha \in [0,1] \):

\[
\begin{align*}
\text{Pos}(\tilde{a} \leq \tilde{b}) &= \sup \{ \min(\mu_a(x), \mu_b(y)) \mid x \leq y \} \geq \alpha \iff a^L \leq b^R \quad (5-6a) \\
\text{Nes}(\tilde{a} \leq \tilde{b}) &= \inf \{ \max(1-\mu_a(x),1-\mu_b(y)) \mid x \leq y \} \geq \alpha \iff a^L \leq b^L, b^R \quad (5-6b)
\end{align*}
\]

where \( a^L \) and \( a^R \) are the lower and upper bound of the \( \alpha \)-cut of fuzzy number \( \tilde{a} \), respectively, and \( a_L = \inf(x \mid x = \mu_a^{-1}(\alpha)) \), \( a_R = \sup(x \mid x = \mu_a^{-1}(\alpha)) \), and \( b_L \) and \( b_R \) are the lower and upper bounds of the \( \alpha \)-cut of fuzzy number \( \tilde{b} \), respectively. The measures of possibility and necessity correspond to the optimistic and pessimistic preferences of the decision makers.

The fuzzy random chance constraint based on the measures of possibility and necessity, are expressed by Equation (5-5) and can be converted into the following two formulations:

\[
\begin{align*}
\text{Ch}\{f_i(\xi) \leq 0, i = 1, 2, ..., m\}(\alpha) &= \sup \{ \beta \mid \Pr(\omega \in \Omega \mid \text{Pos}\{f_i(\xi) \leq 0, i = 1, 2, ..., m\} \geq \beta) \geq \alpha \} \\
\iff \Pr\{\text{Pos}\{f_i(\xi) \leq 0\} \geq \beta\} \geq \alpha \quad (5-7a) \\
\text{Ch}\{f_i(\xi) \leq 0, i = 1, 2, ..., m\}(\alpha) &= \sup \{ \beta \mid \Pr(\omega \in \Omega \mid \text{Nec}\{f_i(\xi) \leq 0, i = 1, 2, ..., m\} \geq \beta) \geq \alpha \} \\
\iff \Pr\{\text{Nec}\{f_i(\xi) \leq 0\} \geq \beta\} \geq \alpha \quad (5-7b)
\end{align*}
\]

Consider a fuzzy programming problem with ambiguous coefficients expressed as fuzzy sets, formulated as follows:

\[
\begin{align*}
\text{Max } f &= \sum_{j=1}^{n} c_j \times x_j \quad (5-8a) \\
\text{Subject to } &
\sum_{j=1}^{n} a_{ij} x_j \leq b_i, \ i = 1, 2, ..., m \quad (5-8b)
\end{align*}
\]
\[
\sum_{j=1}^{\hat{m}} d_{ij} x_j \leq \hat{b}_i (\omega), \quad i = 1, 2, \ldots, m' 
\]
\[
x_j \geq 0
\]

where \( c \in \{ R \}^\text{boa} \), \( X \in \{ R \}^\text{mod} \), \( \hat{b}_i \in \{ R \}^\text{mod} \), \( \hat{b}_i (\omega) \in \{ \hat{R}(\omega) \}^\text{mod} \), \( \hat{a}_{ij} \in \{ \hat{R} \}^\text{mod} \), \( \hat{R} \) denotes a set of fuzzy sets, and \( \hat{R}(\omega) \) denotes a set of random fuzzy sets. A fuzzy set \( \tilde{A} \) in \( X \) can be defined as \( \{ x, \mu_{\tilde{A}}(x) \mid x \in X, \mu_{\tilde{A}}(x) : X \to [0, 1] \} \), where \( \mu_{\tilde{A}}(x) \) is the membership function or grade of membership (Zimmermann, 1985). The value of \( \mu_{\tilde{A}}(x) \) varies between 0 and 1, indicating the possibility of an element \( x \) belonging to \( \tilde{A} \). \( \mu_{\tilde{A}}(x) = 1 \) indicates \( x \) definitely belongs to the fuzzy set \( \tilde{A} \), while \( \mu_{\tilde{A}}(x) = 0 \) denotes that \( x \) does not belong to \( \tilde{A} \). The closer \( \mu_{\tilde{A}}(x) \) is to 1, the more likely \( x \) belongs to \( \tilde{A} \). Conversely, the closer \( \mu_{\tilde{A}}(x) \) is to 0, the less likely \( x \) belongs to \( \tilde{A} \) (Zimmermann, 1985; Lai and Hwang, 1992).

Based on Equations (5-6) and (5-7), model (5-8) can be converted into to model scenarios based on the decision makers’ preferences (optimistic or pessimistic):

**Optimistic**

\[
\text{Max } f = \sum_{j=1}^{n} c_j x_j 
\]

Subject to:

\[
\text{Pos}\{ \sum_{j=1}^{\hat{m}} d_{ij} x_j \leq \hat{b}_i \} \geq \beta, \quad i = 1, 2, \ldots, m 
\]

\[
\text{Pr}\{ \text{Pos}\{ \sum_{j=1}^{\hat{m}} d_{ij} x_j \leq \hat{b}_i (\omega) \} \geq \beta \} \geq \alpha, \quad i = 1, 2, \ldots, m' 
\]

\[
x_j \geq 0 
\]
Pessimistic

Max $f = \sum_{j=1}^{n} c_j \times x_j$  \hfill (5-10a)

Subject to:

$\text{Nec}\{ \sum_{j=1}^{n} a_{ij} x_j \leq b_i \} \geq \beta, \ i = 1, 2, \ldots, m$  \hfill (5-10b)

$\Pr\{ \text{Nec}\{ \sum_{j=1}^{n} \tilde{a}_{ij} x_j \leq \tilde{b}_i(\omega) \} \geq \beta \} \geq \alpha, \ i = 1, 2, \ldots, m'$  \hfill (5-10c)

$x_j \geq 0$  \hfill (5-10d)

If $\tilde{a}_{ij}, \tilde{a}'_{ij}, \tilde{b}_i$ are supposed to be triangular fuzzy numbers denoted as

$\tilde{a}_{ij} = (a_{ij}, m_{ij}^a, n_{ij}^a), \quad \tilde{a}'_{ij} = (a'_{ij}, m_{ij}^a', n_{ij}^a'), \quad \tilde{b}_i = (b_i, m_i^b, n_i^b),$ and $\tilde{b}_i(\omega)$ is assumed to be a triangular fuzzy random variable expressed as: $\tilde{b}_i(\omega) = (b'_i(\omega), m_i^b, n_i^b),$ Equation (5-9b) can be converted into:

$\text{Pos}\{ \sum_{j=1}^{n} a_{ij} x_j \leq b_i \} \geq \beta$

$\iff (\sum_{j=1}^{n} a_{ij} x_j, \sum_{j=1}^{n} m_{ij}^a x_j, \sum_{j=1}^{n} n_{ij}^a x_j)^\beta \leq (b_i, m_i^b, n_i^b)^\beta$

$\iff \sum_{j=1}^{n} a_{ij} x_j - \sum_{j=1}^{n} m_{ij}^a x_j + \sum_{j=1}^{n} \beta m_{ij}^a x_j \leq b_i + m_i^b - \beta n_i^b$  \hfill (5-11a)

For Equation (5-9c), it can be converted into crisp constraints as follows:

$\Pr\{ \text{Pos}\{ \sum_{j=1}^{n} a'_{ij} x_j \leq b'_i(\omega) \} \geq \beta \} \geq \alpha$

$\iff \Pr\{ \sum_{j=1}^{n} a'_{ij} x_j - \sum_{j=1}^{n} m_{ij}^a x_j + \sum_{j=1}^{n} \beta m_{ij}^a x_j \leq b'_i(\omega) + m_i^b - \beta n_i^b \} \geq \alpha$

$\iff \Pr\{ \sum_{j=1}^{n} a'_{ij} x_j - \sum_{j=1}^{n} m_{ij}^a x_j + \sum_{j=1}^{n} \beta m_{ij}^a x_j - n_i^b + \beta m_i^b \leq b'_i(\omega) \} \geq \alpha$

$\iff \sum_{j=1}^{n} a'_{ij} x_j - \sum_{j=1}^{n} m_{ij}^a x_j + \sum_{j=1}^{n} \beta m_{ij}^a x_j \leq b'_i(\omega)^a + n_i^b - \beta n_i^b$  \hfill (5-11b)
Similarly, Equations (5-10b) and (5-10c) can be converted into the following equations:

\[\text{Nec}\{ \sum_{j=1}^{n} \tilde{a}_{ij} x_j \leq \tilde{b}_j \} \geq \beta \]

\[\Leftrightarrow \sum_{j=1}^{n} a_{ij} x_j + \sum_{j=1}^{n} n_{ij}^a x_j - \sum_{j=1}^{n} (1-\beta)n_{ij}^b x_j \leq b_j - m_b^i + (1-\beta)m_b^i \tag{5-12a}\]

\[\Pr\{\text{Nec}\{ \sum_{j=1}^{n} \tilde{a}_{ij} x_j \leq \tilde{b}_j(\omega) \} \geq \beta \} \geq \alpha \]

\[\Leftrightarrow \sum_{j=1}^{n} a'_{ij} x_j + \sum_{j=1}^{n} n_{ij}^a x_j - \sum_{j=1}^{n} (1-\beta)n_{ij}^b x_j \leq b'_j(\omega)^a - m_b^i + (1-\beta)m_b^i \tag{5-12b}\]

5.2.3. Inexact Fuzzy Stochastic Chance Constraint Programming

In many real-world management problems, extensive uncertainties may exist and be expressed as various formats (e.g. fuzzy sets and interval numbers). In some specific situations, dual-uncertainties may exist due to the lack of data. For example, a city’s population can hardly be quantified as deterministic values and may be expressed as a random or fuzzy random variable. Inexact fuzzy stochastic chance-constraint programming (IFSCCP) may be a powerful tool to account for the extensive uncertainties existing in a management problem due to its ability to reflect uncertainty expressed in various formats. A typical IFSCCP problem can formulated as:

\[
\text{Max } f^* = \sum_{j=1}^{n} c_j^k x_j^k \tag{5-13a}
\]

Subject to
\[
\sum_{j=1}^{n} a_{ij}^+ x_j^+ \leq b_i^+ , \quad i = 1, 2, \ldots, l \tag{5-13b}
\]
\[
\sum_{j=1}^{n} a_{ij}^- x_j^- \leq \tilde{b}(\omega) , \quad i = l+1, l+2, \ldots, m \tag{5-13c}
\]
\[
x_j^\pm = \text{interval continuous variables, } j = 1, 2, \ldots, p \ (p < n) \tag{5-13d}
\]
\[
x_j^\pm = \text{interval integer variables, } j = p+1, p+1, \ldots, n \tag{5-13e}
\]
\[
x_j^\pm \geq 0 \tag{5-13f}
\]

As presented in Section 5.2.1, the ILP problem can be solved by converting the original problem into two sub-problems corresponding to the upper and lower bounds of the objective function. Model (5-2), which is the sub-problem of the upper bound, corresponds to advantageous (optimistic) conditions, while model (5-3) corresponds to the demanding (pessimistic) conditions (Huang et al., 1992; Fan et al., 2012a; Fan and Huang, 2012). Similarly, fuzzy random stochastic programming can also be solved under optimistic and pessimistic conditions, as expressed in models (5-9) and (5-10). Model (5-13) can be solved by converting it into two sub-problems, corresponding to the optimistic and pessimistic conditions, respectively. The detailed solution process is presented as:

Optimistic

Max \( f^+ = \sum_{j=1}^{k} c_j^+ x_j^+ + \sum_{j=k+1}^{n} c_j^- x_j^- \) \tag{5-14a}

\[
\sum_{j=1}^{k} [a_{ij}^+] \text{Sign}(a_{ij}^+) x_j^+ + \sum_{j=k+1}^{n} [a_{ij}^-] \text{Sign}(a_{ij}^-) x_j^- \leq b_i^+ , \quad i = 1, 2, \ldots, l \tag{5-14b}
\]

\[
\Pr\{\text{Pos}\{\sum_{j=1}^{k} a_{ij}^+ x_j^+ + \sum_{j=k+1}^{n} a_{ij}^- x_j^- \leq \tilde{b}_i\} \geq \alpha \} \geq \beta , \quad i = l+1, l+2, \ldots, m \tag{5-14c}
\]
\[
x_j^\pm = \text{interval continuous variables, } j = 1, 2, \ldots, p \ (p < n) \tag{5-14d}
\]
\( x_j^\pm = \) interval integer variables, \( j = p + 1, p + 1, \ldots, n \)  

