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Inexact Fuzzy Stochastic Chance Constraint Programming for Emergency Evacuation under Climate Change

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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 inexact fuzzy stochastic chance constrained programming (IFSCCP) method is developed to address various uncertainties in evacuation management problems. It integrates the interval-parameter programming (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, and the FCCP 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 is 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 are 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 are valuable for supporting local decision makers to generate effective emergency evacuation strategies.

Keywords: decision making, emergency evacuation, nuclear power station, multiple uncertainty, optimization

1. Introduction

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 (Huang et al., 2006; Qin et al., 2007). 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.

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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 strategiy under multiple uncertainties.

2. Methodology

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 can be intervals (Huang et al., 1992). Specifically, an ILP model can be defined as follows (Cai et al., 2009; Nie et al., 2016, Chen et al., 2016):

$$\text{Max} \quad f^{\pm} = C^{\pm} X^{\pm} \tag{1a}$$

subject to

$$A^{\pm} X^{\pm} \le B^{\pm} \tag{1b}$$

$$X^{\pm} \ge 0 \tag{1c}$$

where $A^{\pm} \in \{R^{\pm}\}^{m\times n}$, $C^{\pm} \in \{R^{\pm}\}^{1\times n}$, $B^{\pm} \in \{R^{\pm}\}^{m\times 1}$, $X^{\pm} \in \{R^{\pm}\}^{n\times 1}$, $R^{\pm}$ denotes a set of interval numbers; $A^{\pm} = (a_{ij}^{\pm})_{m\times n}$, $C^{\pm}$ = $(c_1^{\pm}, c_2^{\pm}, ..., c_n^{\pm})$, $B^{\pm} = (b_1^{\pm}, b_2^{\pm}, ..., b_m^{\pm})^T$, $X^{\pm} = (x_1^{\pm}, x_2^{\pm}, ..., x_n^{\pm})^T$. An interval number ($a^{\pm}$) is defined as (Huang et al., 1992): $a^{\pm} = [a^-, a^+] = \{t \in a \mid a^- \le t \le a^+\}$.

Several approaches have been proposed to generate reasonable solutions for the ILP problem (Huang et al., 1992; Sengupta et al., 2001; Fan et al., 2012; Fan and Huang, 2012; Chen et al., 2015). In this study, an interactive solution algorithm named two-step-method (TSM) was proposed by Huang et al. (1992, 1995) was widely used for interval-parameter programming methods (Huang, 1998; Huang and Loucks, 2000; Li et al., 2008a, 2009, 2010). Interval solutions can be obtained based on the analysis of detailed interrelationships between the parameters and variables and between the objective function and constraints. The main idea of 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. In detail, for n interval coefficients $c_j^{\pm}$ (j = 1, 2, …, n) in the objective function, the former k coefficients are assumed to be positive (i.e. $c_j^{\pm} \ge 0$, for j = 1, 2, …, k), and the latter (n - k) coefficients are negative (i.e. $c_j^{\pm} \le 0$, for j = k + 1, …, n). Thus the first submodel of model (1) would correspond to f^+. It can be formulated as follows (assume that $b_i^{\pm} > 0$ and $f^{\pm} > 0$) (Zeng et al., 2016; Fan et al., 2016):

$$\text{Max} \quad f^+ = \sum_{j=1}^{k} c_j^+ x_j^+ + \sum_{j=k+1}^{n} c_j^+ x_j^- \tag{2a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^- Sign(a_{ij}^{\pm}) x_j^+ + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^+ Sign(a_{ij}^{\pm}) x_j^- \le b_i^+, \; i = 1, 2, \ldots, m \tag{2b}$$

$$x_j^+ \ge 0, \; j = 1, 2, \ldots, k \tag{2c}$$

$$x_j^- \ge 0, \; j = k+1, k+2, \ldots, n \tag{2d}$$

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

$$\text{Max} \quad f^- = \sum_{j=1}^{k} c_j^- x_j^- + \sum_{j=k+1}^{n} c_j^- x_j^+, \tag{3a}$$

subject to:

$$\sum_{j=1}^{k} \left|a_{ij}^{\pm}\right|^+ Sign(a_{ij}^{\pm}) x_j^- + \sum_{j=k+1}^{n} \left|a_{ij}^{\pm}\right|^- Sign(a_{ij}^{\pm}) x_j^+ \le b_i^-, \; i = 1, 2, \ldots, m \tag{3b}$$

$$0 \le x_j^- \le x_{j\,opt}^+, \; j = 1, 2, \ldots, k \tag{3c}$$

$$x_j^+ \ge x_{j\,opt}^-, \; j = k+1, k+2, \ldots, n \tag{3d}$$

From submodel (3), Solutions of x_{jopt}^- (j = 1, 2, …, k) and x_{jopt}^+ (j = k + 1, …, n) can be obtained. Thus, the final solution of $f_{opt}^{\pm} = [f_{opt}^-, f_{opt}^+]$ and $x_{jopt}^{\pm} = [x_{jopt}^-, x_{jopt}^+]$ can be obtained for model (1).

2.2. Fuzzy Stochastic Chance Constraint Programming

2.2.1. Fuzzy Random Variable

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

Definition 1 (Puri and Ralescu, 1986). For a probability space (Ω, F, P), a fuzzy random variable is a function $\xi : \Omega \to F_c(R)$, if only if for $\forall \alpha \in [0, 1]$, the set value function ξ_α: $\Omega \to K_c(R)$:

$$\xi_\alpha(\omega) := (\xi(\omega))_\alpha := \{x \mid x \in R, \mu_{\xi(\omega)} \ge \alpha\} \tag{4}$$

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

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

Definition 2 (Liu, 2001). Let $\boldsymbol{\xi} = (\xi_1, \xi_2, ..., \xi_n)$ be a fuzzy random vector in a probability space (Ω, F, P) and f_i: $R^n \to R$, i = 1,2, …, m be a real-valued continuous function, then the chance measure Ch of the fuzzy random event $f_i(\boldsymbol{\xi}) \le 0$, i = 1, 2, …, m, is defined as:

$$Ch\{f_i(\boldsymbol{\xi}) \le 0, i = 1,2,...,m\}(\alpha)$$
$$= \sup\{\beta \mid Pr\{\omega \in \Omega \mid Ch\{f_i(\boldsymbol{\xi}) \le 0, i = 1,2,...,m\} \ge \beta\} \ge \alpha\} \tag{5}$$

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

To compare the preference between two fuzzy events, the measures of possibility and necessity were introduced to reflect the preferred confidence degrees of decision makers (Dubois and Prade, 1988; Inuiguchi and Ramik, 2000; Zhang et al., 2009; Lv et al., 2010). Suppose a and b be non-interactive fuzzy numbers with continuous membership function. For a confidence level $\alpha \in [0,1]$, then:

$$Pos(a \geq \tilde{b}) = \sup\{\min(\mu_a(x),\ \mu_b(y)) \mid x \geq y\} \geq \alpha \Leftrightarrow a_\alpha^R \geq b_\alpha^L$$

$$\Rightarrow Pos(a \leq \tilde{b}) = \sup\{\min(\mu_a(x), \mu_{\tilde{b}}(y)) \mid x \leq y\} \geq \alpha \Leftrightarrow a_\alpha^L \leq b_\alpha^R \quad (6a)$$

$$Nes(a \geq \tilde{b}) = \inf\{\max(1-\mu_a(x), 1-\mu_{\tilde{b}}(y)) \mid x \geq y\} \geq \alpha \Leftrightarrow a_{1-\alpha}^L \geq b_{1-\alpha}^R \Rightarrow Nes(a \leq \tilde{b}) = \inf\{\max(1-\mu_a(x), 1-\mu_{\tilde{b}}(y)) \mid x \leq y\} \geq \alpha \Leftrightarrow a_{1-\alpha}^R \leq b_{1-\alpha}^L \quad (6b)$$

where a_α^L and a_α^R are the lower and upper bound of the α-cut of fuzzy number a, respectively, and $a_\alpha^L = \inf(x \mid x = \mu_a^{-1}(\alpha))$, $a_\alpha^R = \sup(x \mid x = \mu_a^{-1}(\alpha))$; b_α^L and b_α^R are the lower and upper bound of the α-cut of fuzzy number $\tilde{b}$, respectively. In general, the measures of possibility and necessity correspond to the optimistic and pessimistic preference of the decision makers.

