Hybrid Fuzzy System Dynamics Model for Analyzing the Impacts of Interrelated Risk and Opportunity Events on Project Contingency

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Abstract

Traditional risk analysis techniques are ineffective for capturing the dynamic causal interactions and subjective uncertainties involved in assessing risk and opportunity events. In this paper, a hybrid fuzzy system dynamics (FSD) model is developed to analyze the impacts of interrelated and interacting risk and opportunity events on work package cost and determine work package and project contingencies. Linguistic scales, represented by fuzzy numbers, allow experts to use natural language to assess the probability and impact of risk and opportunity events and the causal relationships between them. The α-cut method and the extension principle based on the drastic *t*-norm are implemented in the FSD model to carry out fuzzy arithmetic operations. The main contributions of this paper are fourfold. First, it provides a systematic risk assessment and prioritization procedure. Second, it provides a hybrid FSD modeling and analysis approach to determining cost contingencies using expert judgment, linguistic scales, and fuzzy numbers. Third, it provides a structured and systematic method for defining the causal relationships among risk and opportunity events and constructing causal loop diagrams in the FSD model. Fourth, it provides a basis for the representation of fuzzy variables in FSD and examines the impact of different fuzzy arithmetic and defuzzification methods in the FSD model.

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Introduction

Contingency estimation, allocation, and management are vital for mitigating the risks associated with construction projects in order to deliver successful outcomes (Salah and Moselhi 2015). However, most traditional quantitative risk analysis techniques and contingency determination methods fail to capture the complex interrelationships and causal interactions that exist among risk and opportunity events and do not account for the dynamic nature of construction risks that results from various feedback processes (Wang and Yuan 2017; Boateng et al. 2012). In many studies, risk and opportunity events in a construction system are assessed and analyzed as if they are independent, when in fact they affect each other. Independent risks rarely exist in reality, and a risk that is triggered by other risks may cause subsequent risks on a construction project (Wang and Yuan 2017; Zhang 2016). The cumulative impact of interrelated and interacting risks is different than the sum of the individual impacts of independent risks (Nasirzadeh et al. 2008). Moreover, traditional risk modeling and analysis approaches tend to focus on a static view of risks rather than considering their time-related behavior. To determine realistic contingency, it is essential that the interrelationships and interactions among risks and the dynamic nature of risks be considered during modeling and analysis.

The system dynamics (SD) approach, which is primarily based on cause-effect relationships, is a viable option for modeling and analyzing construction risks that addresses the aforementioned limitations of traditional risk analysis techniques (Wang and Yuan 2017; Boateng et al. 2012; Nasirzadeh et al. 2008). The types of uncertainties involved in risk modeling and analysis fall under two general categories: probabilistic uncertainties (i.e., randomness) and non-probabilistic uncertainties (i.e., subjective uncertainties). Conventional SD models only capture probabilistic uncertainties. However, probabilistic uncertainties are represented by probability distribution functions developed based on historical data, which are often not available in construction. In cases where historical data are not available in sufficient quantity and quality, analysis relies on linguistically expressed expert knowledge, which is usually uncertain and imprecise. The subjective uncertainties resulting from linguistic approximation and measurement imprecision in risk assessment are best addressed with fuzzy logic. Therefore, a hybrid fuzzy system dynamics (FSD) model that combines the individual strengths of SD and fuzzy logic for analyzing the severity of risk and opportunity events and determining work package and project contingencies has been developed.

The rest of this paper is organized as follows. In the second section, the necessary background to the FSD concepts applied in this paper are discussed. In the third section, the research methodology adopted in this paper is illustrated and the modeling steps are explained. In the fifth section, a case study is presented that illustrates the development of the FSD model for risk analysis and the validation of the model. Conclusions and future work are discussed in the final section.