(5-14e)

\( x_j^\pm \geq 0 \)  

(5-14f)

Pessimistic

\[
\text{Max } f^- = \sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^+ x_j^+ 
\]

(5-15a)

Subject to

\[
\sum_{j=1}^{k} |a_{ij}^-| \text{Sign}(a_{ij}^-) x_j^- + \sum_{j=k+1}^{n} |a_{ij}^+| \text{Sign}(a_{ij}^+) x_j^+ \leq b_i^-
\]

(5-15b)

\[
\text{Pr}\{\text{Nes}\left(\sum_{j=1}^{k} a_{ij}^- x_j^- + \sum_{j=k+1}^{n} a_{ij}^+ x_j^+ \leq \bar{b}_i\right) \geq \beta\} \geq \alpha
\]

(5-15c)

\( 0 \leq x_j^- \leq x_{j,\text{opt}}^-, j = 1, 2, \ldots, k. \)  

(5-15d)

\( x_j^+ \geq x_{j,\text{opt}}^+, j = k+1, k+2, \ldots, n. \)  

(5-15e)

\( x_j^\pm = \) interval continuous variables, \( j = 1, 2, \ldots, p \) \( (p < n) \)  

(5-15f)

\( x_j^\pm = \) interval integer variables, \( j = p + 1, p + 1, \ldots, n \)  

(5-15g)

Model (5-13) can account for various uncertainties expressed as fuzzy, interval and fuzzy random variables. The constraints containing fuzzy random variables are calculated with fuzzy random chance constraint methods based on possibility and necessity measures. Model (5-13) can be converted into two submodels based on the two-step method for ILP proposed by Fan and Huang (2012), and the possibility and necessity measures. As expressed by models (5-14) and (5-15), the optimistic submodel (i.e. model (5-14)) corresponds to the upper bound of the objective function, with the fuzzy constraints accounted for by the possibility measure. The pessimistic model (i.e. model (5-15)) corresponds to the lower bound of the objective function, with fuzzy constraints accounted for by the necessity measure.
5.3. Case Study

5.3.1. Location of the QNPS

The Qinshan nuclear power plant (QNPS) is in the Haiyan County of the Zhejiang province, within a square area of $1.3 \times 10^6$ m$^2$. It is the first nuclear power plant to have been constructed in mainland China, including seven operating units which were built in three different phases. The QNPS is approximately 108 km from Shanghai to the northeast, 82 km from Hangzhou to the west, and 43 km from Jiaxing to the north. The nearest city around the QNPS is Haiyan County, which is 8 km from QNPS to the southeast. QNPS is seated in the Qinshan Town of Haiyan County. The total population in the Haiyan County is about 370 thousand, with about thirty one thousand people in the Qinshan Town.

5.3.2. Emergency Planning Zones

The emergency planning zones are created according to the national standard “Criteria for emergency planning and preparedness for nuclear power plants” and the local natural and social conditions. The emergency planning zones can be classified as plume emergency planning zones and ingestion emergency planning zones. The plume emergency planning zones are further divided into inner and outer zones, in which the population in the inner zones should be evacuated when a nuclear accident occurs. In this study, the population evacuation strategies will be illustrated under different uncertainty conditions, so the plume emergency zones are mainly under consideration.
Based on the meteorological conditions and the MACCS code provided by the US Sandia National Laboratory, the plume emergency zone is centered with the Qinshan #2 nuclear power reactor, with an inner zone radius of 5 km and an outer zone radius of 7 km. The plume emergency zone covers Qinshan District, Ganfu Town and Tongyuan Town, including 18 villages and 2 towns presented in Table 4.1. The inner zone of the plume emergency planning zone mainly contains the villages in Qinshan District, and Gandong, Zhenzhong and Gannan in the Ganfu Town, as presented in Table 4.1. The population in the plume emergency zone is about 52,800, with 46,048 being permanent residents. In the inner zone, the total population is around 23,400, with about 4,500 migrants.

5.3.3. Emergency Evacuation Routes

An emergency-related evacuation management system has been designed in response to nuclear accidents. The detailed evacuation routes are shown in Figure 4.2, in which 5 assembly places (AP) and 3 temporary settlements (TS) are constructed, and the evacuees are transported to four cities. Five assembly places are provided for populations assembling in the emergency-related evacuation management system, in which three of them are in the Qinshan Town (Chuangchuanba Village Committee, Qinshan Middle School and Luotang Village Committee) and the other two are placed in the Ganfu Town (Zhenzhong Village, Cross between Nanbeihu Street and Huhang Road). The evacuees in the inner zone of the plume emergency planning zone are temporarily settled in schoolyards in three temporary settlements (TS). The three TSs
are Xitangqiao Street, Baibu Town, and Yuanhua Town in the City of Haining.

Detailed information for the three TSs are presented in Table 4.2. They are shipped to three cities (i.e. Haining, Jiaxing, Tongxiang and Pinghu).

5.3.4. Emergency Evacuation Model under Uncertainty

Nuclear accidents are frequently associated with the release of harmful radioactive materials, which lead to significant consequences for people, the environment and facilities. Emergency evacuation is required to transfer the local population to safe areas in response to nuclear accidents. Typically, an emergency-related evacuation management system is designed with the following components: Assembly places (ASs) for civilians, temporary settlements (TSs) for first aid, settlements (i.e., towns), and paths to evacuation destinations. The purpose of an evacuation system is to transfer the population in the inner zone of a plume emergency planning zone to settlements. Many process are required, including investigation of evacuees, gathering of civilians, employment of public transit, grouping of evacuees, allocation of transportation resources and services, coordination of roadway capacity, and planning of evacuation routes (Lv et al., 2013). Extensive uncertainties exist in the system components and processes resulting from unforeseeable incidents and deviations in subjective judgments. For example, evacuees in the inner zone can hardly be quantified accurately due to spatial-temporal variations in local communities. The vehicle flux and road capacities for evacuation may not be estimated with deterministic values. Uncertainties may be compounded
due to the interactions among uncertain parameters and integration of various uncertainties. The uncertainties may impact the evacuation management processes from data investigation and model construction to results presentation. One of the major challenges for evacuation management is how to generate appropriate evacuation schemes under various uncertainties. An inexact fuzzy stochastic chance constraint programming (IFSCCP) approach may be a powerful tool for emergency evacuation management which can reflect uncertainties expressed as interval, fuzzy and fuzzy randomness. The IFCCP model for the emergency-related evacuation management system of the Qinshan nuclear power plant can be expressed as:

$$\begin{align*}
\text{Min } & f^\pm = \sum_{k=1}^{K} L_k CAT_{ik}^\pm + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{t=1}^{T} ICT_{jk}^\pm DTT_{jt}^\pm \\
\text{Subject to } & \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{ijk}^\pm \geq TP(\omega) \\
& x_{ijk}^\pm \leq FAS_{i,j}^\pm, \forall i, j, k \\
& y_{jk}^\pm / \alpha_y^\pm \leq VFT_{j}^\pm, \forall k \\
& z_{jkt}^\pm / \alpha_z^\pm \leq SVT_{jt}^\pm, \forall k \\
& y_{jk}^\pm \geq y(\omega) \sum_{i=1}^{I} x_{ijk}^\pm, \forall k
\end{align*}$$

(5-16a)

(5-16b)

(5-16c)

(5-16d)

(5-16e)

(5-16f)
(patient transportation demand)

\[ \sum_{k=1}^{K'} \sum_{t=1}^{T} x_{ijk}^+ + \sum_{k=1}^{K'} \sum_{t=1}^{T} y_{ijk}^+ \leq CS_{j}^\pm, \quad K' = 1,2,3 \quad (5-16g) \]

(TSs capacity constraint)

where \( i \) means the type of emergency assembly place, with \( i = 1, 2, 3, 4, 5 \) indicating Chuangchuanba Village Committee, Qinshan Middle School, Luotang Village Committee, Zhenzhong Village and Cross of Nanbeihu Street and Huhang Road, respectively; \( j \) denotes the temporary settlements (\( j = 1, 2, 3 \) mean Xitangqiao Street, Baibu Town and Yuanhua Town, respectively); \( t \) indicates the ultimate settlement cities, and \( t = 1, 2, 3, 4 \) denote Pinghu, Jiaxing, Tongxiang and Haining, respectively; \( FAS_{ij}^\pm \) is the population evacuation capacity of the route from assembly station \( i \) to TS \( j \) (person/h); \( VFT_j \) is the maximum ambulance flux of the road from TS\( j \) to town 1 (vehicle/h); \( SVT_{jt} \) is the maximum vehicle flux of the route from TS\( j \) to town \( t \) (vehicle/h); \( z_{jk}^+ \) is the population flow from TS \( j \) to town \( t \) during period \( k \) (person/h); \( \gamma_k^{(\phi)} \) is the proportion of injured people at TS \( j \) under level \( \phi \) during period \( k \); \( CS_{j}^\pm \) is the capacity of TS \( j \) (person); \( k \) is the planning time period.

The emergency evacuation management model is constructed with several assumptions proposed by Lv et al. (2013): (i) It is a route-schedule planning approach, assuming a quicker evacuation process is obtained when the evacuees follow the optimal escape routes, and only transport time is considered during the evacuation process, ignoring other processes such as gathering at the origin, waiting for the vehicles, and settling down at the destination, (ii) injured persons are distributed
evenly, so the actual proportions of wounded people to evacuees transported to TSs are equal or very close to the evaluated injured proportion, and the injured persons are shipped to Jiaxing since it has the most advanced hospitals among the four cities, (iii) as the destination of the evacuation route within the system, each town could receive as many evacuees as possible without capacity restriction.

5.3.5. Data Collection

The related data are provided in Table 5.1 to Table 5.6. The data are collected based on the reports provided by local governments and the QNPS. The detailed description for the data collection is provided in Chapter 4. The main purpose of the study in this chapter is to identify the desired evacuation plan under various uncertainties. Due to the temporal-spatial variation in the distribution of the population, the distribution of local residents is presented as a fuzzy random variable, expressed as $N((22000, 500, 500), 150^2)$. $N$ indicates the distribution obeys a normal distribution, with the mean value being a fuzzy number expressed as (22000, 500, 500), and a standard deviation of 150.
Table 5.1. The maximum evacuation capacity from APs to TSs (person)

<table>
<thead>
<tr>
<th></th>
<th>CVC ((i = 1))</th>
<th>QMS ((i = 2))</th>
<th>LVC ((i = 3))</th>
<th>ZVG ((i = 4))</th>
<th>CNSHR ((i = 5))</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS ((j = 1))</td>
<td>([812, 1117])</td>
<td>([812, 1115])</td>
<td>([812, 1115])</td>
<td>([812, 1115])</td>
<td>([812, 1115])</td>
</tr>
<tr>
<td>BT ((j = 2))</td>
<td>([984, 1424])</td>
<td>([984, 1424])</td>
<td>([984, 1424])</td>
<td>([692, 895])</td>
<td>([692, 895])</td>
</tr>
<tr>
<td>YT ((j = 3))</td>
<td>([809, 1155])</td>
<td>([2037, 2640])</td>
<td>([2037, 2640])</td>
<td>([809, 1155])</td>
<td>([809, 1155])</td>
</tr>
</tbody>
</table>
Table 5.2. The related cost from APs to TSs ($/person×km))

<table>
<thead>
<tr>
<th></th>
<th>CVC (i = 1)</th>
<th>QMS (i = 2)</th>
<th>LVC (i = 3)</th>
<th>ZVG (i = 4)</th>
<th>CNSHR (i = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS (j = 1)</td>
<td>[3.48, 4.21]</td>
<td>[3.48, 4.21]</td>
<td>[3.48, 4.21]</td>
<td>[3.48, 4.21]</td>
<td>[3.48, 4.21]</td>
</tr>
<tr>
<td>BT (j = 2)</td>
<td>[2.60, 3.58]</td>
<td>[2.60, 3.58]</td>
<td>[2.60, 3.58]</td>
<td>[4.61, 4.80]</td>
<td>[4.61, 4.80]</td>
</tr>
<tr>
<td>YT (j = 3)</td>
<td>[3.24, 4.31]</td>
<td>[1.56, 1.63]</td>
<td>[1.56, 1.63]</td>
<td>[3.24, 4.31]</td>
<td>[3.24, 4.31]</td>
</tr>
</tbody>
</table>
Table 5.3. The distance between APs and TSs (km)

<table>
<thead>
<tr>
<th></th>
<th>CVC ($i = 1$)</th>
<th>QMS ($i = 2$)</th>
<th>LVC ($i = 3$)</th>
<th>ZVG ($i = 4$)</th>
<th>CNSHR ($i = 5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS ($j = 1$)</td>
<td>19.1</td>
<td>16.7</td>
<td>15.5</td>
<td>24.8</td>
<td>26.5</td>
</tr>
<tr>
<td>BT ($j = 2$)</td>
<td>25.1</td>
<td>22.7</td>
<td>21.5</td>
<td>28.3</td>
<td>26.7</td>
</tr>
<tr>
<td>YT ($j = 3$)</td>
<td>22.3</td>
<td>23.2</td>
<td>22</td>
<td>18.3</td>
<td>16.6</td>
</tr>
</tbody>
</table>
Table 5.4. The maximum allowable vehicle flux from TSs to Cities (vehicle/h).