Based on the measures of possibility and necessity, the fuzzy random chance constraint, expressed by Equation (5) can be converted into the flowing two formulations:

$$Ch\{f_i(\xi) \leq 0, i = 1,2,...,m\}(\alpha) = \sup\{\beta \mid Pr\{\omega \in \Omega \mid \mathrm{Pos}\{f_i(\xi) \leq 0, i=1,2,...,m\} \geq \beta\} \geq \alpha\} \Leftrightarrow Pr\{Pos\{f_i(\xi) \leq 0\} \geq \beta\} \geq \alpha \quad (7a)$$

$$Ch\{f_i(\xi) \leq 0, i = 1,2,...,m\}(\alpha) = \sup\{\beta \mid Pr\{\omega \in \Omega \mid Nec\{f_i(\xi) \leq 0, i=1,2,...,m\} \geq \beta\} \geq \alpha\} \Leftrightarrow Pr\{Nec\{f_i(\xi) \leq 0\} \geq \beta\} \geq \alpha \quad (7b)$$

2.2.2 Fuzzy Stochastic Chance Constraint Programming

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

$$\text{Max } f = \sum_{j=1}^{n} c_j x_j \quad (8a)$$

subject to

$$\sum_{j=1}^{n} a_{ij} x_j \leq \tilde{b}_i,\ i = 1,2,...,m \quad (8b)$$

$$\sum_{j=1}^{n} a'_{ij} x_j \leq \tilde{b}'_i(\omega),\ i = 1,2,...,m' \quad (8c)$$

$$x_j \geq 0 \quad (8d)$$

where $c \in \{U\}^{1\times n}$, $X \in \{U\}^{n\times 1}$, $\tilde{b}_i \in \{\tilde{U}\}^{m\times 1}$, $\tilde{b}'_i(\omega) \in \{\tilde{U}(\omega)\}^{m\times 1}$, $a_{ij} \in \{\tilde{U}\}^{m\times n}$; $\tilde{U}$ denotes a set of fuzzy sets; $\tilde{U}(\omega)$ denotes a set of random fuzzy sets. A fuzzy set (Ã) in X can be defined as $\{x, \mu_{\tilde{A}}(x) \mid x \in X, \mu_{\tilde{A}}(x): X \rightarrow [0, 1]\}$, where $\mu_{\tilde{A}}(x)$ is the membership function or grade of membership (Zimmermann, 1985; Dubois and Prade, 1988). The value of $\mu_{\tilde{A}}(x)$ va- ries between 0 and 1, indicating the possibility of an element x belonging to Ã. $\mu_{\tilde{A}}(x) = 1$ means that x definitely belongs to the fuzzy set (Ã), while $\mu_{\tilde{A}}(x) = 0$ denotes that x does not belong to Ã. The closer $\mu_{\tilde{A}}(x)$ is to 1, the more likely that x belongs to Ã; conversely, the closer $\mu_{\tilde{A}}(x)$ is to 0, the less likely x belongs to Ã (Zimmermann, 1985; Lai and Hwang, 1992, Li and Huang, 2009; Fan et al., 2015).

Based on Equations (6) and (7), Model (8) can be converted into to model scenarios based on the decision makers' preference (optimistic or pessimistic) (Fan et al., 2017a, b).

Optimistic:

$$\text{Max } f = \sum_{j=1}^{n} c_j x_j \quad (9a)$$

subject to

$$Pos\{\sum_{j=1}^{n} a_{ij} x_j \leq \tilde{b}_i\} \geq \beta,\ i = 1,2,...,m \quad (9b)$$

$$Pr\{Pos\{\sum_{j=1}^{n} a'_{ij} x_j \leq \tilde{b}'_i(\omega)\} \geq \beta\} \geq \alpha,\ i = 1,2,...,m' \quad (9c)$$

$$x_j \geq 0 \quad (9d)$$

Pessimistic:

$$\text{Max } f = \sum_{j=1}^{n} c_j x_j \quad (10a)$$

subject to

$$Nec\{\sum_{j=1}^{n} a_{ij} x_j \leq \tilde{b}_i\} \geq \beta,\ i = 1,2,...,m \quad (10b)$$

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

$$x_j \geq 0 \quad (10d)$$

If $a_{ij}, a'_{ij}, \tilde{b}_i$ are supposed to be triangular fuzzy numbers denoted as $a_{ij} = (a_{ij}, m_{ij}^a, n_{ij}^a)$, $a'_{ij} = (a'_{ij}, m_{ij}^{a'}, n_{ij}^{a'})$, $b_i = (b_i, m_i^b, n_i^b)$ and $b'_i(\omega)$ is assumed to be a triangular fuzzy random variable expressed as: $b'_i(\omega) = (b'_i(\omega), m_i^{b'}, n_i^{b'})$, Equation (9b) can be converted into (An et al., 2016):

$$Pos\{\sum_{j=1}^{n} a_{ij} x_j \leq \tilde{b}_i\} \geq \beta$$

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

$$\Leftrightarrow \sum_{j=1}^{n} a_{ij}x_j - \sum_{j=1}^{n} m_{ij}^{a}x_j + \sum_{j=1}^{n} \beta m_{ij}^{a}x_j \le b_i + n_i^b - \beta n_i^b \quad (11a)$$

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

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

$$\Leftrightarrow Pr\{\sum_{j=1}^{n} a'_{ij}x_j - \sum_{j=1}^{n} m_{ij}^{a'}x_j + \sum_{j=1}^{n} \beta m_{ij}^{a'}x_j \le b'_i(\omega) + n_i^{b'} - \beta n_i^{b'}\} \ge \alpha$$

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

$$\Leftrightarrow \sum_{j=1}^{n} a'_{ij}x_j - \sum_{j=1}^{n} m_{ij}^{a'}x_j + \sum_{j=1}^{n} \beta m_{ij}^{a'}x_j \le b'_i(\omega)^{\alpha} + n_i^{b'} - \beta n_i^{b'} \quad (11b)$$

Similarly, Equations (10b) and (10c) can be converted into the following equations:

$$Nec\{\sum_{j=1}^{n} a_{ij}x_j \le \tilde{b}_i\} \ge \beta$$

$$\Leftrightarrow \sum_{j=1}^{n} a_{ij}x_j + \sum_{j=1}^{n} n_{ij}^{a}x_j - \sum_{j=1}^{n} (1-\beta)n_{ij}^{a}x_j \le b_i - m_i^b + (1-\beta)m_i^b \quad (12a)$$

$$Pr\{Nec\{\sum_{j=1}^{n} a'_{ij}x_j \le \tilde{b}'_i(\omega)\} \ge \beta\} \ge \alpha$$

$$\Leftrightarrow \sum_{j=1}^{n} a'_{ij}x_j + \sum_{j=1}^{n} n_{ij}^{a'}x_j - \sum_{j=1}^{n} (1-\beta)n_{ij}^{a'}x_j \le b'_i(\omega)^{\alpha} - m_i^{b'} + (1-\beta)\mathrm{m}_i^{b'} \quad (12b)$$

2.2.3. Inexact Fuzzy Stochastic Chance Constaint Programming

In many real-world management problems, extensive uncertainties may exist and be expressed as various formats (e.g. fuzzy sets, interval numbers). In some specific situations, dual-uncertainties may exist due to the data availability. For example, the total population in a city can hardly be quantified as deterministic values and may be expressed as a random or fuzzy random variable. To deal with those extensive uncertainties existing in a management problem, an inexact fuzzy stochastic chance-constraint programming (IFSCCP) may be a powerful tool due to its capability in reflecting uncertainty expressed as various formats. A typical IFSCCP problem can formulated as follows:

$$\text{Max} \quad f^{\pm} = \sum_{j=1}^{n} c_j^{\pm}x_j^{\pm} \quad (13a)$$

subject to

$$\sum_{j=1}^{n} a_{ij}^{\pm}x_j^{\pm} \le b_i^{\pm},\ i = 1, 2, ..., l \quad (13b)$$

$$\sum_{j=1}^{n} a_{ij}x_j^{\pm} \le \tilde{b}(\omega)_i,\ i = l+1, l+2, ..., m \quad (13c)$$

$x_j^{\pm}$ = interval continuous variables, j = 1, 2, …, p (p < n) (13d)

$x_j^{\pm}$ = interval integer variables, j = p + 1, p + 1, …, n (13e)

$$x_j^{\pm} \ge 0 \quad (13f)$$

As presented in Section 2.1, the ILP problem can be solved through converting the original problem into two sub-problem corresponding to the upper and lower bounds of the objective function. Model (2), which is the sub-problem of the upper bound, corresponds to advantageous (optimistic) conditions, while Model (3) corresponds to the demanding (passimistic) conditions (Huang et al., 1992; Li et al., 2008b; Fan et al., 2012; Fan and Huang, 2012). Similarly, the fuzzy random stochastic programming can also be solved under both optimistic and pessimistic conditions, as expressed as Models (9) and (10). Consequently, Model (13) can be solve through being converted into two sub-problem, corresponding to the optimistic and pessimistic conditions, respectively. The detailed solution process is presented as follows:

Optimistic:

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

subject to

$$\sum_{j=1}^{k} |a_{ij}^{\pm}|^{-} Sign(a_{ij}^{\pm})x_j^{+} + \sum_{j=k+1}^{n} |a_{ij}^{\pm}|^{+} Sign(a_{ij}^{\pm})x_j^{-} \le b_i^{+},\ i = 1, 2, \ldots, l \quad (14b)$$

$$\Pr\{Pos\{\sum_{j=1}^{k} a_{ij}x_j^{+} + \sum_{j=k+1}^{n} a_{ij}x_j^{-} \le \tilde{b}_i\} \ge \beta\} \ge \alpha,\ i = l+1, l+2, \ldots, m \quad (14c)$$

$x_j^{\pm}$ = interval continuous variables, j = 1, 2, …, p (p < n) (14d)

$x_j^{\pm}$ = interval integer variables, j = p + 1, p + 1, …, n (14e)

$$x_j^{\pm} \ge 0 \quad (14f)$$

Pessimistic:

$$\text{Max} \quad f^{-} = \sum_{j=1}^{k} c_j^{-}x_j^{-} + \sum_{j=k+1}^{n} c_j^{-}x_j^{+} \quad (15a)$$

subject to

$$\sum_{j=1}^{k} |a_{ij}^{\pm}|^{+} Sign(a_{ij}^{\pm})x_j^{-} + \sum_{j=k+1}^{n} |a_{ij}^{\pm}|^{-} Sign(a_{ij}^{\pm})x_j^{+} \le b_i^{-} \quad (15b)$$

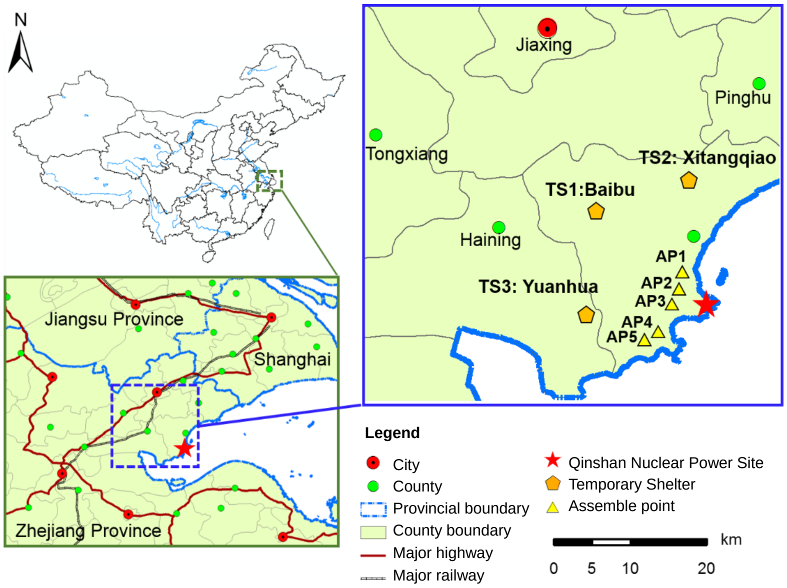
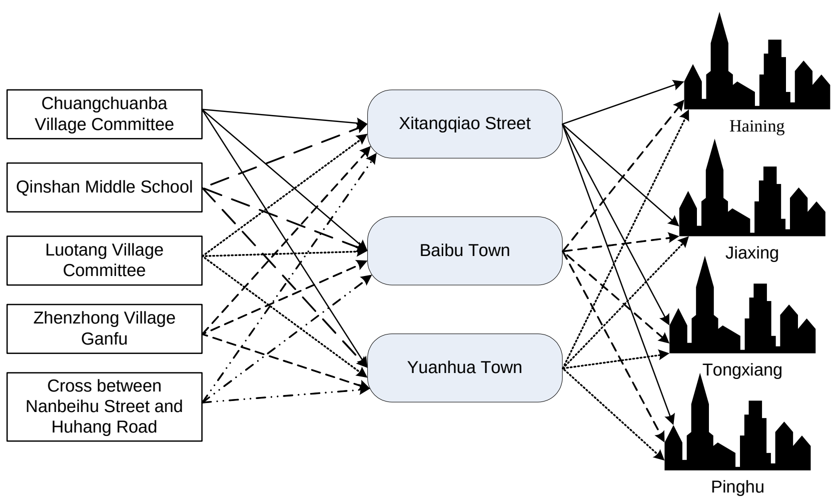


Figure 1. The location of Qinshan Nuclear Plant.



$$\Pr\{Nes\{\sum_{j=1}^{k} a_{ij}x_j^{+} + \sum_{j=k+1}^{n} a_{ij}x_j^{-} \le \tilde{b}_i\} \ge \beta\} \ge \alpha \quad (15c)$$

$$0 \le x_j^{-} \le x_{j\,opt}^{+},\ j = 1, 2, \dots, k. \quad (15d)$$

$$x_j^{+} \ge x_{j\,opt}^{-},\ j = k+1, k+2, \dots, n. \quad (15e)$$

$x_j^{\pm}$ = interval continuous variables, $j = 1, 2, \dots, p$ ($p < n$)(15f)

$x_j^{\pm}$ = interval integer variables, $j = p + 1, p + 2, \dots, n$ (15g)

Obviously, Model (13) can deal with various uncertainties expressed as fuzzy, interval and fuzzy random variables. Particlulary, the constraints containing fuzzy random variables are treated through fuzzy random chance constraint methods based on possibility and necessity measures. Model (13) can be converted into two submodels based on the two-step method for ILP proposed by Fan and Huang (2012), as well as the possiblity and necessity meausres. As expressed by Models (14) and (15), the optimistic submodel (i.e. Model (14)) corresponds to the upper bound of the objective function, with the fuzzy constraints treated by the possibility measure; while the pessimistic model (i.e. Model (15)) corresponds to the lower bound of the objective function, with fuzzy constraints treated by the necessity measure.

3. Case Study

3.1. Location of the Qinshan Nuclear Power Site

Qinshan nuclear power plant (QNPS) is located in Haiyan County of the Zhejiang province (Figure 1), with an area of 1.3 × 10^6 m^2. It is the first nuclear power plant to have been constructed in mainland China, including seven operating units

Table 1. The Ranges for the Inner and Outer Zones for the Plume Emergency Planning Zone

Town/District	Inner Zone	Outer Zone
Qinshan	Qinshan, Yangliushan, Qinxing, Changchuanba, Fegnshan, Yongxing, Beituan, Qinshanjizhen	Qinshan, Yangliushan, Qinxing, Changchuanba, Fegnshan, Yongxing, Beituan, Qinshanjishzen, Xinlian, Qingfeng
Ganfu	Gandong, Zhenzhong, Gannan	Gandong, Zhenzhong, Gannan, Baoshan, Yongxin, Ganfu, Ganfujizhen
Tongyuan		Xueshuigang, Fengyi

Table 2. The Capacities of Three Temporary Settlements

Temporary Settlement	Construction Area (m^2)	Education Usage Area (m^2)	Population Settlement (person)
Xitangqiao Street	32101	13482	[4400, 4600]
Baibu Town	21216	8911	[2900, 3100]
Yuanhua Town	11267	14732	[4700, 4900]

Table 3. The Maximum Evacuation Capacity from APs to TSs (person)

	CVC (i = 1)	QMS (i = 2)	LVC (i = 3)	ZVG (i = 4)	CNSHR (i = 5)
XS (j = 1)	[812, 1117]	[812, 1115]	[812, 1115]	[812, 1115]	[812, 1115]
BT (j = 2)	[984, 1424]	[984, 1424]	[984, 1424]	[692, 895]	[692, 895]
YT (j = 3)	[809, 1155]	[2037, 2640]	[2037, 2640]	[809, 1155]	[809, 1155]

Note: CVC: Chuangchuanba Village Committee; QMS: Qinshan Middle School; LVC: Luotang Village Committee; ZVG: Zhenzhong Village; CNSHR: Cross between Nanbeihu Street and Huhang Road; XS: Xitangqiao Street; BT: Baibu Town; YT: Yuanhua Town

Table 4. The Related Cost from APs to TSs ($/person×km)

	CVC (i = 1)	QMS (i = 2)	LVC (i = 3)	ZVG (i = 4)	CNSHR (i = 5)
XS (j = 1)	[3.48, 4.21]	[3.48, 4.21]	[3.48, 4.21]	[3.48, 4.21]	[3.48, 4.21]
BT (j = 2)	[2.60, 3.58]	[2.60, 3.58]	[2.60, 3.58]	[4.61, 4.80]	[4.61, 4.80]
YT (j = 3)	[3.24, 4.31]	[1.56, 1.63]	[1.56, 1.63]	[3.24, 4.31]	[3.24, 4.31]

Table 5. The Distance between APs and TSs (km)

	CVC (i = 1)	QMS (i = 2)	LVC (i = 3)	ZVG (i = 4)	CNSHR (i = 5)
XS (j = 1)	19.1	16.7	15.5	24.8	26.5
BT (j = 2)	25.1	22.7	21.5	28.3	26.7
YT (j = 3)	22.3	23.2	22	18.3	16.6

Table 6. The Maximum Allowable Vehicle Flux from TSs to Cities (vehicle/h)

	JX (t = 1)	PH (t = 2)	TX (t = 3)	HN (t = 4)
XS (j = 1)	[34, 36]	[33, 83]	[34, 36]	[33, 83]
BT (j = 2)	[34, 36]	[33, 83]	[11, 15]	[11, 15]
YT (j = 3)	[33, 83]	[33, 83]	[33, 83]	[24, 26]

Note: HN: Haining; JX: Jiaxing; TX: Tongxiang; PH: Pinghu

which are built in three different phases. 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 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 are about 370 thousand, with about 31 thousand people in the Qinshan Town.