Background and Literature Review

SD is a feedback-based and object-oriented modeling approach that was pioneered by Jay Forester in the 1950s for modeling and analyzing the dynamic behavior of complex social systems in the industrial domain (Sterman 2000). SD uses modeling elements such as causal loop diagrams (CLDs), delays, flows (i.e., rates), and stocks to determine the dynamic behavior of complex systems over time (Sterman 2000). According to Sterman (1992), construction projects meet the characteristics of complex dynamic systems as they are extremely complex and highly dynamic;

they involve interdependent components, multiple feedback processes, and nonlinear relationships; and they require both qualitative and quantitative data. Since SD is capable of handling such characteristics, it is an appropriate technique for modeling construction management processes in general and risk and contingency in particular (Nasirzadeh et al. 2008). In the past two decades, SD has been successfully applied to model and analyze a wide variety of construction-project-related problems, such as resource management, project performance, planning and control, productivity, rework and change, and others (Raoufi et al. 2018).

The use of SD for risk analysis and contingency determination is not new. Most recently, Wang and Yuan (2017) adopted an SD approach to quantitatively examine the impact of dynamic risk interactions on schedule delays on infrastructure projects. Wan and Liu (2014) developed a qualitative SD model for risk analysis during the construction stage. Boateng et al. (2012) employed SD to simulate the interaction between social and environmental risks during the development and construction of a megaproject. Nasirzadeh et al. (2007) utilized SD models to analyze the impact of different response strategies for identified risks on project cost, quality, and schedule. Ford (2002) adopted an SD model to test the effectiveness of aggressive and passive contingency management strategies on cost, timeliness, and the facility value of a real estate development project. Traditional SD models do not effectively account for non-probabilistic (i.e., subjective) uncertainties associated with system variables, the imprecise nature of factors that influence the variables, and vague interdependencies between variables (Nasirzadeh et al. 2008). It is common practice in traditional SD modeling to use numerical values or probability distribution functions to define system variables and to use mathematical or table functions to define the causal relationships between variables (Sterman 2000). However, a construction system involves subjective variables that do not have numerical metrics and that are qualitative in nature and better expressed linguistically. In addition, system variables that have quantitative metrics may not always be expressed by a precise (i.e., crisp) value due to the ambiguity involved in specifying an exact value for variables. The development of probability distribution functions for defining system variables requires a large set of historical data, which is not usually available. Moreover, it is not always possible to express the causal relationships among system variables using analytical functions or statistical methods due to a lack of sufficient historical data. These limitations of traditional SD modeling led to a need for integrating fuzzy logic and SD.

Even though promising endeavors have been made to integrate fuzzy logic and SD in various fields, the application of FSD in construction has been limited, and there is very little literature on the application of FSD to risk modeling and analysis. Nasirzadeh et al. (2008) adopted a fuzzy-based SD approach to integrated risk management processes on construction projects. Using a similar approach, Nasirzadeh et al. (2014) developed an FSD model for determining the optimum percentage of risk allocation between owners and contractors on construction projects. In both approaches, very few fuzzy variables were considered in the FSD models. The impacts of risks on project objectives were assessed at a project level and opportunities were not considered in the assessment procedure. A fuzzy Delphi method, which requires several rounds of revisions to reach to an acceptable level of agreement, were used in both approaches for aggregating expert inputs, but they did not take into account the expertise levels of the experts. Moreover, only the α-cut fuzzy arithmetic method and center of area (COA) defuzzification method were employed.

FSD Modeling Methodology

In this section, the overall methodology and detailed steps for developing the hybrid FSD model are presented. The methodology is illustrated in Fig. 1 and described below.