<table>
<thead>
<tr>
<th></th>
<th>JX ($t = 1$)</th>
<th>PH ($t = 2$)</th>
<th>TX ($t = 3$)</th>
<th>HN ($t = 4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS ($j = 1$)</td>
<td>[34, 36]</td>
<td>[33, 83]</td>
<td>[34, 36]</td>
<td>[33, 83]</td>
</tr>
<tr>
<td>BT ($j = 2$)</td>
<td>[34, 36]</td>
<td>[33, 83]</td>
<td>[11, 15]</td>
<td>[11, 15]</td>
</tr>
<tr>
<td>YT ($j = 3$)</td>
<td>[33, 83]</td>
<td>[33, 83]</td>
<td>[33, 83]</td>
<td>[24, 26]</td>
</tr>
</tbody>
</table>
Table 5.5. The unit cost for people from TSs to Cities ($/person×km)).

<table>
<thead>
<tr>
<th></th>
<th>JX ($t = 1$)</th>
<th>PH ($t = 2$)</th>
<th>TX ($t = 3$)</th>
<th>HN ($t = 4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS ($j = 1$)</td>
<td>[1.12, 1.17]</td>
<td>[0.48, 1.20]</td>
<td>[1.12, 1.17]</td>
<td>[0.48, 1.20]</td>
</tr>
<tr>
<td>BT ($j = 2$)</td>
<td>[1.12, 1.17]</td>
<td>[0.48, 1.20]</td>
<td>[2.60, 3.58]</td>
<td>[2.60, 3.58]</td>
</tr>
<tr>
<td>YT ($j = 3$)</td>
<td>[0.48, 1.20]</td>
<td>[0.48, 1.20]</td>
<td>[0.48, 1.20]</td>
<td>[1.56, 1.63]</td>
</tr>
</tbody>
</table>
Table 5.6. The distance between TSs to Cities (km)).

<table>
<thead>
<tr>
<th></th>
<th>JX ($t = 1$)</th>
<th>PH ($t = 2$)</th>
<th>TX ($t = 3$)</th>
<th>HN ($t = 4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XS ($j = 1$)</td>
<td>33.4</td>
<td>36</td>
<td>28</td>
<td>19</td>
</tr>
<tr>
<td>BT ($j = 2$)</td>
<td>29.4</td>
<td>32.6</td>
<td>48.6</td>
<td>26.8</td>
</tr>
<tr>
<td>YT ($j = 3$)</td>
<td>45.8</td>
<td>23.4</td>
<td>17.8</td>
<td>38.9</td>
</tr>
</tbody>
</table>
5.4. Results Analysis

Considering the fuzzy random feature for evacuees, three fuzzy confidence levels and three probabilistic confidence levels are considered, leading to a total of nine scenarios for the final evacuation model. The three fuzzy confidence levels are assumed to be 0.3, 0.5 and 0.8, while the probabilistic confidence levels are set to 0.01, 0.05, and 0.1. Figure 5.1 presents the evacuees in the Qinshan Nuclear Power Site (QNPS) under different fuzzy and probability confidence levels. The results show the number of evacuees in the Qinshan Nuclear Power Site vary under different fuzzy and probability confidence levels, ranging from 19,924 to 21,143 for the lower bound and from 22,143 to 23,143 for the upper bound. Due to variations in the number of evacuees in the QNPS, the desired evacuation patterns may also differ. Among the nine scenarios, three of them are analyzed with fuzzy and probability confidence levels of 0.3 and 0.01, 0.5 and 0.05, and 0.8 and 0.1. The three scenarios cover lower, medium, and high confidence levels.

5.4.1. Scenario 1: $\beta = 0.3, \alpha = 0.01$

This scenario selects the lowest fuzzy and probability confidence intervals, with the lower and upper bounds for the evacuated population being 20,934 and 22,934, respectively. Table 5.7 presents the evacuated population from Assembly Place to Temporary Settlement. The people living in the inner zone of the plume emergency planning zone can be safely evacuated in the first two hours. Most of the population are transferred to Xitangqiao Street and Baibu Town, with Yuanhua Town receiving about 3,700 people from the Luotang Village Committee. Xitangqiao Street would
Figure 5.1. The lower and upper bound of evacuated people under different fuzzy and probability confidence levels
Table 5.7. Evacuated population from AS to TS under Scenario 1

<table>
<thead>
<tr>
<th>X(i, j, k)</th>
<th>i = 1</th>
<th>i = 2</th>
<th>i = 3</th>
<th>i = 4</th>
<th>i = 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>k = 1</td>
<td>1624</td>
<td>1624</td>
<td>1624</td>
<td>1604</td>
<td>1624</td>
</tr>
<tr>
<td>k = 2</td>
<td>1624</td>
<td>1624</td>
<td>1624</td>
<td>1587</td>
<td>1624</td>
</tr>
<tr>
<td>j = 3</td>
<td>1624</td>
<td>1624</td>
<td>158</td>
<td>1624</td>
<td></td>
</tr>
<tr>
<td>k = 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>k = 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>k = 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>j = 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>X(i, j, k)</th>
<th>i = 1</th>
<th>i = 2</th>
<th>i = 3</th>
<th>i = 4</th>
<th>i = 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>k = 1</td>
<td>1967</td>
<td>1967</td>
<td>1967</td>
<td>[1375, 1382]</td>
<td>1383</td>
</tr>
<tr>
<td>k = 2</td>
<td>1967</td>
<td>1967</td>
<td>1967</td>
<td>[0, 1379]</td>
<td>[0, 1383]</td>
</tr>
<tr>
<td>k = 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>j = 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>k = 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>j = 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
receive a deterministic population from the five Assembly Places in the first two periods, with 1,624 people from AP1, AP2, AP3, and AP5. At AP4, a slight decrease occurs during periods 1 and 2, with 1,604 people being transported to Xitangqiao Street and 1,587 in period 2. This may due to the capacity of the Temporal Settlement at Xitangqiao Street. Baibu Town would receive most of the evacuees in the first two periods. The Temporal Settlement at Baibu Town will offer its capacity to receive the fluctuated people living near the QNPS. After the deterministic population is transferred to the three Temporal Settlements, the remaining population, which may vary due to local residents’ conditions, would be transferred to the Baibu Town. For instance, there would be [0, 52] people shipped to the Baibu Town in period 4, and none would be transferred to the Baibu Town under advantageous conditions but 52 people are required to be transferred under demanding conditions. Figure 5.2 shows the detailed evacuation patterns from the five Assembly Places to the three Temporal Settlements in Xiatangqiao Street, Baibu Town and Yuanhua Town. Figure 5.3 presents the contributions of the five Assembly Places in the emergency evacuation system. The LVC (i.e. Luotang Village Committee) offers the most capacity for evacuating residents in the QNPS, with more than 30% of the total population under advantageous conditions. More than 20% of the population would be evacuated from the QMS (i.e. Qinshan Middle School), with the detailed proportions being 21.85 and 20.03% under advantageous and demanding conditions. The results in Figure 5.3 show the LVC and QMS are the two dominant assembly places for assembly. The remaining population would go to CVC, ZVG and CNSHR. This would lead to a population decrease for LVC and QMS and an increase for CVC, ZVG and CNSHR.
Figure 5.2. Population evacuation pattern under the fuzzy and probability confidence levels being 0.3 and 0.01, respectively
Figure 5.3. Proportion of the five Assembly Place to evacuate population under Scenario 1
between advantageous and demanding conditions.

The three Temporal Settlements in Xitagnqiao Street, Baibu Town and Yuanhua Town will receive the evacuees from the five Assembly Places. Figure 5.4 presents the proportions for the three Temporal Settlements when receiving evacuees in the evacuation system. The results show the Baibu Town would contribute most for settling evacuees from the QNPS. More than half of the population would be transferred to Baibu Town, with a proportion being 52.5% under advantageous conditions (i.e. lower bound for the residents in the QNPS), and 56.7% under demanding conditions (corresponding to the upper bound of the residents in the QNPS). This is due to the lower cost and short distances for the five routes from the five Assembly Places to Baibu Town. Following the Baibu Town, the Temporal Settlement in Xitangqiao Street also presents a significant contribution in the designated evacuation system, with the proportions being 38.7 and 35.2% under advantageous and demanding conditions.

Due to the limited capacity of the three Temporal Settlements in Xitagnqiao Street, Baibu Town and Yuanhua Town, some population would be shipped to cities. Jiaxiang, Pinghu, Tongxiang and Haining are the potential cities to receive the evacuated population from the QNPS. Figure 5.4 presents the evacuation patterns from the three Temporal Settlements to the five cities. Only the population transferred to Xitangqiao Street and Baibu Town are required to be further evacuated to cities, and the people evacuated to the TS in Yuanhua Town would not need to be transferred to the cities, as presented in Table 5.8. Only a limited population would be evacuated
Figure 5.4. Proportion of the three TSs to receive evacuated population under Scenario 1
Table 5.8. Evacuated population from TS to cities under Scenario 1

<table>
<thead>
<tr>
<th>$Z(j, t, k)$</th>
<th>$j = 1$</th>
<th>$j = 2$</th>
<th>$j = 3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k = 1$</td>
<td>0</td>
<td>[2567, 3425]</td>
<td>0</td>
</tr>
<tr>
<td>$k = 2$</td>
<td>0</td>
<td>3425</td>
<td>0</td>
</tr>
<tr>
<td>$k = 3$</td>
<td>0</td>
<td>[0, 3425]</td>
<td>0</td>
</tr>
<tr>
<td>$k = 4$</td>
<td>0</td>
<td>[0, 57]</td>
<td>0</td>
</tr>
<tr>
<td>$k = 5$</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$t = 2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k = 1$</td>
<td>0</td>
<td>3199</td>
<td>0</td>
</tr>
<tr>
<td>$k = 2$</td>
<td>0</td>
<td>3148</td>
<td>0</td>
</tr>
<tr>
<td>$k = 3$</td>
<td>0</td>
<td>3185</td>
<td>0</td>
</tr>
<tr>
<td>$k = 4$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 5$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$t = 3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k = 1$</td>
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</tr>
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<td>$k = 2$</td>
<td>[139, 351]</td>
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</tr>
<tr>
<td>$k = 3$</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 4$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 5$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$t = 4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k = 1$</td>
<td>3333</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 2$</td>
<td>3333</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 3$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 4$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 5$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
to the TS in Yuanhua Town, which does not reach the maximum capacity of the TS in Yuanhua Town. The population in the Baibu Town would be transferred to the cities of Jiaxing and Pinghu during the first three periods. Deterministic people will go to the city of Pinghu, with the detailed numbers being 3,199, 3,148 and 3,185 in periods 1, 2 and 3, respectively. For the population going to Jiaxing, the number would vary during the planning period, with more than 3,400 evacuees under demanding conditions in the first three periods. Under advantageous conditions, which correspond to the lower bound of the evacuated population in the QNPS, about 2,567 and 3,425 people will go to Jiaxing in periods 1 and 2, but no one is required to be transferred in period 3. This is due to the limited population shipped to the Baibu Town under advantageous conditions. Some people (about 57) need to be transferred to the city of Jiaxing under demanding conditions in period 4.