3.2. Emergency Planning Zones

The emergency planning zones are set up based on the national standard "Criteria for emergency planning and preparedness for nuclear power plants" and the local natural and social conditions. These emergency planning zones can be classified as plume emergency planning zones and ingestion emergency planning zones. The plume emergency planning zones are further divided as inner and outer zones, in which the population in the inner zones should be evacuated when a nuclear accident happens. In our study, we aim to illustrate the population evacuation strategies under different uncertainty conditions, so the plume emergency zones are mainly under consideration.

Based on the meteorological conditions as well as the MACCS code provided by the US Sandia National Laboratory, the plume emergency zone is centered with the Qinshan #2 nuclear power reactor, with the radius of the inner zone being 5 km and the radius for the outer zone being 7 km. In detail, the plume emergency zone covers Qinshan District, Ganfu Town and Tongyuan Town, including 18 villages and two towns presented in Table 1. Furthermore, the inner zone of the plume emergency planning zone mainly contains the villages in Qinshan District, as well as Gandong, Zhenzhong and Gannan in the Ganfu Town, as presented in Table 1. The population in the whole plume emergency zone are about 52,800, with 46,048 being permanent residents. In the inner zone, the total population are around 23,400, with the migrants being about 4500.

Table 7. The Unit Cost for People from TSs to Cities ($/person × km)

	JX (t = 1)	PH (t = 2)	TX (t = 3)	HN (t = 4)
XS (j = 1)	[1.12, 1.17]	[0.48, 1.20]	[1.12, 1.17]	[0.48, 1.20]
BT (j = 2)	[1.12, 1.17]	[0.48, 1.20]	[2.60, 3.58]	[2.60, 3.58]
YT (j = 3)	[0.48, 1.20]	[0.48, 1.20]	[0.48, 1.20]	[1.56, 1.63]

Table 8. The Distance between TSs to Cities (km)

	JX (t = 1)	PH (t = 2)	TX (t = 3)	HN (t = 4)
XS (j = 1)	33.4	36	28	19
BT (j = 2)	29.4	32.6	48.6	26.8
YT (j = 3)	45.8	23.4	17.8	38.9

Table 9. Evacuated Population from AS to TS under Scenario 1

$X(i, j, k)$	i = 1	i = 2	i = 3	i = 4	i = 5
k = 1	1624	1624	1624	1604	1624
k = 2	1624	1624	1624	1587	1624
j = 1 k = 3	0	0	0	0	0
k = 4	0	0	0	0	0
k = 5	0	0	0	0	0
k = 1	1967	1967	1967	[1316, 1383]	1383
k = 2	1967	1967	1967	[1375, 1382]	1383
j = 2 k = 3	[799, 1967]	1967	1967	[0, 1379]	[0, 1383]
k = 4	[0, 1]	[0, 52]	0	0	0
k = 5	0	0	0	0	0
k = 1	0	0	3700	0	0
k = 2	0	0	0	0	0
j = 3 k = 3	0	0	0	0	0
k = 4	0	0	0	0	0
k = 5	0	0	0	0	0

3.3. Emergency Evacuation Routes

An emergency-related evacuation management system has been designed in response to the nuclear accidents. The detailed evacuating routes are shown in Figure 2, in which 5 assembly places (AP) and 3 temporary settlements (TS) are constructed, and the evacuating people are finally transported to four cities. In detail, five assembly places are provided for population assembling in the emergency-related evacuation management system, in which three of them are located 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, Cross between Nanbeihu Street and Huhang Road). For the evacuated people from the inner zone of the plume emergency planning zone, they are firstly temporarily settled in the schoolyards in three temporary settlements (TS). These three TS are Xitangqiao Street, Baibu Town, and Yuanhua Town located in the City of Haining. The detailed information for the three TS are presented in Table 2. Those temporarily settled people would be finally shipped to three cities (i.e. Haining, Jiaxing, Tongxiang and Pinghu)

3.4. Emergency Evacuation Model under Uncertainty

Nuclear accidents are frequently associated with releasing harmful radioactive materials, which would lead to significant consequences to people, the environment or the facility. Consequently, emergency evacuation is required to transfer local population to safe areas in response to the nuclear accedents. Typically, an emergency-related evacuation management system is designed to involve the following components: assembly places (ASs) for civilians assembling, temporary settlements (TSs) for the first aid, ultimate places to settle down (i.e., towns), as well as paths between the original location and evacuation destinations. The main purpose for such an evacuation system is to transferring all the population in the inner zone of the plume emergency planning zone to the ultimate settlements. Many process are should be done to construct such a system, including investigation of evacuees, gathering of civilians, employment of public transit, grouping of evacuees, allocation of transportation resources and services, coordination of roadway capacity, planning of evacuation routes, and so on (Lv et al., 2013). Particularly, extensive uncertainties exist in the system components and processes resulting from unforeseeable incidents and deviations in subjective judgments. For example, the evacuated people in the inner zone can hardly be quantified accurately due to the spatial-temporal variation of population in the local communities. Moreover, the vehicle flux and road capacity that are available for evacuation may not be estimated by deterministic values. Such uncertainties may be compounded due to the interactions among uncertain parameters as well as integration of various uncertainties. These uncertainties may pose impact on all the evacuation management processes from data investigation, model construction to results presentation. Consequently, one of the major challenge 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 well reflect uncertainties expressed as interval, fuzzy and fuzzy randomness. The IFCCP model for the emergency-related evacuation management system of Qinshan nuclear power plant can be expressed as:

$$Min\ f^{\pm} = \sum_{k=1}^{K} L_k CAT_{ijk}^{\pm} \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ijk}^{\pm} DAT_{ij} + \sum_{k=1}^{K} L_k \sum_{j=1}^{J} ICT_{jk} y_{jk}^{\pm} DTT_{j1} + \sum_{k=1}^{K} L_k \sum_{j=1}^{J}\sum_{t=1}^{T} CTT_{jtk} z_{jtk}^{\pm} DTT_{jt} \quad (16a)$$

subject to

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} L_k x_{ijk}^{\pm} \geq \tilde{TP}(\omega) \quad (16b)$$

(available evacuated population)

$$x_{ijk}^{\pm} \leq FAS_{i,j}^{\pm} \quad \forall i,j,k \quad (16c)$$

(evacuation capacity constraint)

$$y_{jk}^{\pm} / \alpha_Y^{\pm} \leq VFT_j^{\pm}, \forall k \quad (16d)$$

$$z_{jtk}^{\pm} / \alpha_Z^{\pm} \leq SVT_{jt}^{\pm}, \forall k \quad (16e)$$

(vehicle flux constraint)

$$y_{jk}^{\pm} \geq \gamma_k^{(\varphi)} \sum_{i=1}^{I} x_{ijk}^{\pm}, \forall k \quad (16f)$$

(patient transportation demand)

$$\sum_{k=1}^{K'}\sum_{i=1}^{I} x_{ijk}^{\pm} - \sum_{k=1}^{K'}\sum_{t=1}^{T} z_{jtk}^{\pm} - \sum_{k=1}^{K'}\sum_{t=1}^{T} y_{jk}^{\pm} \leq CS_j^{\pm}, K'=1,2,3 \quad (16g)$$

(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; $FAS_{i,j}^{\pm}$ 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); $z_{jtk}^{\pm}$ is the population flow from TS j to town t during period k (person/h); $\gamma_k^{(\varphi)}$ is the proportion of injured people at TS j under level φ during period k; $CS_j^{\pm}$ is the capacity of TS j (person); k is the planning time period.