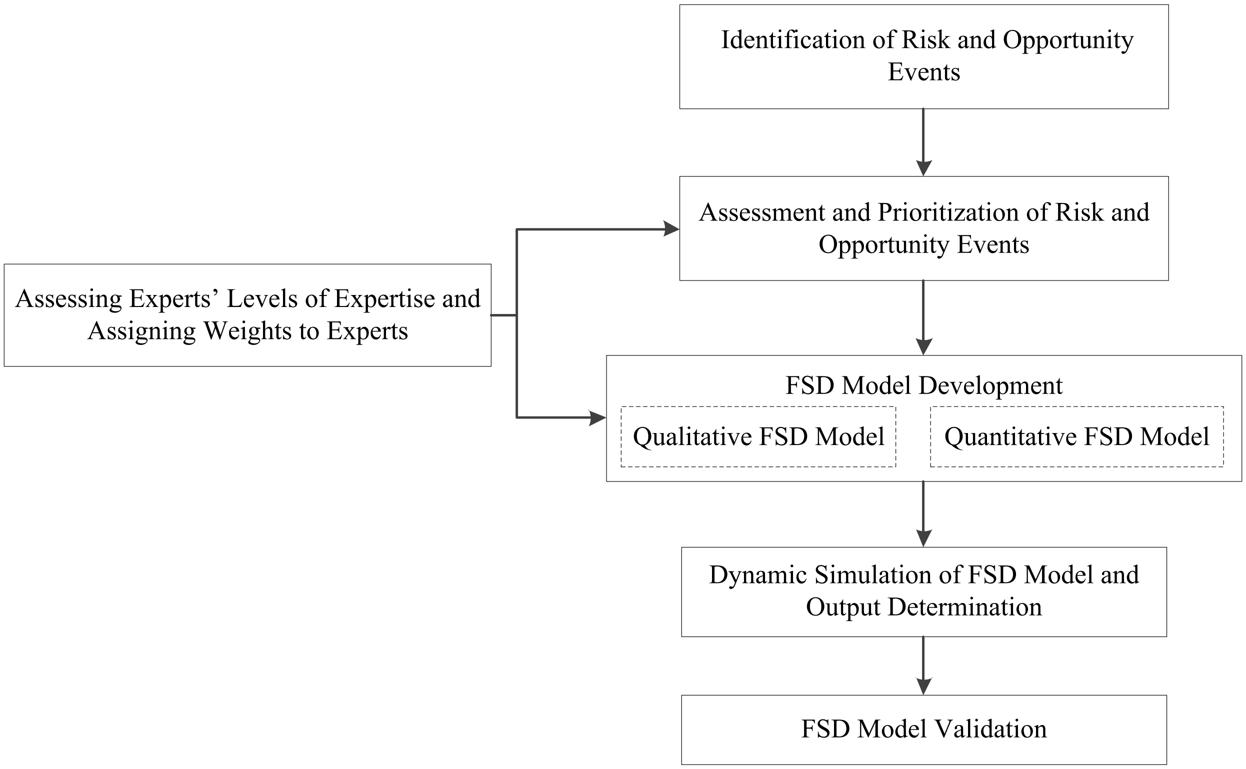


Fig. 1. Steps for developing the FSD model for risk analysis and contingency determination.

Identification of Risk and Opportunity Events

A systematic literature review and detailed content analysis of 130 articles selected from 14 well-regarded academic journals in construction engineering and management published between 1990 and 2017 was conducted to identify common risk and opportunity events in construction (Siraj and Fayek 2019). The identified risk and opportunity events were grouped into 11 categories: management, technical, construction, resource-related, site conditions, contractual and legal, economic and financial, social, political, environmental, and health and safety. The identified risk and opportunity events and the risk categorization method were refined and verified by expert knowledge.

Assessing Experts' Levels of Expertise and Assigning Importance Weights to Experts

In this paper, the importance weights of the experts were considered when combining experts' assessments of the probability and impact of risk and opportunity events, the percentage of work package cost affected by risk and opportunity events, and the degrees of the causal relationships among risk and opportunity events. To determine the importance weights of the experts, their levels of expertise in risk management were assessed based on seven criteria: experience, knowledge, professional performance, risk management practice, project specifics, reputation, and personal attributes and skills, as proposed by Monzer et al. (2019). Each criterion comprises sub-criteria (i.e., qualification attributes) that are quantitative or qualitative. A predetermined rating scale (1–5) was established for assessing each of the qualitative qualification attributes. Then, the importance weights of the experts (W_k) were determined using the fuzzy analytic hierarchy process (FAHP) weight-assigning method developed by Monzer et al (2019).