In this evacuation system, the injured people are required to be shipped to the city of Jiaxing since a high level hospital is located there. Table 5.9 presents the number of injured people to be transferred to Jiaxing City from the three TSs in the five planning periods. The number of injured people are proportional to the total population in the three TSs. The number of injured people sent to Jiaxing City also varies, as a result of variation in the evacuated population to the three TSs.

5.4.2. Scenario 2: $\beta = 0.5$, $\alpha = 0.05$

This scenario selects the medium fuzzy and probability confidence intervals, with the lower and upper bounds for the evacuated population being 20,671 and 22,671, respectively. Table 5.10 presents the evacuated population from Assembly
Table 5.9. Injured population transferred to Jiaxing City

<table>
<thead>
<tr>
<th>$Y(j, k)$</th>
<th>$j = 1$</th>
<th>$j = 2$</th>
<th>$j = 3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k = 1$</td>
<td>81</td>
<td>86</td>
<td>37</td>
</tr>
<tr>
<td>$k = 2$</td>
<td>97</td>
<td>104</td>
<td>0</td>
</tr>
<tr>
<td>$k = 3$</td>
<td>0</td>
<td>[71, 130]</td>
<td>0</td>
</tr>
<tr>
<td>$k = 4$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$k = 5$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 5.10. Evacuated population from AS to TS under Scenario 2

<table>
<thead>
<tr>
<th>$X(i, j, k)$</th>
<th>$i = 1$</th>
<th>$i = 2$</th>
<th>$i = 3$</th>
<th>$i = 4$</th>
<th>$i = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k = 1$</td>
<td>1624</td>
<td>1624</td>
<td>1624</td>
<td>1604</td>
<td>1624</td>
</tr>
<tr>
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<tr>
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<tr>
<td></td>
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<td>0</td>
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</tr>
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<td>$k = 5$</td>
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<td>0</td>
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</tr>
</tbody>
</table>
Place to Temporary Settlement under this scenario. Compared with the evacuation scheme under Scenario 1, the desired evacuation scheme in this scenario would not change significantly. Most can safely be transferred to the three TSs in Xitangqiao Street, Baibu Town and Yuanhua Town during the first three periods, in which TSs in Xitangqiao Street and Baibu Town are the major evacuation destinations. The TS in Xitangqiao Street would receive a deterministic population from the five Assembly Places, and the varying population is transferred to the TS in the Baibu Town. Population transferred to the TS in the Xitangqiao Street is quite similar to the scheme in Scenario 1, with only slight differences for the evacuation routes from APs 4 and 5 to Xitangqiao Street. For the routes from the five APs (Assembly Places) to Baibu Town, the population evacuated through these routes are also similar with those under Scenario 1. But due to the lower people living in the QNPS, no people are required to evacuated through these routes in period 4, which is different from the evacuation scheme under Scenarios 1. Furthermore, for the TS in the Yuanhua Town, it will contribute most of its capacity to the population from AP2 (i.e. Qinshan Middle School), and also receive about 100 and 61 people from AP1 and AP3, respectively. Figure 5.5 presents the detailed evacuation scheme from the five APs to the three TSs. Compared with, the highest evacuation population happens on the route from AP2 to the TS in Yuanhua Town under Scenario 2, while the highest evacuation route under Scenario 1 is from Luotang Village Committee (AP3) to the TS in Yuanhua Town. Figure 5.6 shows the proportions the three TSs to receive the evacuated populations.
Figure 5.5. Population evacuation pattern under the fuzzy and probability confidence levels being 0.5 and 0.05, respectively
Figure 5.6. Proportion of the three TSs to receive evacuated population under Scenario 2
The results indicate that the Baibu Town contributes most in this designated emergency evacuation plan, followed by the Xitangqiao Street and Yuanhua Town. In detail, the Baibu Town would receive more than half of the total evacuees in this scenario, with 53% under advantageous conditions and 57 under demanding conditions.

The limitation of the three TSs in Xitangqiao Street, Baibu Town and Yuanhua Town require the evacuees to be further transferred to nearby cities. Table 5.11 presents the evacuation patterns from the three Temporal Settlements to the four cities. As presented in Figure 5.6, the TS in Baibu Town receives most evacuees from the QNPS. The people in Baibu Town are shipped to the four cities. As presented in Table 5.11, the population in Baibu Town is evacuated to Jiaxiang and Pinghu in the first three periods. The population would be shipped to Pinghu City, with the detailed number being 3,080, 3,133 and 3,252. The population from Baibu Town to Jiaxing City would vary, with 2,588, 3,347 and 0 under advantageous conditions but 3,425 under demanding conditions, in the first three periods. There would no need to transport anyone from Baibu Town to Jiaxing under advantageous conditions, since everyone would have been safely evacuated in the first three periods and no one would be shipped to Baibu Town in the last two periods. There are more than 6,000 people being shipped from Xitangqiao Street to Haiyan in the first two periods, with 3,333 people in each period. There would be some injured people being transferred from three Temporal Settlements to Jiaxiang City, as presented in Table 5.12
Table 5.11. Evacuated population from TS to cities under Scenario 2

<table>
<thead>
<tr>
<th>Z(j, t, k)</th>
<th>j = 1</th>
<th>j = 2</th>
<th>j = 3</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>k = 1</td>
<td>0</td>
<td>[2588, 3425]</td>
</tr>
<tr>
<td></td>
<td>k = 2</td>
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<td>[3347, 3425]</td>
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<tr>
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<td>[0, 3425]</td>
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</tr>
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<td>0</td>
<td>3133</td>
</tr>
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<td></td>
<td>k = 3</td>
<td>0</td>
<td>3252</td>
</tr>
<tr>
<td></td>
<td>k = 4</td>
<td>0</td>
<td>0</td>
</tr>
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<td>0</td>
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<td>k = 1</td>
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<tr>
<td></td>
<td>k = 5</td>
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</tbody>
</table>
Table 5.12. Injured population transferred to Jiaxing City under Scenario 2

<table>
<thead>
<tr>
<th>k</th>
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<th>j = 2</th>
<th>j = 3</th>
</tr>
</thead>
<tbody>
<tr>
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<td>33</td>
</tr>
<tr>
<td>2</td>
<td>97</td>
<td>104</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>[69, 128]</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
5.4.3. Scenario 3: $\beta = 0.8$, $\alpha = 0.1$

Under this scenario, the fuzzy and probabilistic confidence levels are 0.8 and 0.1, respectively, leading to potential evacuees fluctuating within [20143, 22143]. The evacuation schemes from Assembly Places to Temporal Settlements are presented in Table 5.13. The results show similar evacuation patterns with Scenarios 1 and 2. Most people will be safely evacuated from the QNPS in the first three periods, with about 57 people required to be transferred in the fourth period under demanding conditions. Figure 5.7 presents the population flow patterns under the scenarios. It shows similar features with Figure 5.2 and Figure 5.5. The QMS, namely Qinshan Middle School, would evacuate the population in this emergency evacuation system, with about 27.9% of the total evacuees being transferred to the Temporal Settlements from QMS under advantageous conditions and about 25.4% under demanding conditions. The LVC (i.e. Luotang Village Committee) would evacuate about 22.7 and 20.66% of the total population in the QNPS under advantageous and demanding conditions. The slightly decrease in the proportion for QMS and LVC between advantageous and demanding conditions is due to routes from these to Assembly Places have reached their maximum capacity under demanding and advantageous conditions. When more population are required to be evacuated under demanding conditions, the flexible population would be transferred from the other three Assembly Places since QMS and LVC cannot receive more people. This leads to an increase in the proportion for AVG, CNSHR, and CVC between advantageous and demanding conditions, as presented in Figure 5.8.
Figure 5.7. Population evacuation pattern under the fuzzy and probability confidence levels being 0.8 and 0.1, respectively.
Table 5.13. Evacuated population from AS to TS under Scenario 3

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<th>$i = 3$</th>
<th>$i = 4$</th>
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<td>1967</td>
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<td>[0, 1383]</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
</tbody>
</table>
Figure 5.8. Proportion of the five Assembly Place to evacuate population under Scenario 3
Baibu Town would contribute most to the emergency evacuation scheme under this scenario, which is similar to those under Scenarios 1 and 2. Compared with the results under Scenarios 1 and 2, the Baibu Town contributes a larger role in receiving the evacuees under Scenario 3. As presented in Figure 5.9, under advantageous conditions, the Baibu Town would receive about 54.5% of the total evacuees, compared with 52.5 and 52.8% under Scenarios 1 and 2, respectively. It would stabilize at about 58.7% of the total evacuated population under the demanding conditions in this scenario, compared to 56.7 and 57.0% for the first two scenarios. The residents living then the plume emergency planning zone would be evacuated to the Baibu Town, until the maximum capacity of Baibu Town is reached. Then the remaining evacuees would be transferred to the Xitangqiao Street and Yuanhua Town. This would lead to the Baibu Town offering more capacity.

Due to the limited capacity for the three Temporal Settlements in the Xitangqiao Street, Baibu Town and Yuanhua Town, some evacuees would be transferred to the adjacent cities. The injured would be shipped to the Jiaxing City for recovery. Table 5.14 shows the evacuation schemes from the temporal settlements to cities. There is a large number of people from Baibu Town being evacuated to the cities of Jiaxing and Pinghu, which would mainly happen in the first three periods. For the evacuees in Xitangqiao Street, they are further transported to the city of Haiyan due to the short distance between the two places. Also, some evacuees need to be shipped to the city of Tongxiang in the second period, with 57 under advantageous conditions and 269 under demanding
Figure 5.9. Proportion of the three Temporal Settlements to receive evacuees under Scenario 3
Table 5.14. Evacuated population from TS to cities under Scenario 3

<table>
<thead>
<tr>
<th>Z(j, t, k)</th>
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<tr>
<td>k = 2</td>
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<td>3425</td>
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<td>[0, 3425]</td>
<td>0</td>
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<td>[0, 57]</td>
<td>0</td>
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<td>[0, 57]</td>
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<tr>
<td>k = 3</td>
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<td>0</td>
</tr>
<tr>
<td>k = 5</td>
<td>0</td>
<td>0</td>
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</table>
Table 5.15. Injured population transferred to Jiaxing City under Scenario 3

<table>
<thead>
<tr>
<th>Y(j, k)</th>
<th>j = 1</th>
<th>j = 2</th>
<th>j = 3</th>
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</thead>
<tbody>
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<td>22</td>
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<tr>
<td>k = 2</td>
<td>96</td>
<td>104</td>
<td>0</td>
</tr>
<tr>
<td>k = 3</td>
<td>0</td>
<td>[71, 129]</td>
<td>0</td>
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<tr>
<td>k = 4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>k = 5</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>
conditions. Table 5.15 presents the injured population being evacuated to the Jiaxing City for health recovery. The estimated, injured population is based on the total population evacuated to the three Temporal Settlements in Xitangqiao Street, Baibu Town and Yuanhua Town, respectively.

5.4.4. Estimated Costs

The total number of evacuees may vary under different fuzzy and probability confidence levels due to the uncertainties in the model parameters, and the fuzzy random features for the residents in the plume emergency zone of the QNPS, as shown in Figure 5.1. The variation of the evacuees would change the evacuation schemes and lead to fluctuations in the final costs of the system. Table 5.16 shows the total costs for the evacuation under the selected combinations of fuzzy and probability confidence levels. For the predefined probability confidence levels, the system cost would decrease with an increase in the fuzzy confidence level. Conversely, the system cost would increase with an increase in the probability confidence level under the same predefined fuzzy confidence level. However, as presented in Figure 5.10, the changing trend for the lower bound of the system cost is more likely linear but the changing trend for the upper bound of system cost is more likely nonlinear. The lower bound of the system cost corresponds to the advantageous conditions (i.e. lower bound of evacuees). So under advantageous conditions, the potential evacuation routes would not change significantly, leading to the system cost being proportional to the evacuees. Under demanding conditions, which
Table 5.16. The system cost under different combinations of fuzzy and probability confidence levels ($x\times 10^7$)

<table>
<thead>
<tr>
<th>Probability level</th>
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<th>0.5</th>
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<td>[1.355, 1.511]</td>
<td>[1.333, 1.462]</td>
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<tr>
<td>0.05</td>
<td>0.3</td>
<td>[1.372, 1.555]</td>
<td>[1.357, 1.522]</td>
<td>[1.335, 1.473]</td>
</tr>
<tr>
<td>0.1</td>
<td>0.3</td>
<td>[1.376, 1.562]</td>
<td>[1.361, 1.529]</td>
<td>[1.339, 1.479]</td>
</tr>
</tbody>
</table>
Figure 5.10. The system cost under different fuzzy and probability confidence levels
correspond to the upper bound of the evacuees, the designated evacuation schemes under one scenario may not be applicable to another. More routes would be required, as illustrated by the three scenarios. This would lead to a nonlinearity between the system cost and the fuzzy and probability confidence levels.