The above emergency evacuation management model is constructed based on several assumptions proposed by Lv et al. (2013): (i) it is a route-schedule planning approach, assuming that a quicker evacuation process would be obtained when the evacuees follow the optimal escape routes, and only transport time is considered during evacuation process, ignoring other processes such as gathering at the origin, waiting for the vehicles, and settling down at the destination; (ii) the people who get injured in the accident are distributed evenly, so that the actual proportions of wounded people to the evacuees transported to TSs are equal or very close to the evaluated injured proportion, and those injured people would be finally 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.

3.5. Data Collection

The related data are provided in Tables 3 to 8. The data are collected based on the reports provided by local governments and the QNPS. The main purpose of the study in this chapter is to identify the desired evacuation plan under various

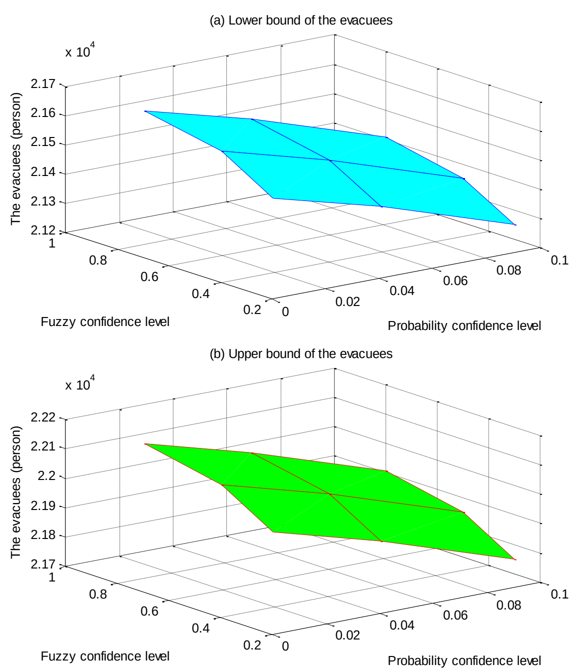


Figure 3. The lower and upper bound of evacuated people under different fuzzy and probability confidence levels.

Table 10. Evacuated Population from TS to Cities under Scenario 1

$Z(j, t, k)$		j = 1	j = 2	j = 3
t = 1	k = 1	0	[2567, 3425]	0
	k = 2	0	3425	0
	k = 3	0	[0, 3425]	0
	k = 4	0	[0, 57]	0
	k = 5	0	0	0
t = 2	k = 1	0	3199	0
	k = 2	0	3148	0
	k = 3	0	3185	0
	k = 4	0	0	0
	k = 5	0	0	0
t = 3	k = 1	0	0	0
	k = 2	[139, 351]	0	0
	k = 3	0	0	0
	k = 4	0	0	0
	k = 5	0	0	0
t = 4	k = 1	3333	0	0
	k = 2	3333	0	0
	k = 3	0	0	0
	k = 4	0	0	0
	k = 5	0	0	0

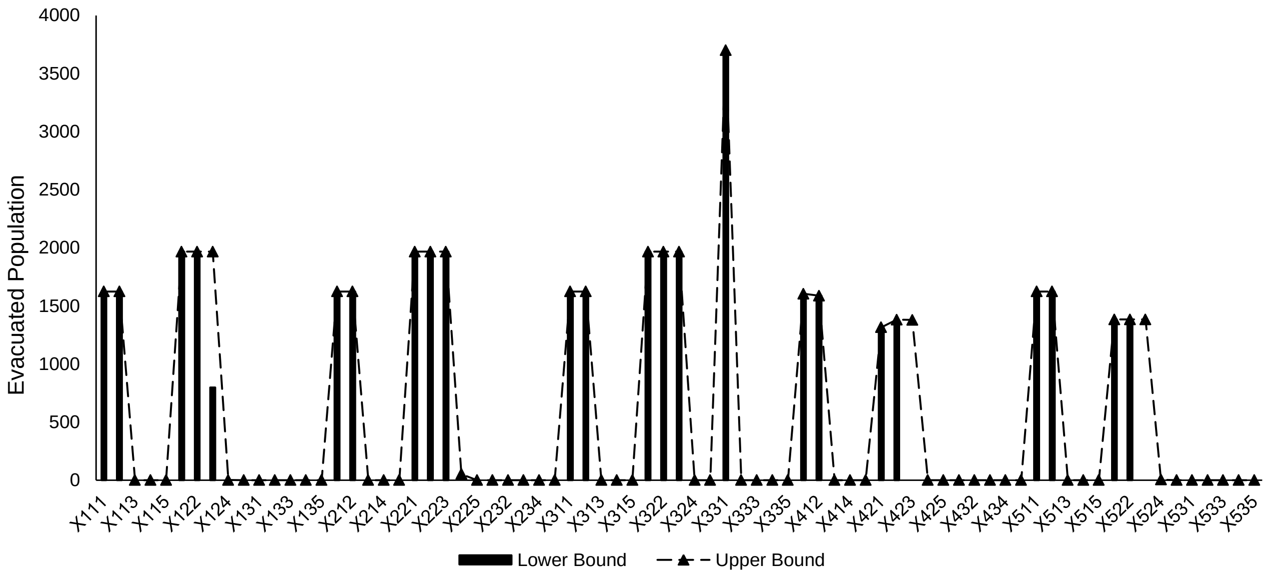


Figure 4. Population evacuation pattern under the fuzzy and probability confidence levels being 0.3 and 0.01, respectively.

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.

4. Results Analysis

Considering the fuzzy random feature the for evacuated people, three fuzzy confidence levels and three probabilistic confidence levels are considered, leading to total nine scenarios for the final evacuation model. In detail, the three fuzzy confidence levels are assumed to be 0.3, 0.5 and 0.8, while the probabilistic confidence levels are set to be 0.01, 0.05, 0.1. Figure 3 presents the evacuated people in the Qinshan Nuclear Power Site (QNPS) under different fuzzy and probability confidence levels. The results shows the residents needed to be evacuated in the Qinshan Nuclear Power Site would be varied 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 the variations in the evacuated people in the QNPS, the desired evacuate patterns may also be different. Among these nine scenarios, three of them would be analyzed, with the corresponding fuzzy and probability confidence levels being 0.3 and 0.01, 0.5 and 0.05, and 0.8 and 0.1. These three scenarios cover lower, medium and high confidence levels.

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

This scenario choose the lowest fuzzy and probability confidence intervals, with the lower and upper bound for the evacuated population being 20,934 and 22,934, respectively. Table 9 presents the evacuated population from Assembly Place to Temporary Settlement. The results indicate that for the people living in the inner zone of plume emergency planning zone can be safely evacuated in the first two hours. Most population would be transferred to Xitangqiao Street and Baibu Town, with Yuanhua Town receiving about 3,700 people from the Luotang Village Committee. In detail, for the Xitangqiao Street, it would receive deterministic population from the five Assembly Places in the first two periods, with 1,624 people from AP1, AP2, AP3, and AP5. For AP4, a slightly decrease happens during periods 1 and 2, with 1604 people being transported to Xitangqiao Street and 1587 in period 2. This may due to the capacity of the Temporal Settlement at Xitangqiao Street. For the Baibu Town, it would receive most evacuation population in the first two periods. Particularly, the Temporal Settlement at Baibu Town will contribute its capacity to receive the fluctuated people living near the QSNS. This means that, after deterministic population being transferred to the three Temporal Settlements, the remaining population, which may be varied 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, meaning that no people would be transferred to Baibu Town under advantageous conditions but 52 people are required to be transferred there under demanding conditions. Figure 4 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 presents the contributions of the five Assembly Places in the emergency evacuation system. The LVC (i.e. Luotang Village Committee) contributes most in evacuating the residents in the QSNS, with a proportion more than 30% of the total population under advantageous conditions. Moreover, more than 20% population would be evacuated from the QMS (i.e. Qinshan Middle School), with the detailed proportion being 21.85 and 20.03% under advantageous and demanding conditions. The results in Figure 5 indicate that the LVC and QMS are the two dominant assembly places for people assembling. The remaining population would go to CVC, ZVG and CNSHR. This would lead to decrease of

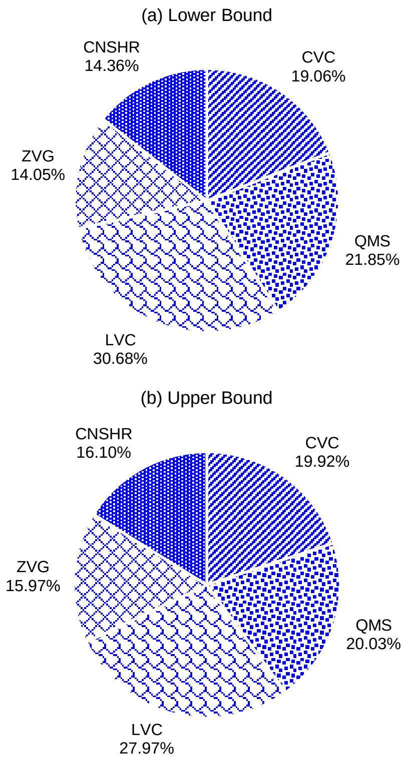


Figure 5. Proportion of the five Assembly Place to evacuate population under Scenario 1.