Assessment and Prioritization of Risk and Opportunity Events

In this paper, a fuzzy-based risk assessment and prioritization procedure was employed that assesses the probability and impact of risk and opportunity events at the work package level, takes into account the percentage of work package affected, and considers the experts' expertise levels. An interview survey was designed based on the refined list of risk and opportunity events. The survey was divided into two major sections: the first section includes general information to assess project and work package characteristics, and the second section deals with the assessment of potential risk and opportunity events affecting work packages. The probability of occurrence of risk and opportunity events and their respective impacts on work package cost were assessed by experts using five linguistic terms represented by triangular or trapezoidal fuzzy numbers. The percentage of work package cost affected by each risk and opportunity event was also determined by the experts.

The experts' assessments of each risk and opportunity event for a given work package were aggregated using Eq. (1) and Eq. (2) to obtain the collective assessment of the experts.

$$\tilde{P}_{R_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{P}_{R_{ib}}^{(k)}\,;\ \tilde{I}_{R_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{I}_{R_{ib}}^{(k)}\,;\ \tilde{P}_{O_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{P}_{O_{ib}}^{(k)}\ ;\ \tilde{I}_{O_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{I}_{O_{ib}}^{(k)} \qquad (1)$$

$$C_{ib} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k C_{ib}^{(k)} \qquad (2)$$

where $\tilde{P}_{R_{ib}}$, $\tilde{I}_{R_{ib}}$, $\tilde{P}_{O_{ib}}$, and $\tilde{I}_{O_{ib}}$ $(i = 1, 2, \dots, n; b = 1,2, \dots, g)$ are aggregated fuzzy numbers describing, respectively, the risk probability, risk impact, opportunity probability, and opportunity impact of the ith risk and opportunity event on the bth work package; W_k $(k = 1, 2, \dots, v \ and\ \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k = 1\ )$ is the importance weight of the kth expert; $\tilde{P}_{R_{ib}}^{(k)}$, $\tilde{I}_{R_{ib}}^{(k)}$, $\tilde{P}_{O_{ib}}^{(k)}$, and $\tilde{I}_{O_{ib}}^{(k)}$ are fuzzy numbers describing, respectively, the risk probability, risk impact, opportunity probability, and opportunity impact of the ith risk and opportunity event on the bth work package assessed by the kth expert; C_{ib} is the aggregated percentage of the bth work package cost affected by the ith risk and opportunity event; $C_{ib}^{(k)}$ is the percentage of the bth work package cost affected by the ith risk and opportunity event assessed by the kth expert; and ⊗ is fuzzy multiplication, and the summation in Eq. (1) is carried out using fuzzy addition.

The net severity percentage of the ith risk and opportunity event on the bth work package ($\widetilde{NS}_{ib}$) were determined as follows:

$$\widetilde{NS}_{ib} = C_{ib} \otimes \left[\tilde{S}_{R_{ib}} \ominus \tilde{S}_{O_{ib}}\right] = C_{ib} \otimes [(\tilde{P}_{R_{ib}} \otimes \tilde{I}_{R_{ib}}) \ominus (\tilde{P}_{O_{ib}} \otimes \tilde{I}_{O_{ib}})] \qquad (3)$$

where $\tilde{S}_{R_{ib}}$ is the risk severity of the ith risk and opportunity event on the bth work package; $\tilde{S}_{O_{ib}}$ is the opportunity severity of the ith risk and opportunity event on the bth work package; and ⊗

and $\ominus$ are fuzzy multiplication and fuzzy subtraction, respectively. The net severity percentage of risk and opportunity events on a work package ($\widetilde{NS}_{ib}$) was defuzzified using the COA method. Then, the risk and opportunity events were ranked and prioritized at the work package level based on their defuzzified net severity percentage (NS_{ib}^{Def}). Finally, the most severe risk and opportunity events that need to be considered in the FSD model were determined.