5.5. Summary

An inexact fuzzy stochastic chance constrained programming (IFSCCP) model was developed to identify a desired evacuation scheme in response to accidents and disasters under various uncertainties. This model is based on interval-parameter programming (IPP) and fuzzy stochastic chance constrained programming (FSCCP) methods, in which the IPP method addresses the uncertainties presented as intervals defined by crisp lower and upper bounds, and the FSCCP method is proposed to address dual-uncertainties expressed as fuzzy random variables. The measures of possibility and necessity are employed to convert the fuzzy random variables into crisp values. Uncertainties expressed as discrete intervals and fuzzy random variables can be well addressed within the optimization framework.

The IFSCCP model was applied to support a nuclear emergency evacuation management in the QNPS, which is one of the largest nuclear plants in China. The results provided stable intervals for the objective function and decision variables with different fuzzy and probability confidence levels regarding the local residents’ distribution. The evacuation system was designed based on the “Emergency Planning Zone of Off-site
Nuclear Power Station” provided by the QNPS. It has three Temporal Settlements and four designated cities for population evacuation. The objective was to safely evacuate the residents in the plume emergency planning zone with minimum cost. Decision alternatives for the evacuation schemes have been generated, and nine scenarios have been analyzed to reflect the impacts of the imprecision (fuzziness and randomness) associated with the amount of population in the plume emergency planning zone. The results are valuable for supporting local decision makers generating effective emergency evacuation strategies.
Chapter 6  Inexact Mixed-integer Credibility-constrained de Novo Programming for Qinshan Nuclear Power Site (IMCDP-QNPS) Evacuation under Uncertainty

6.1 Background

The Nuclear power plant evacuation problem has drawn the world’s attention for it is extreme danger and vulnerability. An efficient and scientific evacuation plan for a nuclear power plant emergency is essential, identifying how to improve the reaction ability of an emergency of the NPP system and minimize rescue time and property losses (Yueming and Deyun, 2008). An optimal system (searching for effectiveness) can be designed to improve the performance of a given system and search for the best system configuration (Zeleny, 1990). The system is optimized with de Novo programming and multiple objectives (Zeleny, 1986). The optimality concept is identified through the post-design of the system. The method can improve upon existing evacuation management methods by incorporating interval, credibility constrained, integral and de Novo programing into the optimization framework. Two conflicting objectives are considered, including maximization of the evacuees during the disaster and minimizing the system costs.

6.2 Model Development

6.2.1 de Novo programming

The de Novo programming can effectively address the single or multi-objective
problems through reformulating the given system. It was initially proposed by Zeleny to solve the trade-offs between different objectives and reset the system configurations (Zeleny, 1981). In a de Novo programming problem, a given system can be formulated as follows (Zeleny, 1990):

\[
\text{Max } z = \sum_{j=1}^{n} C_{mj} \times X_j, \quad m = 1, \ldots, k
\]  

(6-1a)

Subject to:

\[
\sum_{j=1}^{n} a_{ij} X_j \leq b_i, \quad i = 1, \ldots, l
\]  

(6-1b)

\[
\sum_{i=1}^{l} p_i b_i \leq B,
\]  

(6-1c)

\[
X_j \geq 0, \quad j = 1, \ldots, n
\]  

(6-1d)

where \( p_i \) is the given unit prices of \( m \) resources, \( B \) is total variable budget, \( b_i \) is the resulting portfolio of resources, which denote decision variables that would be designed in this problem, \( X_j \) are the production levels, which represent system decision variables. Objective functions are designed to be maximized simultaneously. This model allocates budget to resource \( b_i \), determining \( X_j \), and maximizes the benefit value \( z \) (Li and Lee, 1990). Problem (6-1) can be transformed into (Zhang et al., 2009):

\[
\text{Max } z = \sum_{j=1}^{n} C_{mj} \times X_j, \quad m = 1, \ldots, k
\]  

(6-2a)

Subject to:

\[
\sum_{j=1}^{n} V_j X_j \leq b_i, \quad i = 1, \ldots, l
\]  

(6-2b)

\[
X_j \geq 0, \quad j = 1, \ldots, n
\]  

(6-2c)
where \( z = (z_1, \ldots, z_l) \) and \( V = (V_1, \ldots, V_n) = p_i \times a_j \). Problem (6-2) can be solved through the theory of de Novo optimal design programming. Let \( z^*_m = \max z, m = 1, \ldots, k \) subject to constraints of (6-2). Let \( z^* = (z^*_1, \ldots, z^*_l) \) denote the performance of the optimal design under a given budget. \( z^* \) must be attainable for a given budget level \( B \) (Zeleny, 1981).

For each \( z^* \), a corresponding \( z^*_i \) optimal portfolio \( b^*_i \) can be calculated as in the previous section. Vector \( z^* \) represents the meta optimal performance, and the corresponding \( x^* \) and \( b^* \) can be obtained by solving the following meta optimum model (Zeleny, 1990):

\[
\begin{align*}
\text{Min } B &= \sum_{j=1}^{n} V_j X_j \\
\text{Subject to:} & \quad \sum_{j=1}^{n} C_{mj} \times X_j \geq Z^*, \ m = 1, \ldots, k \\
& \quad X_j \geq 0, \ j = 1, \ldots, n
\end{align*}
\]  

(6-3a)  
(6-3b)  
(6-3c)

The minimum budget \( B^* \) can be obtained by solving problem (6-3), and the metaoptimum performance \( z^* \) can be realized with \( x^* \) and \( b^* \). The solution of problem (6-3), \( B^* \) and \( x^* \), can be designated as metaoptimum solution. The optimum ratio \( r \) can be used:

\[ r = B / B^* . \]

The final solutions are: \( x = r x^* \), \( b = r b^* \), \( z = r z^* \). The optimum ratio \( r \) could provide an efficient tool for virtually instantaneous optimal redesign. It could be used as a
powerfully competitive tool to maintain complex multicriteria decision systems by expanding or shrinking budget $B$.

The de Novo programming approach is capable of designing the resource portfolio by modifying the interactions of each constraint (Zhang et al., 2009). New feasible regions could be modified to satisfy the post-proposed metaoptimum constraints. The optimal concept of de Novo solutions is to determine the minimum budget necessary to achieve the metaoptimum. However, if the metaoptimum constraints are not equal, the de Novo model aspires to at least achieve metaoptimum results, since it is possible to over attain the metaoptimum (Kotula, 1997).

### 6.2.2 Credibility-constrained programming

Credibility-constrained programming is one of the most important fuzzy measure types. It is widely applied under different circumstances. Fuzzy sets are capable of addressing uncertainties on the left-hand side expressed as a probability distribution. Credibility-constrained programming is used to address system risks with credibility measures (Liu et al., 2001). When the stochastic distribution data are unavailable, and with another type of uncertainty such as interval parameters are considered, the effectiveness of credibility-constrained fuzzy programming is improved in system analysis. Thus an Inexact Credibility-constrained fuzzy programming model can be formulated as follows (Zhang and Huang, 2011):

\[
\text{Max } f = \sum_{j=1}^{n} C_{mj} \times X_j, \quad m = 1, ..., k \tag{6-4a}
\]

s.t.
\[ Cr \left\{ \sum_{j=1}^{n} a_{ij} x_j \leq b_i \right\} \geq \lambda, \quad i = 1, \ldots, l \]  

(6-4b)

\[ X_j \geq 0, \quad j = 1, \ldots, n \]  

(6-4c)

where \( B \in \{R\}^m \), \( C \in \{R\}^{n} \), \( X \in \{R\}^n \), and \( R \) denote a set of numbers, \( X = (x_1, x_2, \ldots, x_n) \) are a vector of decision variables, \( B = (b_1, b_2, \ldots, b_m) \) are right-hand-side coefficients, \( C = (c_1, c_2, \ldots, c_n) \) are cost coefficients, and \( \tilde{A} \) are fuzzy technical coefficients. Formulation (6-4b) shows that the satisfaction of \( \tilde{A} X \geq B \) should be equal to or greater than level \( \lambda \). According to Liu et al. (2001) the credibility measure is the average of the possibility and necessity measures, as shown in Figure 6.1 (Zhang and Huang, 2010):

\[ Cr\{\xi \geq \gamma\} = \frac{1}{2} (Pos\{\xi \geq \gamma\} + Nec\{\xi \geq \gamma\}) \]  

(6-5)

Since a triangular fuzzy variable \( (\xi) \) is determined by a triplet \((t, t, \tilde{t})\) of crisp numbers, represented as \( t < t < \tilde{t} \), the membership function is given by (Huang, 2006):

\[ u(r) = \begin{cases} 
\frac{r-t}{t-t} & \text{if} \quad t \leq r \leq t \\
\frac{r-\tilde{t}}{t-\tilde{t}} & \text{if} \quad t \leq r \leq \tilde{t} \\
0 & \text{otherwise}
\end{cases} \]  

(6-6a)
Figure 6.1. Fuzzy membership, possibility, necessity, and credibility of a fuzzy set
Based on the membership function in model (6-6a), the possibility, necessity, and credibility functions of $\xi \geq \gamma$ would be shown as (X. Huang, 2006):

\[
\text{Pos}(\xi \geq \gamma) = \begin{cases} 
1 & \text{if } r \leq t \\
\frac{r - t}{t - \tilde{t}} & \text{if } t \leq r \leq \tilde{t} \\
0 & \text{if } r \geq \tilde{t}
\end{cases}
(6-6b)
\]

\[
\text{Nec}(\xi \geq \gamma) = \begin{cases} 
1 & \text{if } r \leq \tilde{t} \\
\frac{r - t}{t - \tilde{t}} & \text{if } t \leq r \leq \tilde{t} \\
0 & \text{if } r \geq \tilde{t}
\end{cases}
(6-6c)
\]

\[
\text{Cr}(\xi \geq \gamma) = \begin{cases} 
1 & \text{if } r \leq \tilde{t} \\
\frac{2t - \tilde{t} - r}{2(t - \tilde{t})} & \text{if } t \leq r \leq \tilde{t} \\
\frac{r - \tilde{t}}{2(t - \tilde{t})} & \text{if } t \leq r \leq \tilde{t} \\
0 & \text{if } r \geq \tilde{t}
\end{cases}
(6-6d)
\]

Based on the concept of fuzzy theory, where $\tilde{AX}$ can be replaced by fuzzy set $(t_\tilde{t}, t_i, \tilde{t}_i)$. Thus, formulation (6-4b) can be represented as:

\[
\text{Cr}\{t_i \geq r\} \geq \lambda_i, \quad i = 1, 2, \ldots, m
(6-7)
\]

In the optimization of system risk management, the credibility level is generally assumed to be over 0.5. Thus, the constraint can be represented as:

\[
\text{Cr}\{t_i \geq r\} = \frac{2(t_i - \tilde{t}_i - r)}{2(t_i - \tilde{t}_i)} \geq \lambda_i \geq 0.5, \quad i = 1, 2, \ldots, m
(6-8)
\]

The following result is obtained through conversion of the inequality above:

\[
\lambda_i \geq 0.5 
\]

\[
r \leq t_i + (1 - 2\lambda)(t_i - \tilde{t}_i)
(6-9)
\]
when it is assumed $r = b_i$, the equation (6-9) becomes:

$$t_i + (1 - 2\lambda)(t_i - t_i) \geq b_i$$  (6-10)

Model (6-4) can be solved by substituting $\tilde{AX}$ for $\tilde{t_i}$. Some decision variables are integers in practical system management problems. For example, in the capacity expansion option, the people need to be evacuated in an emergency. Integer programming would be introduced into the inexact credibility-constrained programming. Integer programming can be combined within the inexact credibility-constrained fuzzy programming framework as:

$$\text{Max } f = \sum_{j=1}^{n} C_{mj} \times X_j, \ m = 1,\ldots, k$$  (6-11a)