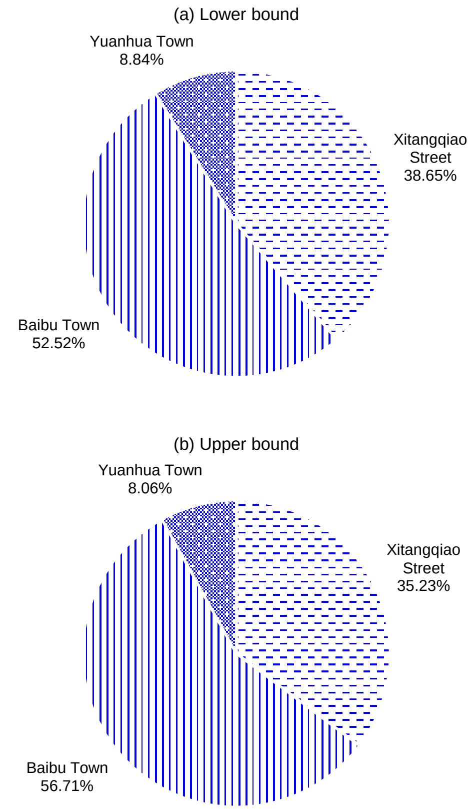


Figure 6. Proportion of the three TSs to receive evacuated population under Scenario 1.

the proportion for LVC and QMS and increase for CVC, ZVG and CNSHR between advantageous and demandingionditons.

For the three Temporal Settlements located in Xitagnqiao Street, Baibu Town and Yuanhua Town, they will receive the evacuees from the five Assembly Places. Figure 6 presents the proportions for the three Temporal Settlements in receiving evacuees in the evacuation system. The results show that the Baibu Town would contribute most in settling down the evacuees from QSNS. More than half population would be transferred to Baibu Town, with a proportion being 52.5% under advantageous conditions (i.e. lower bound of the residents in QSNS), and 56.7% under demanding conditions (corresponding to the upper bound of the residents in QSNS). 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 located in Xitangqiao Street also present a significant contribution in the designated evacuation system, with the proportion being 38.7 and 35.2% under advantageous and demanding conditions.

Due to the capacity limits for the three Temporal Settlements in Xitagnqiao Street, Baibu Town and Yuanhua Town, some population would be further shipped to some cities. In detail, Jiaxiang, Pinghu, Tongxiang and Haining are the potential selected cities to receive the evacuated population from QSNS. Table 10 presents the evacuation patterns from the three Temporal Settlements to the five cities. The results suggest that 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. This is because that only limited population would be evacuated to the TS in Yuanhua Town, which do not reach the maximum capacity of the TS in Yuanhua Town. Population in the Baibu Town would be mainly transferred to the cities of Jiaxing and Pinghu during the first three periods. Particularly, deterministic people will go to the city of Pinghu, with the detailed amounts being 3199, 3148 and 3,185 in period 1, 2 and 3, respectively. For population going to Jiaxing, the amount would be varied during the planning period, with more than 3,400 people under demanding conditions in the first three periods. But under advantageous conditions, which corresponds to the lower bound of evacuated population in QSNS, about 2,567 and 3,425 people will go to Jiaxing in periods 1 and 2, but no people is required to be transferred in period 3. This is due to that limited population will be shipped to the Baibu Town under advantageous conditions. Moreover, there are still some people (about 57) needed 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 highest level hospital is located there. Table 11 presents the number of injured people to be carried to Jiaxing City from the three TSs in the

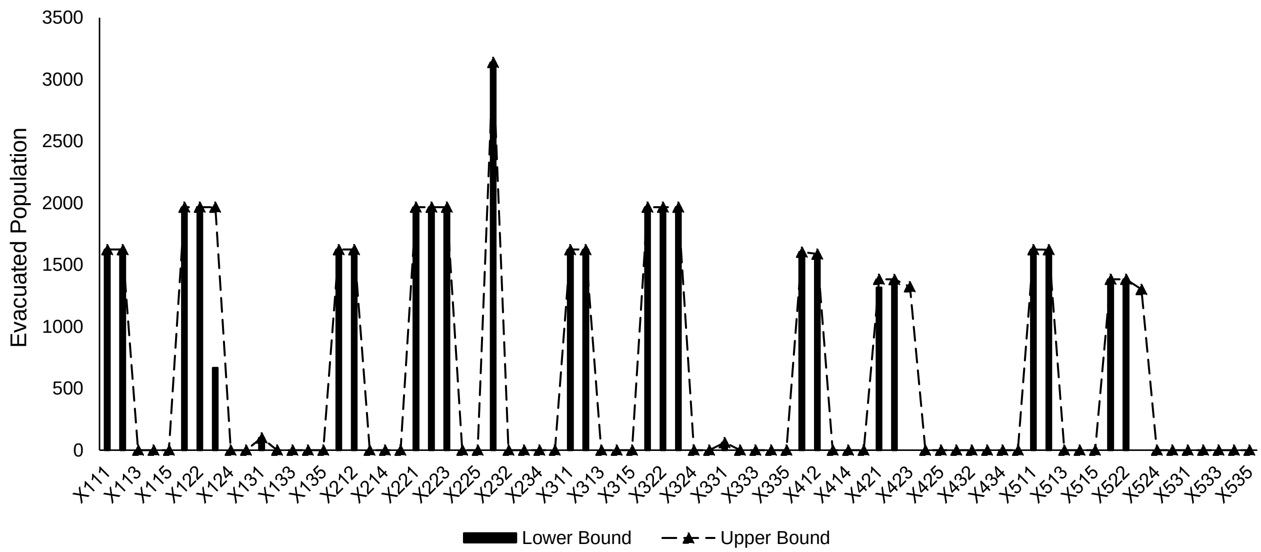


Figure 7. Population evacuation pattern under the fuzzy and probability confidence levels being 0.5 and 0.05, respectively.

five planning periods. These injured people are proportional to the total number of population in the three TSs. Therefore, the number of injured people to Jiaxing City is also varied, as a result of variation in the evacuated population to the three TSs.

Table 11. Injured Population Transferred to Jiaxing City

Y(*j*, *k*)	*j* = 1	*j* = 2	j = 3
k = 1	81	86	37
k = 2	97	104	0
k = 3	0	[71, 130]	0
k = 4	0	0	0
k = 5	0	0	0

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

This scenario chooses the medium fuzzy and probability confidence intervals, with the lower and upper bound for the evacuated population being 20,671 and 22,671, respectively. Table 12 presents the evacuated population from Assembly 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 people can safely be carried to the three TSs in Xitangqiao Street, Baibu Town and Yuanhua Town in the first three periods, in which TSs in Xitangqiao Street and Baibu Town are the major evacuation destinations. The TS in the Xitangqiao Street would receive deterministic population from those five Assembly Places, and the varied population mainly be transferred to the TS in Baibu Town. For the population carried to the TS in the Xitangqiao Street, the detailed amount is quite similar with the scheme in Scenario 1, with only slight differences happen 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 number of population evacuated through these routes is also similar with those under Scenario 1. But due to the lower people living in the QSNS, no people are required to be 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 contri- bute most of its capacity to the population from AP2 (i.e. Qin- shan Middle School), and also receive about 100 and 61 people from AP1 and AP3, respectively. Figure 7 presents the detailed evacuation scheme from the five APs to the three TSs. Compared with Figure , the highest evacuation population happens on the route from AP2 (i.e. Qinshan Middle School) 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 8 shows the proportions the three TSs to receive the evacuated populations. The results indicate that

Table 12. Evacuated Population from AS to TS under Scenario 2

X(*i*, *j*, *k*)		*i* = 1	*i* = 2	*i* = 3	*i* = 4	*i* = 5
j = 1	*k* = 1	1624	1624	1624	1604	1624
	k = 2	1624	1624	1624	1588	1623
	k = 3	0	0	0	0	0
	k = 4	0	0	0	0	0
	k = 5	0	0	0	0	0
j = 2	*k* = 1	1967	1967	1967	[1316, 1383]	1383
	k = 2	1967	1967	1967	[1375, 1382]	1383
	k = 3	[666, 1967]	1967	1967	[0, 1323]	[0, 1302]
	k = 4	0	0	0	0	0
	k = 5	0	0	0	0	0
j = 3	*k* = 1	100	3139	61	0	0
	k = 2	0	0	0	0	0
	k = 3	0	0	0	0	0
	k = 4	0	0	0	0	0
	k = 5	0	0	0	0	0

Table 13. Evacuated Population from TS to Cities under Scenario 2

$Z(j, t, k)$		$j = 1$	$j = 2$	$j = 3$
	$k = 1$	0	[2588, 3425]	0
	$k = 2$	0	[3347, 3425]	0
$t = 1$	$k = 3$	0	[0, 3425]	0
	$k = 4$	0	0	0
	$k = 5$	0	0	0
	$k = 1$	0	3080	0
	$k = 2$	0	3133	0
$t = 2$	$k = 3$	0	3252	0
	$k = 4$	0	0	0
	$k = 5$	0	0	0
	$k = 1$	0	0	0
	$k = 2$	[139, 351]	0	0
$t = 3$	$k = 3$	0	0	0
	$k = 4$	0	0	0
	$k = 5$	0	0	0
	$k = 1$	3333	0	0
	$k = 2$	3333	0	0
$t = 4$	$k = 3$	0	0	0
	$k = 4$	0	0	0
	$k = 5$	0	0	0

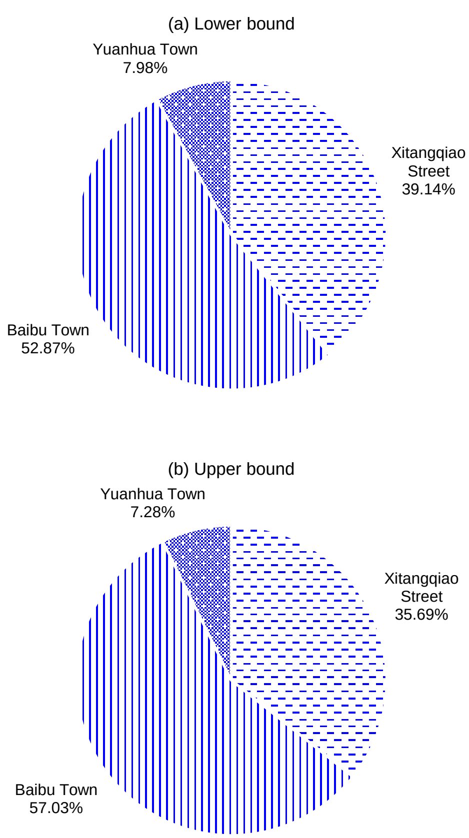


Figure 8. Proportion of the three TSs to receive evacuated population under Scenario 2.

the Baibu Town contributes most in this designated emergency evacuation plan, followed by the Xitangqiao Street and Yuanhua Town. In detail, the Baibu To- wn would receive more than half of the total evacuees in this scenario, with 53% under advantageous conditions and 57 under demanding conditions. Furthermore, the limitation of the three TSs in Xitangqiao Street, Baibu Town and Yuanhua Town require the evacuees to be further carried to the nearby cities. Table 13 presents the evacuation patterns from the three Temporal Settlements to the four cities. As presented in Figure 8, the TS in Baibu Town contributes most in receiving evacuees from the QSNS. The people in Baibu Town are required to be further shipped to the selected four cities. As presented in Table 13, population in Baibu Town would mainly be further evacuated to Jiaxiang and Pinghu in the first three periods. In detail, deterministic 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 be varied, with 2,588, 3,347 and 0 under advantageous conditions but 3,425 under demanding conditions, in the first three periods. Particularly, there would no need to transport people from Baibu Town to Jiaxing under advantageous conditions, since all people would have safely been evacuated in the first three periods and no people would be shipped to Baibu Town in the last two periods. Moreover, there are more than 6000 people being shipped from Xitangqiao Street to Haiyan in the first two periods, with 3333 people in each period. Also, there would be some injured people being transferred from three Temporal Settlements to Jiaxiang City, as present in Table 14.

Table 14. Injured Population Transferred to Jiaxing City under Scenario 2

$Y(j, k)$	$j = 1$	$j = 2$	$j = 3$
$k = 1$	81	[86, 87]	33
$k = 2$	97	104	0
$k = 3$	0	[69, 128]	0
$k = 4$	0	0	0
$k = 5$	0	0	0

4.3. Scenario 3: $\beta = 0.8$, $\alpha = 0.1$

Under this scenario, the fuzzy and probabilistic confidence levels being 0.8 and 0.1, respectively, leading to the potential evacuated people fluctuating within [20,143, 22,143]. The evacuation schemes from Assembly Places to Temporal Settlements are presented in Table 15. The results show similar evacuation patterns with those under Scenarios 1 and 2. Most people will be safely evacuated from QSNS in the first three periods, with about 57 people required to be transferred in the fourth period under demanding conditions. Figure 9 presents the detailed population flow patterns under this scenario. It shows similar features with Figure 4 and Figure 7. In detail, the QMS, namely Qinshan Middle School, would evacuate population in this emergency evacuation system, with about 27.9% of the total evacuees would be transferred to the Temporal Settlements from QMS under advantageous conditions and about 25.4% under demanding conditions. The LVC (i.e.

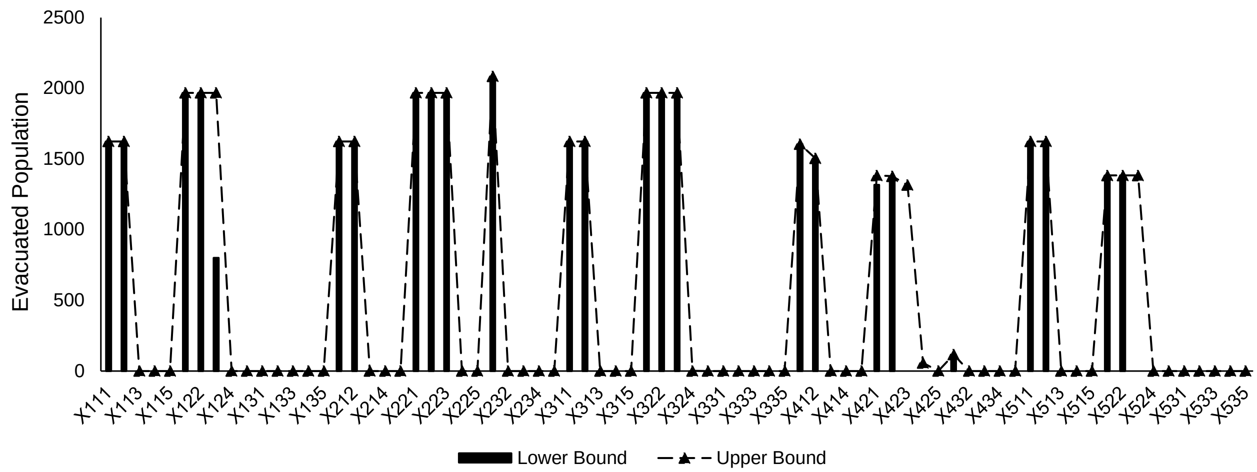


Figure 9. Population evacuation pattern under the fuzzy and probability confidence levels being 0.8 and 0.1, respectively.

Luotang Village Committee) would evacuate about 22.7 and 20.66% of the total population in QSNS under advantageous and demanding conditions. The slightly decrease in the proportion for QMS and LVC between advantageous and demanding conditions is because the routes from these to Assembly Places have reached their maximum capacity under both demanding and advantageous conditions. When more population are required to be evacuated under demanding conditions, those flexible population would be transferred from the other three Assembly Places since QMS and LVC cannot receive more population. This leads to increase in the proportion for AVG, CNS-HR, and CVC between advantageous and demanding conditions, as presented in Figure 10.