Subject to

$$\text{Subject to }$$

$$Cr\left\{ \sum_{j=1}^{n} a_{ij} X_j \leq b_i \right\} \geq \lambda, \ i = 1,\ldots, l$$  (6-11b)

$$\sum_{j}^{n} d_{ij} X_j + \sum_{k}^{l} f_{ik} Y_k \leq g_i, \ \forall i$$  (6-11c)

$$X_j \geq 0, \ j = 1,\ldots, n$$  (6-11d)

$$y_k = \{ \text{integer, the expansion is undertaken} \} \begin{cases} 0, \text{Otherwise} \end{cases}$$  (6-11e)

Based on equation (6-10), the fuzzy constraints (6-11b) can be substituted with the corresponding deterministic constraints. Model (6-11) can then be made deterministic as:

$$\text{Max } f = \sum_{j=1}^{n} C_{mj} \times X_j, \ m = 1,\ldots, k$$  (6-12a)

Subject to
\[ \sum_{j}^{n} \left[ a_{ij} + (1-2\lambda_{j}) \times (a_{ij} - a_{ij}) \right] \times X_{j} \geq b_{i}, \quad \forall i \]  

(6-12b)

\[ \sum_{j}^{n} d_{ij} x_{j} + \sum_{k} f_{ik} y_{k} \leq g_{i}, \quad \forall i \]  

(6-12c)

\[ X_{j} \geq 0, \quad j = 1, ..., n \]  

(6-12d)

\[ y_{k} = \begin{cases} \text{integer, the expansion is undertaken} \\ 0, \text{Otherwise} \end{cases} \]  

(6-12e)

The characteristics of the mixed-integer credibility-constrained fuzzy programming model will generally be effective at addressing uncertainties presented as fuzzy sets, facilitating dynamic analysis for system planning by mixed integer variables, and evaluating the system stability that satisfies the system constraints with credibility theory.

### 6.2.3 Inexact Mixed-integer Credibility-constrained de Novo programming

According to methods of interval linear programming, the proposed programming can be solved with the following steps. The model can be generalized into an IMCDP problem as:

\[ \text{Max } z^{\pm} = C^{\pm} X^{\pm} \]  

(6-13a)

Subject to

\[ Cr \left\{ A^{\pm} X^{\pm} - B^{\pm} \leq 0 \right\} \geq \lambda \]  

(6-13b)

\[ p^{\pm} b^{\pm} \leq B^{\pm} \]  

(6-13c)

\[ X_{j} \geq 0, \quad j = 1, ..., n \]  

(6-13d)
where \( C \in R^{m \times n} \) and \( A \in R^{k \times n} \) are matrices of dimension of \( m \times n \) and \( k \times n \), respectively. 

\( c_{mn} \) represents the element of Matrix \( C \), \( a_{kn} \) represents the elements of Matrix \( A \);

\( b^+ = (b_1^+, b_2^+, \ldots, b_t^+) \) is a vector of design decision variables, \( x^+ = (x_1^+, x_2^+, \ldots, x_t^+) \) is a vector of management decision variables, \( p^+ = (p_1^+, p_2^+, \ldots, p_t^+) \) represents the unit prices of \( i \) resources, \( B^+ \) is the total budget, and \( R^+ \) denotes a set of interval numbers.

Decision variables in this IMCDP model include two types, design decision variables and system management decision variables. This is unlike other ordinary optimization problems. Thus, it is essential to highlight the specificity in the proposed model. All of the decision variables are expressed in inexact numbers on a realistic basis.

The further solution algorithm was developed to solve the proposed problem by examining interactions between decision variables and uncertain parameters in the objective function and constraints. The model’s solution process involves two sub-models. The first step is to formulate and solve the lower bound sub-model, when the objective function is to be maximized (Fan, 2012). Then, the upper bound sub-model can be solved based on the results from the first sub-model. According to Huang et al. (1993), for \( n \) interval variables \( X_j^+ (j = 1, 2, \ldots, n) \), if \( k_1 \) of them are positive and \( k_2 \) of them are negative, let the \( k_1 \) coefficients \( c_i^+ \geq 0 (j = 1, 2, \ldots, k_1) \), and the latter \( k_2 \) coefficients \( c_i^+ \leq 0 (j = k_1 + 1, k_1 + 2, \ldots, k_1 + k_2) \), where \( k_1 + k_2 = n \) (Huang and Moore, 1993). It is assumed \( b_i^+ > 0 \) and \( f^+ > 0 \). The lower bound sub-model can be formulated as:

\[
\text{Max } z_k^- = \sum_{j} c_{kj}^- x_j^- - \sum_{j=t+1}^{n} c_{kj}^+ x_j^+, \forall k 
\]

Subject to
\[
Cr \left\{ \sum_{j} |a_{ij}|^+ \text{Sign}(a_{ij})x_j^- + \sum_{j=k_i+1}^{n} |a_{ij}|^- \text{Sign}(a_{ij})x_j^+ \geq b_i^- (t) \right\} \geq \lambda, \forall i \quad (6-14b)
\]
\[
\sum |p_i|^+ \text{Sign}(p_i)b_i^- \leq B^- \quad (6-14c)
\]
\[
x_j^+ \geq 0, \forall j \quad (6-14d)
\]

The solution to this model can be obtained as \( x_{j_opt}^- (j = 1, 2, ..., k_i) \), \( x_{j_opt}^+ (j = k_i + 1, k_1 + 2, ..., n) \) and \( z_{opt}^- \). Equations (6-14b) and (6-14c) can be transformed into:
\[
\sum |p_i|^+ \text{Sign}(p_i)b_i^- \geq b_i^- + (1 - 2\lambda_i) \times (b_i^- - b_i^-), \forall i \quad (6-14e)
\]

Let \( ^*z_k^- = \text{max } z_k^- , k = 1, ..., q \) be the optimal value for \( k \)th objective of the first submodel with equations (6-14). Let \( ^*z_k^- = (^*z_1^-, ^*z_2^-, ..., ^*z_q^-) \) be the \( q \)th objective value of the design system. Then the metaoptimum lower submodel can be formulated as follows:
\[
\text{Min } B^- = \sum |p_i|^+ \text{Sign}(p_i)(\sum_{j} |a_{ij}|^+ \text{Sign}(a_{ij})x_j^-) + \sum |p_i|^+ \text{Sign}(p_i)(\sum_{j=k_i+1}^{n} |a_{ij}|^- \text{Sign}(a_{ij})x_j^+)
\]
\[
(6-15a)
\]
Subject to
\[
\sum_{j} c_{kj}^- x_j^- - \sum_{j=t+1}^{n} c_{kj}^+ x_j^+ \geq ^*z_k^-, \forall k \quad (6-15b)
\]
\[
x_j^+ \geq 0, \forall j \quad (6-15c)
\]
Through solving the problem, results of \( ^*x_j^- \), \( ^*B^- \), \( ^*b^- \), and \( ^*r^- \) can be obtained.
The upper bound submodel corresponding to \( z^+ \) can be formulated based on the solutions obtained from the previous model.

\[
\begin{align*}
\text{Max } z_k^+ & = \sum_j c_{kj}^+ x_j^+ - \sum_{j=1}^n c_{kj}^- x_j^- \quad \forall k \\
\text{s.t.} & \\
Cr \left\{ \sum_j a_{ij}^- \text{Sign}(a_{ij}^+) x_j^+ + \sum_{j=k+1}^n a_{ij}^+ \text{Sign}(a_{ij}^-) x_j^- \geq b_i^- (t) \right\} & \geq \lambda, \forall i
\end{align*}
\] (6-16a)

\[
\sum |p_i|^+ \text{Sign}(p_i) b_i^+ \leq B^+
\] (6-16b)

\[
x_j^+ \geq 0, \forall j
\] (6-16c)

Let \( z_k^+ = \max z_k^+, k = 1, \ldots, q \) be the optimal value for \( k \)th objective of the second submodel with equations (6-16). Let \( z_k^+ = (z_1^+, z_2^+, \ldots, z_q^+) \) be the \( q \)th objective value of the design system. Then the metaoptimum upper submodel can be formulated as follows:

\[
\begin{align*}
\text{Min } B^+ & = \sum |p_i|^+ \text{Sign}(p_i^-) \left( \sum_j a_{ij}^- \text{Sign}(a_{ij}^+) x_j^+ \right) + \sum |p_i|^+ \text{Sign}(p_i^-) \left( \sum_{j=k+1}^n a_{ij}^+ \text{Sign}(a_{ij}^-) x_j^- \right) \\
\text{s.t.} & \\
\sum_j c_{kj}^+ x_j^+ - \sum_{j=1}^n c_{kj}^- x_j^- & \geq z_k^+, \forall k
\end{align*}
\] (6-17a)

\[
x_j^+ \geq 0, \forall j
\] (6-17b)

Through solving the problem, results of \( x_j^+, B^+, b^+, \) and \( r^+ \) can be obtained.

Final solutions could be obtained with the solving process of submodels and metaoptimum models from equations from (6-14) to (6-17). Figure 6.2 shows the scheme for the modeling structure. The steps for this algorithm can be summarized as:

**Step 1.** Define an IMCDP problem.
Step 2. Transform the IMCKP model into two submodels from its uncertain nature.

Step 3. Formulate the lower bound model of $z^-$, and obtained $\hat{z}_k^-$

Step 4. Formulate the metaoptimum submodel and obtain $\hat{x}_j^-$, $\hat{B}$, $\hat{b}$, and $\hat{r}$

Step 5. Calculation of $x_{opt}^{\pm}$, $b_{opt}^-$, and $z_{opt}^-$

Step 6. Formulate the lower bound model of $z^+$, and obtain $\hat{z}_k^+$

Step 7. Formulate the metaoptimum submodel and obtain $\hat{x}_j^+$, $\hat{B}$, $\hat{b}$, and $\hat{r}$

Step 8. Calculation of $x_{opt}^{\pm}$, $b_{opt}^+$, and $z_{opt}^+$

Step 9. Obtain solution of the IMCDP model: $z_{opt}^{\pm} = [z_{opt}^-, z_{opt}^+]$, $b_{opt}^{\pm} = [b_{opt}^-, b_{opt}^+]$ and $x_{opt}^{\pm} = [x_{opt}^-, x_{opt}^+]$

Step 10. Stop.
Figure 6.2. Flow chart of inexact mixed-integer credibility-constrained de Novo (IMCDP) Programming
6.3 Case study

6.3.1 Overview of the system

Nuclear accidents can cause severe disasters with environment pollution over large areas and cause great harm to human health with the release of harmful radioactive materials. Emergency evacuation is the most immediate and urgent movement of people. The disasters can be controlled and reduced through effective evacuation planning before the event occurs. Generally, an evacuation system includes an assembly station (AS) from the responsible facilities to the 1st level evacuation site, temporary settlements (TS) as the 2nd level evacuation of first aid and large building for shelter, town or cities for the 3rd level with enough resources for settling, and evacuation paths from the emergency responders to the three levels of locations.

Qinshan nuclear power base includes three nuclear power plants, with two types of reactors for a total of six nuclear power units in operation. The site is a multi-stack, multi-reactor type nuclear power base. The Qinshan Nuclear Power Site (QNPS) Unit 4 and new Qinshan nuclear power under construction, have resulted in great changes in the natural environment and human surroundings of the Qinshan Nuclear Power Base. If an accident occurs at the Qinshan nuclear power base, particularly those with off-site radiological consequences of a nuclear accident, the provincial nuclear emergency committee must have a clear, detailed and most importantly, timely contingency plan. The decision maker’s duties are to access accident information, start an emergency response, organize the public, appeal to the public around the Qinshan Nuclear Power Base utmost to avoid or reduce exposure to radiation from nuclear accidents, and eventually protect public health and safety. Currently, there are five types of emergency
assembly points within a 3 km area within the QNPS, which are Chuangchuanba Village (AS1), Qinshan Middle School (AS1), Luotang Village (AS1), Ganpu Min Committee (AS1), and Nanbeihu Street (AS1). Three temporary settlements for shelter include: Xitangqiao Street (TS1), Baibu Village (TS2), and Yuanhua Village (TS3). The evacuees would be transported to four cities nearest to the QNPS, which are Jiaxin, Pinghu, Tongxiang, and Haining. Since Jiaxin is the largest city and the only location with medical facilities for nuclear related diseases, all the injuries would be transported to the City of Jiaxin.

Thus the objective in the evacuation plan is to ensure the safest and most efficient evacuation time. Decision makers face challenging system optimization in a short time with limited resources management in an unexpected event. The system is highly uncertain with unforeseeable incidents. For example, the evacuees and shelter capacity may be uncertain because of population fluctuations. The optimal evacuation system is desired. However, most of the uncertainties and complexities cannot be assessed with conventional systems analysis methods. A robust decision-support approach for addressing critical issues during an evacuation process is desired. The issues include how to: Evacuate as many people as possible from ASs to TSs to avoid direct harm from the radiation, optimistically design the evacuation route within the irradiated area, redesign the system due to the resource availability at each site and lastly, integrate the uncertainties and complexities in many system components within a general evacuation planning framework.
6.3.2 Modeling formulation

According to the evacuation regulations for the study area in the QNPS, the evacuation task is planned to be completed in 2.5 hrs with 0.5 hrs in each period. Considering the inaccurate information in the system, an inexact mixed-integer programming is formulated for the QNPS as follows. The objective is to maximize the evacuees during the limited time and with limited resources.

(1) Inexact Mixed-integer QNPS Model (IMP)

Objective function

$$\text{Max } f^\pm = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{ijk}^\pm$$

(6-18a)

Subject to

1. Available evacuated population

$$\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{ijk}^\pm \geq \text{TP}^\pm$$

(6-18b)

2. Evacuation capacity constraint

$$\sum_{k=1}^{K} x_{ijk}^\pm \leq FAS_{i,j}^\pm \ \forall i, j$$

(6-18c)

3. Vehicle flux constraint

$$\sum_{k=1}^{K} y_{jkt}^\pm / \alpha_{Y}^\pm \leq VFT_{j}^\pm, \ \forall j$$

(6-18d)

$$\sum_{k=1}^{K} z_{jtk}^\pm / \alpha_{Z}^\pm \leq SVT_{j,t}^\pm, \ \forall j, t$$

(6-18e)

4. Patient transportation demand
\[ y_{jk}^+ \geq \gamma \sum_{i=1}^{I} x_{ijk}^+, \forall j, k \]  
\[ (6-18f) \]

5. TSs capacity constraint

\[ \sum_{k=1}^{K'} \sum_{i=1}^{I} x_{jk}^+ - \sum_{k=1}^{K'} \sum_{t=1}^{T} z_{jk}^- - \sum_{k=1}^{K'} y_{jk}^- \leq CS_{j}, \forall j, K' = 1, 2, 3 \]  
\[ (6-18g) \]

6. Technical constraint

\[ x_{jk}^+ \in N, \forall i, j, k \]  
\[ (6-18h) \]

\[ y_{jk}^+ \in N, \forall j, k \]  
\[ (6-18i) \]

\[ z_{jk}^- \in N, \forall j, t, k \]  
\[ (6-18j) \]

\( (2) \) Inexact mixed-integer credibility-constrained QSPPE Model (IMCP)

The credibility-constrained programming was incorporated into the IMP model to formulate the IMCP model by considering the system risks of constraint violations and uncertainties in the number of evacuees due to population fluctuations and uncertainties existing in the TS capacity:

Objective function

\[ \text{Max } f^\pm = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{ijk}^\pm \]  
\[ (6-19a) \]

Subject to

1. Available evacuated population

\[ Cr \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{ijk}^\pm \geq TP^\pm \right\} \geq \lambda \]  
\[ (6-19b) \]

2. Evacuation capacity constraint
\[ \sum_{k=1}^{K} x_{ijk}^\pm \leq FAS_{ij}^\pm \quad \forall i, j \]  

(6-19c)

3  Vehicle flux constraint

\[ \sum_{k=1}^{K} y_{jk}^\pm / \alpha_Y^\pm \leq VFT_j^\pm \quad \forall j \]  

(6-19d)

\[ \sum_{k=1}^{K} z_{jtk}^\pm / \alpha_Z^\pm \leq SVT_{jt}^\pm \quad \forall j, t \]  

(6-19e)

4  Patient transportation demand

\[ y_{jk}^\pm \geq \gamma \sum_{i=1}^{I} x_{ijk}^\pm \quad \forall j, k \]  

(6-19f)

5  TSs capacity constraint

\[ Cr\left\{ \sum_{k=1}^{K} \sum_{i=1}^{I} x_{ijk}^\pm - \sum_{k=1}^{K} \sum_{t=1}^{T} z_{jtk}^\pm - \sum_{k=1}^{K} y_{jk}^\pm \leq CS_j^\pm \right\} \geq \lambda, \quad \forall j, K' = 1, 2, 3 \]  

(6-19j)

6  Technical constraint

\[ x_{ijk}^\pm \in N, \forall i, j, k \]  

(6-19h)

\[ y_{jk}^\pm \in N, \forall j, k \]  

(6-19i)

\[ z_{jtk}^\pm \in N, \forall j, t, k \]  

(6-19j)

Often the number of evacuees is considered a single-objective problem in evacuation system management. In reality, emergency information is always limited the efficiency is restricted and adversely affected by it. de Novo programming is introduced into the IMCP model for further system optimization on the economic side. The evacuating resources and materials are represented in U.S. dollars. An original inexact mixed-integer
credibility-constrained de Novo QSPPE Model and its Metaoptimimum Model are formulated as follows:

(3) *Inexact mixed-integer credibility-constrained de Novo QSPPE Model (IMCDP)*

**Objective function**

\[
\text{Max } Z^\pm = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{ijk}^\pm
\]  

(6-20a)

**Subject to**

1. Available evacuated population

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_k x_{ijk}^\pm \geq \text{TP}^\pm
\]  

(6-20b)

2. Evacuation capacity constraint

\[
\sum_{k=1}^{K} x_{ijk}^\pm \leq FAS_{i,j}^\pm \ \forall i, j
\]  

(6-20c)

3. Vehicle flux constraint

\[
\sum_{k=1}^{K} y_{jk}^\pm / \alpha_y^\pm \leq VFT_j^\pm, \ \forall j
\]  

(6-20d)

\[
\sum_{k=1}^{K} z_{jk}^\pm / \alpha_z^\pm \leq SVT_{jt}^\pm, \ \forall j, t
\]  

(6-20e)

4. Patient transportation demand

\[
y_{jk}^\pm \geq \gamma \sum_{i=1}^{I} x_{ijk}^\pm, \ \forall j, k
\]  

(6-20f)

5. TSs capacity constraint

\[
\sum_{i=1}^{I} \sum_{k=1}^{K} x_{ijk}^\pm - \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} z_{ijk}^\pm - \sum_{k=1}^{K} y_{jk}^\pm \leq CS_j^\pm, \ \forall j, K', 1, 2, 3
\]  

(6-20g)
6. Economic constraint

\[
\sum_{k=1}^{K} (L_{kj} \sum_{j=1}^{J} CAT_{ij}^{+} x_{ijk}^{+} Y_{ij}) + \sum_{j=1}^{J} (L_{k}^{+} ICT_{ij}^{+} y_{jk}^{+} DTT_{ji}) + \sum_{j=1}^{J} (L_{k}^{+} TTT_{ij}^{+} z_{jk}^{+} DTT_{ji}) \leq TC^{+} \]

(6-20h)

7. Technical constraint

\[
x_{jk}^{+} \in N, \forall i, j, k \]

(6-20i)

\[
y_{jk}^{+} \in N, \forall j, k \]

(6-20j)

\[
z_{jk}^{+} \in N, \forall j, t, k \]

(6-20k)

(4) Inexact mixed-integer credibility-constrained de Novo QSPPE Metaoptimus

Model

Objective function

\[
\text{Max } B^{\pm} = \sum_{k=1}^{K} (L_{k} \sum_{i=1}^{I} \sum_{j=1}^{J} CAT_{ij}^{+} x_{ijk}^{+} Y_{ij}) + \sum_{i=1}^{I} (L_{k}^{+} ICT_{ij}^{+} y_{jk}^{+} DTT_{ji}) + \sum_{j=1}^{J} (L_{k}^{+} TTT_{ij}^{+} z_{jk}^{+} DTT_{ji})
\]

(6-21a)

Subject to

1. Available evacuated population

\[
\sum_{i=1}^{I} \sum_{k=1}^{K} L_{k} x_{ijk}^{+} \geq TP^{\pm}
\]

(6-21b)

2. Evacuation capacity constraint

\[
\sum_{k=1}^{K} x_{ijk}^{+} \leq FAS_{ij}^{\pm} \forall i, j
\]

(6-21c)

3. Vehicle flux constraint
\[
\sum_{k=1}^{K} y_{jk}^\pm / \alpha_i^\pm \leq VFT_j^\pm, \forall j
\]  
(6-21d)

\[
\sum_{k=1}^{K} z_{jk}^\pm / \alpha_k^\pm \leq SVT_{j_t}^\pm, \forall j, t
\]  
(6-21e)

4. Patient transportation demand

\[
y_{jk}^\pm \geq \gamma \sum_{i=1}^{I} x_{ijk}^\pm, \forall j, k
\]  
(6-21f)

5. TSs capacity constraint

\[
\sum_{k=1}^{K} \sum_{i=1}^{I} x_{ijk}^\pm - \sum_{k=1}^{K} \sum_{r=1}^{R} z_{jk}^\pm - \sum_{k=1}^{K} y_{jk}^\pm \leq CS_j^\pm, \forall j, K' = 1, 2, 3
\]  
(6-21g)

6. Budget constraint

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} L_i x_{ijk}^\pm \geq Z_k^\pm
\]  
(6-21h)

7. Technical constraint

\[
x_{ijk}^\pm \in N, \forall i, j, k
\]  
(6-21i)

\[
y_{jk}^\pm \in N, \forall j, k
\]  
(6-21j)

\[
z_{jk}^\pm \in N, \forall j, t, k
\]  
(6-21k)

where:

**Superscript:**

\(i\) is the type of emergency assembly station, \(i=1, 2, 3, 4, 5\);

\(j\) is the type of temporary settlement, \(i=1, 2, 3\);

\(t\) is the type of city for eventual settlement, \(i=1, 2, 3, 4\);

\(k\) is the 0.5 hr time period during the evacuation process, \(i=1, 2, 3, 4, 5\);
**Decision variables:**

\[ x_{ijk}^{±} \] is the population flow from AS I to TS J during period k (person/h)

\[ y_{jtk}^{±} \] is the patient population flow from TS j to city of Jiaxing during period k (person/h)

\[ z_{jtk}^{±} \] is the population flow from TS j to city t during period k (person/h)

**Parameters:**

\( TP \) is the total population at QNPS within 3 km (person)

\( FAS_{i,j} \) is the population evacuation capacity of the route from assembly station i to TS j (person/h)

\( VFT_j \) is the maximum ambulance flux of the road from TS j to city 1 (vehicle/h)

\( SVT_{jt} \) is the maximum vehicle flux for the route from TS j to city t (vehicle/h)

\( \gamma_k^{(\phi)} \) is the proportion of injured people at TS j under level \( \phi \) during period k

\( CS_j \) is the capacity of TS j (person)

\( DAT_{ij} \) is the distance from AS to TS (km)

\( DTT_{jt} \) is the distance from TS to city (km)

\( CAT_{ij} \) is cost of transportation from AS to TS ($/km)

\( ICT_{j1} \) is cost of transportation of injuries from TS to city of Jiaxing ($/km)

\( CTT_{jt} \) is cost of transportation from TS to cities ($/km)
6.3.3 Results analysis

Since tradeoffs between safety and available resources in the management of the QNPS evacuation system have been analyzed, three sets of solutions have been obtained for different uncertainties considered and system configurations. The first set of solutions is acquired through inexact mixed-integer programming. The second set of solutions can be obtained by solving the inexact mixed-integer credibility-constrained programming. The first set of solutions equals one of the solutions in the second solution when $\lambda = 0.5$, which means the necessity and possibility of the event are equal. Table 6.1 shows the second set of solutions. The evacuation rate would higher from AS 4 and AS 5 to TS 1 during five periods, which are all [2376, 2376] people/hour. The conditional evacuation routes from the two ASs are better than the alternative routes. Most evacuees from the five ASs would be transported to TS1, its largest capacity shelter. The evacuated population rate to TS1 would be [2136, 2875], [2376, 2797], [2376, 2376], [2376, 2376], and [2376, 2376] people/hour from AS 1 to 5, respectively. Table 1 represents the evacuating population rate under different conditions (i.e. $\lambda$ levels, from 0.5 to 1.0) with respect to the population fluctuations and sheltering capacity variations. The significance of different $\lambda$ levels is that population from AS 2 to TS 2. For example, during period 1, the population rate from AS 2 to TS 2 would be [955, 955], [915, 915], [875, 875], [835, 835], [795, 795] and [755, 755] people/hour under $\lambda = 0.5$, 0.6, 0.7, 0.8, 0.9, and 1.0, respectively.