Table 15. Evacuated Population from AS to TS under Scenario 3

$X(i, j, k)$		i = 1	i = 2	i = 3	i = 4	i = 5
j = 1	k = 1	1624	1624	1624	1604	1624
	k = 2	1624	1624	1624	1504	1624
	k = 3	0	0	0	0	0
	k = 4	0	0	0	0	0
	k = 5	0	0	0	0	0
j = 2	k = 1	1967	1967	1967	[1316, 1383]	1383
	k = 2	1967	1967	1967	[1369, 1378]	1383
	k = 3	[799, 1967]	1967	1967	[0, 1315]	[0, 1383]
	k = 4	0	0	0	[0, 57]	0
	k = 5	0	0	0	0	0
j = 3	k = 1	0	2084	0	116	0
	k = 2	0	0	0	0	0
	k = 3	0	0	0	0	0
	k = 4	0	0	0	0	0
	k = 5	0	0	0	0	0

For the three Temporal Settlements located in Xitangqiao Street, Baibu Town and Yuanhua Town, Baibu Town would contribute most in the emergency evacuation scheme under this scenario, which is similar to those under Scenarios 1 and 2. Moreover, compared with the results under Scenarios 1 and 2, the Baibu Town contributes a more important role for receiving the evacuees under Scenario 3. As presented in Figure 11, 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 settle down about 58.7% of the total evacuation population under the demanding conditions in this scenario, compared to 56.7 and 57.0% for the first two scenarios. This results indicate that, when an accident happens in QSNS, the residents living then the plume emergency planning zone would be firstly 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. So, this wou-

Table 16. Evacuated Population from TS to Cities under Scenario 3

$Z(j, t, k)$		j = 1	j = 2	j = 3
t = 1	k = 1	0	[2567, 3425]	0
	k = 2	0	3425	0
	k = 3	0	[0, 3425]	0
	k = 4	0	[0, 57]	0
	k = 5	0	0	0
t = 2	k = 1	0	3185	0
	k = 2	0	3194	0
	k = 3	0	3154	0
	k = 4	0	0	0
	k = 5	0	0	0
t = 3	k = 1	0	0	0
	k = 2	[57, 269]	0	0
	k = 3	0	0	0
	k = 4	0	0	0
	k = 5	0	0	0
t = 4	k = 1	3333	0	0
	k = 2	3333	0	0
	k = 3	0	0	0
	k = 4	0	0	0
	k = 5	0	0	0

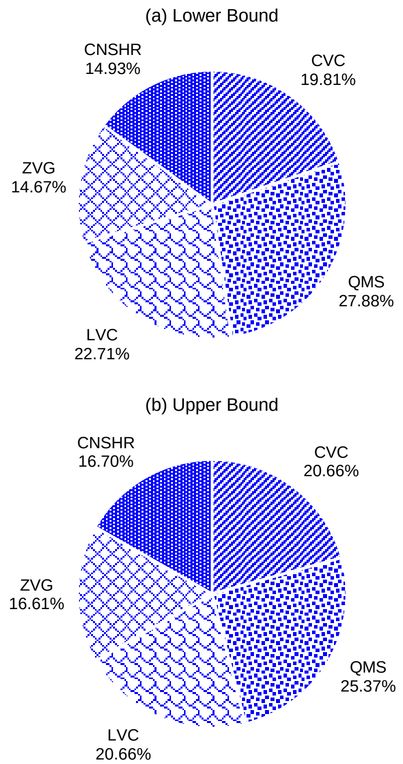


Figure 10. Proportion of the five Assembly Place to evacuate population under Scenario 3.

ld lead to the Baibu Town contribute more for less evacuees.

Due to the capacity limitations for the three Temporal Settlement in the Xitangqiao Street, Baibu Town and Yuanhua Town, some evacuees would be further transferred to the adjacent cities. Moreover, the injured people would be shipped to the Jiaxing City for recovery. Table 16 shows the evacuation schemes from the temporal settlements to cities. There are a large number of population 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 would mainly be further transported to the city of Haiyan due to the short distance between these two places. Also, some evacuees needed to be shipped to the city of Tongxiang in the second period, with 57 under advantageous conditions and 269 under demanding conditions. Moreover, Table 17 presents the injured population being evacuated to the Jiaxing City for health recovery. These injured population are estimated based on the total population evacuated to the three Temporal Settlements located in Xitangqiao Street, Baibu Town and Yuanhua Town, respectively.

5.4.4. Estimated Costs

Due to the uncertainties in the model parameters, as well as the fuzzy random feature for the residents in the plume emergency zone of QSNS, the total number of evacuees may be varied under different fuzzy and probability confidence levels, as shown in Figure 3. The variation of the evacuees would change the evacuation schemes and thus lead to fluctuation in

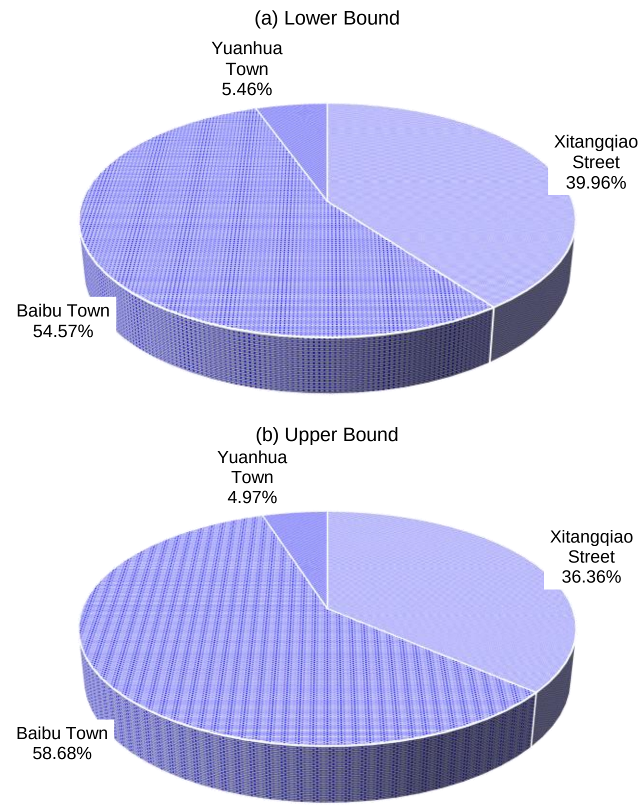


Figure 11. Proportion of the three Temporal Settlements to receive evacuees under Scenario 3.

Table 17. Injured Population Transferred to Jiaxing City under Scenario 3

$Y(j, k)$	$j = 1$	$j = 2$	j = 3
$k = 1$	81	[86, 87]	22
$k = 2$	96	104	0
$k = 3$	0	[71, 129]	0
$k = 4$	0	0	0
$k = 5$	0	0	0

the final costs of the system. Figure 18 shows the total costs for the evacuation under the selected combinations of fuzzy and probability confidence levels. The results show that, for the predefined probability confidence levels, the system cost would decrease as the increase of the fuzzy confidence level; conversely, the system cost would increase as the increase of the probability confidence level under the same predefined fuzzy con- fidence level. However, as presented in Figure 12, the changing trend for the lower bound of system cost is more likely li- near but the changing trend for the upper bound of system cost is more likely nonlinear. This is because that the lower bound of 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, and thus lead to the system cost being proportional to the evacuees. In comparison, under demanding conditions, which corresponds to the upper bound of the evacuees, the designated evacuation schemes under one scenario may not be applicable to another one. More routes would be required, as illustrated by the three scenarios in this study. This would lead to nonlinearity between the system cost and the fuzzy and probability confidence levels.

Table 18. The System Cost under Different Combinations of Fuzzy and Probability Confidence Levels $\$(\times 10^7)$

	Fuzzy level		
Probability level	0.3	0.5	0.8
0.01	[1.370, 1.544]	[1.355, 1.511]	[1.333, 1.462]
0.05	[1.372, 1.555]	[1.357, 1.522]	[1.335, 1.473]
0.1	[1.376, 1.562]	[1.361, 1.529]	[1.339, 1.479]

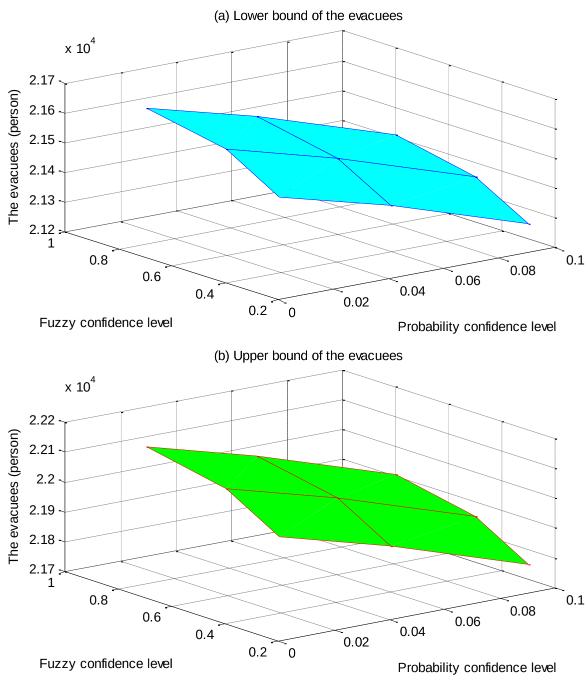


Figure 12. The system cost under different fuzzy and probability confidence levels.

5. Conclusions

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 mergency 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.

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