Table 6.2 shows the patient population flow from ASs to TS1 for five periods. From the table, the population would be the highest at TS2 during period 1, and from periods 2
to 5, the evacuation rate would eventually decrease to 0. In TS1 and TS2, the variation in population rate would differ slightly. The evacuating population rate in TS1 would decrease from [2136, 2875] to [1978, 1978] in period 2, and increase to [2376, 2376] and [2365, 2365] in periods 2 and 3, respectively, decreasing to [1298, 1298] in period 5. The population injury rate would vary due to unforeseen circumstances in situ.

Figure 6.3 shows the total number of evacuees as a function of credibility level. It presents the trend of system risk due to constraint violations. It shows a decrease in evacuees as $\lambda$ increases. When $\lambda=1.0$, the system requirement for shelter capacity cannot be satisfied, and the population number within 3 km of the QNPS would be the largest, and the system risk would be the highest. Table 3 shows the population rate transported from TSs to Cities for settlement. The population is consistent during each period. The total number of recurred people would be [53439, 63729], [53439, 63709], [53439, 63689], [53439, 63669], [53439, 63649], and [53439, 63629] under six levels of credibility, respectively. The higher the level of credibility, the higher the risk the system would be credible, meaning fewer evacuees under the same system conditions.
Table 6.1. Results of the emergency evacuation scheme under IMCP. (people/hour)

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\( \lambda = 0.5 \) \( \lambda = 0.6 \)

168
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<tr>
<td>k = 1</td>
<td>[2136, 2875]</td>
<td>[2376, 2797]</td>
<td>[2376, 2376]</td>
</tr>
<tr>
<td>k = 2</td>
<td>[1978, 1978]</td>
<td>[579, 1561]</td>
<td>[2376, 2376]</td>
</tr>
<tr>
<td>k = 3</td>
<td>[2376, 2376]</td>
<td>[0, 0]</td>
<td>[938, 1405]</td>
</tr>
<tr>
<td>k = 4</td>
<td>[2365, 2365]</td>
<td>[0, 0]</td>
<td>[0, 412]</td>
</tr>
<tr>
<td>k = 5</td>
<td>[1298, 1298]</td>
<td>[0, 0]</td>
<td>[0, 350]</td>
</tr>
</tbody>
</table>
The solutions obtained in Table 6.3 result from the IMCP model ($\lambda = 0.5$) integrated with de Novo programming for system economic redesign. It shows a significant difference between the original and Metaoptimum models. Table 6.3 shows the total number of evacuees under IMCP and IMCDP is [51955, 127458], [45000, 51955] during five periods, respectively. The budgets are $[2500000, 2,900,000]$ and $[553047.30, 1089,697.70]$. The number of evacuees and budget would be smaller to obtain. This may introduce higher risks in evacuees recurring under most situations. However, in the QNPS model, the minimum number of employees and residents within 3 km of the QNPS has been considered in the modeling constraints, which makes the model economically efficient and an effective approach for a flexible meta evacuation planning based on the original budget. The IMCDP approach is useful for designing an optimal rather than conditional system.
Figure 6.3. The evacuated population rate under different $\lambda$ level ($\$$)
Table 6.3. The results of IMCP and IMCDP

<table>
<thead>
<tr>
<th></th>
<th>Evacuated people</th>
<th>budget</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>IMCP</td>
<td>51955</td>
<td>127458</td>
</tr>
<tr>
<td>IMCDP</td>
<td>45000</td>
<td>51955</td>
</tr>
</tbody>
</table>
6.4 Summary

Three methods for evacuation system management under uncertainty have been developed for the QNPS, i.e., Inexact mixed-integer QNPS model (IMP), inexact mixed-integer credibility-constrained QNPS model (IMCP), and inexact mixed-integer credibility-constrained de Novo QNPS model (IMCDP). The proposed methods can effectively address the multiple objectives between evacuation safety and the limited resources and materials with multiple uncertainties expressed as interval numbers and probabilistic distributions. The IMCP methods are effective for system risk analysis based on different credibility-levels. As the credibility level increases, the population rate recurrence would decrease. The IMCDP was developed to solve the multi-objective between the system efficiency and economic restrictions. The approach is capable of addressing system design problems, which cannot be realized with conventional multi-objective programming. The proposed IMCDP approach is capable of reducing the computational efficiency by transforming the objective into the constraints.

The system efficiency in the QNPS problem, under restricted resources and materials, is recognized as the most important issue during evacuation. The conflicting objectives make it difficult for decision makers to select the optimial solutions from several decision alternatives. There are no trade-offs in the new system with the proposed IMCDP method, which can allow the decision makers to have access to the preferred optimal system rather than multiple series of solutions.
There are limitations to the proposed methods, such as the transportation sector updating every year, thus the planning needs to be continually modernized. The dynamic programming is capable of addressing the issues, which can be incorporated into the system in the future. Only linear relations between decision variables and coefficients were considered in the proposed optimization approach. The system may be more complicated for non-linear relationships and interactions. Nonlinear programming and its algorithms can be integrated into evacuation system management.
Chapter 7 Conclusions

7.1. Summary

A series of inexact optimization approaches have been proposed to reflect multiple uncertainties existing in the emergency evacuation planning system and inexact optimization approaches were applied for emergency evacuation strategy identification for the QNPS under various uncertainty scenarios. The proposed inexact optimization approaches include: (i) an interval-based evacuation management (IBEM) model in response to nuclear-power plant accidents, (ii) an inexact gradient-based fuzzy chance constrained programming (IGFCCP) method for balancing a decision maker’s optimism and pessimism regarding evacuation route capacities in the QNPS emergency evacuation system, (iii) an inexact fuzzy stochastic chance constrained programming (IFSCCP) for tackling various uncertainties and optimizing the planning of an evacuation scheme for the Qinshan Nuclear Power Site (QNPS), and (iv) an inexact mixed-integer credibility-constrained de Novo programming method for emergency evacuation management for the QNPS.

An interval-based evacuation management (IBEM) model has been developed based on an interval-parameter linear programming (ILP) technique that can address uncertainties presented as interval values. The IBEM model is applied to a case study and solved with an interactive algorithm that does not lead to more complicated intermediate submodels and has a relatively low computational requirement. Two scenarios have been
analyzed based on different policies for total capital considerations. Decision alternatives could be generated based on results from the IBEM model, which provide a basis for in-depth analyses of tradeoffs among an evacuated population, system cost, and constraint-violation risk.

An inexact gradient-based fuzzy chance constrained programming (IGFCCP) model was proposed based on interval-parameter programming (IPP) and gradient-based fuzzy chance constrained programming (GFCCP). The GFCCP method was based on the concept of a fuzzy gradient measure, which is a combination of possibility and necessity and can balance a decision maker’s optimism and pessimism. The IGFCCP model was applied to support nuclear emergency evacuation management in the Qinshan Nuclear Power Site in China. The evacuation management system includes five assembly places (APs), three temporary settlements (TSs) and four settlement cities (CSs). The objective is to maximize the number of evacuees from the inner Plume Emergency Planning Zone (PEPZ). Optimized evacuation schemes were generated, and five scenarios were analyzed to reflect the impacts of the imprecision (fuzziness) associated with the transportation capacity of village level evacuation routes.

Chapter 5 introduced an inexact fuzzy stochastic chance constrained programming (IFSCCP) model to identify the desired evacuation scheme in response to accidents and disasters under various uncertainties. This model integrated the IPP and fuzzy stochastic chance constrained programming (FSCCP) methods into a general framework, in which the IPP method addresses the uncertainties presented as intervals defined by crisp lower
and upper bounds. The FSCCP method was proposed to treat the dual-uncertainties expressed as fuzzy random variables. The measures of possibility and necessity were employed to convert the fuzzy random variables into crisp values to reflect the decision maker’s pessimistic and optimistic preferences. The IFSCCP model was applied to support nuclear emergency evacuation management in the Qinshan Nuclear Power Site, which is one of the largest nuclear plants in China. The results provide stable intervals for the objective function and decision variables with different fuzzy and probability confidence levels regarding the local residents’ distribution. Nine scenarios were analyzed to reflect the impacts of the imprecision (fuzziness and randomness) associated with the size of the population in a plume emergency planning zone. The results were valuable for supporting local decision makers to generate effective emergency evacuation strategies.

Chapter 6 introduced an inexact mixed-integer credibility-constrained de Novo programming method to improve existing evacuation management methods by incorporating interval, credibility constrained, integral and de Novo programing into the optimization framework. Two conflicting objectives are considered, including maximizing the number of evacuees during the disaster and minimizing system costs. The number of evacuees and budget would be smaller. There is a higher risk of people recurring under most situations. However, in the QNPS model, the minimum number of employees and residents within 3 km of QSNPP has been considered in the modeling constraints, which makes the model economically efficient and an effective approach for
flexible meta evacuation planning based on the original budget. The system efficiency under restricted resources and materials was recognized as the most important issue during the evacuation.

7.2. Research Achievements

A set of inexact programming methods have been developed and applied to emergency evacuation management under various uncertainties. From a general systems analysis perspective, three inexact optimization techniques and their solution algorithms have been developed from previous interval and fuzzy chance constraint programming methods. The IGFCCP approach extended the measures of possibility and necessity in a gradient-based measure (GM) to balance the decision maker’s optimism and pessimism. The GM was introduced into the interval programming framework, leading to an IGFCCP approach reflecting the decision maker’s optimistic and pessimistic preferences. The IFSCCP approach extended the measures of fuzzy possibility and necessity to fuzzy random variables, and incorporated the measures of possibility and necessity into the interval programming framework. This IFSCCP could address dual uncertainties existing in the system components and parameters and reveal the impacts of fuzzy and probability confidence levels on final decision alternatives. The IMCDP approached is proposed to incorporate interval, credibility constrained, integral and de Novo programing into the optimization framework. This method can consider conflicting objectives in evacuation
management problems, and provide a trade-off between maximizing the number of evacuees during the disaster, and minimizing system costs.

The emergency evacuation planning problem for nuclear accidents was introduced from an environmental systems engineering application perspective. Emergency evacuation is important to prevent injuries and deaths, resulting from natural or man-made disasters, especially nuclear accidents. There are limited studies addressing the emergency evacuation strategies for nuclear accidents. Only a small amount of research has identified appropriate evacuation actions for nuclear power accidents under uncertainty. This research has investigated various uncertainties such as interval, fuzzy and fuzzy random variable that may exist in the system components and parameters in the emergency evacuation system for nuclear power accidents and revealed the potential evacuation actions under various uncertainties to achieve trade-offs between system risks and costs.

7.3. Recommendations for Future Research

(1) More research is needed on the reflection of multiple uncertainties existing in many environmental systems. Compound uncertainties are responsible for the existence of various complexities when evaluating environmental vulnerability and risk. The uncertainties existing in the evacuation system components and parameters may be correlated with each other and further affect the performance of the optimization model. The inexact fuzzy stochastic programming methods (i.e. IGFCCP, IFSCCP, and IMCDP)
could be further enhanced by incorporating methods of factorial analysis into its framework to address interactive uncertainties and their impacts on optimization models.

(2) Evacuation management systems for nuclear power accidents involve multiple interactive and dynamic components. The development of the evacuation management model is difficult. The proposed evacuation management model in this dissertation was based on assumptions. Further research should contribute to improving the evacuation model and develop a more robust and realistic evacuation model.

(3) The proposed IGFCCP and IFSCCP and IMCDP methods need to be extended to other environmental fields (e.g. air pollution control planning, groundwater remediation, and watershed environmental planning) and multiple regions, nationally and internationally.
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