Constructing the Qualitative FSD Model

CLDs are employed in SD and FSD models to map interdependencies and causal structures among model variables. A structured and systematic method based on fuzzy decision making trial and evaluation laboratory (DEMATEL) is proposed in this paper to define the causal relationships among risk and opportunity events and to develop the corresponding CLDs. DEMATEL, which is based on graph and matrix theory, is a systematic and efficient method of structuring and analyzing complex cause and effect relationships among the elements of a system (Jalal and Shoar 2017). In classical DEMATEL, the causal interactions between the elements of a system are evaluated using crisp values. However, experts naturally tend to give assessments based on their experience and knowledge, and their assessments are often expressed linguistically. Therefore, DEMATEL was extended to suit fuzzy environments. The steps for determining the causal interactions among risk and opportunity events based on fuzzy DEMATEL are adopted from Seker and Zavadskas (2017) and Can and Toktas (2018) and are described as follows.

Step 1: Design the survey form to assess the causal relationships among risk and opportunity events. The prioritized risk and opportunity events of the work packages are combined to form the final list of risk and opportunity events for which the causal relationships will be investigated. Then, a fuzzy DEMATEL survey form comprising a pairwise comparison matrix is created. The experts assess the degree of causal influence of risk and opportunity event i (row) on risk and opportunity event j

(column) using five linguistic terms that are represented by triangular fuzzy numbers (Table 1). The experts also define the types of causal relationships between risk and opportunity events as positive, negative, or N/A-not applicable.

Table 1. Linguistic terms and fuzzy numbers for assessing the degree of causal influence.

Linguistic term	Triangular fuzzy number
Very low influence (VL)	(0.00 0.00 0.25)
Low influence (L)	(0.00 0.25 0.50)
Medium influence (M)	(0.25 0.50 0.75)
High influence (H)	(0.50 0.75 1.00)
Very high influence (VH)	(0.75 1.00 1.00)

Step 2: Obtain the initial fuzzy matrices ($\tilde{X}^{(k)}$) from experts' assessments.

The pairwise assessment carried out by each expert based on the linguistic terms is converted to nxn initial fuzzy matrix ($\tilde{X}^{(k)}$) for each work package, which is expressed as

$$\tilde{X}^{(k)} = \left[\tilde{x}_{ij}^{(k)}\right]_{nxn} = \begin{bmatrix} 0 & \tilde{x}_{12}^{(k)} & \cdots & \tilde{x}_{1n}^{(k)} \\ \tilde{x}_{21}^{(k)} & 0 & \cdots & \tilde{x}_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1}^{(k)} & \tilde{x}_{n2}^{(k)} & \cdots & 0 \end{bmatrix} \qquad (4)$$

where $\tilde{x}_{ij}^{(k)}$ $(i, j = 1, 2, \dots, n; k = 1, 2, \dots, v)$, defined by a triplet $(l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)})$, denotes the degree of causal influence of the ith risk and opportunity event on the jth risk and opportunity event as assessed by the kth expert, and when $i = j$, all principal diagonal elements are set to zero.

Step 3: Generate a fuzzy direct-relation matrix ($\tilde{X}^{C}$).

The initial fuzzy matrices $\tilde{X}^{(1)}, \tilde{X}^{(2)}, \dots, \tilde{X}^{(v)}$ of v experts are aggregated using Eq. (5), and as a result, the fuzzy direct-relation matrix ($\tilde{X}^{C}$), represented by Eq. (6), is generated.

$$\tilde{x}_{ij}^{C} = \sum_{k=1}^{v} W_k \otimes \tilde{x}_{ij}^{(k)} = \sum_{k=1}^{v} W_k \otimes \left(l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)}\right) \qquad (5)$$

$$\tilde{X}^C = \left[\tilde{x}_{ij}^C\right]_{nxn} = \begin{bmatrix} 0 & \tilde{x}_{12}^C & \cdots & \tilde{x}_{1n}^C \\ \tilde{x}_{21}^C & 0 & \cdots & \tilde{x}_{2n}^C \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1}^C & \tilde{x}_{n2}^C & \cdots & 0 \end{bmatrix} \qquad (6)$$

where $\tilde{x}_{ij}^C$ $(i, j = 1, 2, \dots, n)$, defined by a triplet $(\bar{l}_{ij}, \bar{m}_{ij}, \bar{u}_{ij})$, denotes the aggregated degree of causal influence of the *i*th risk and opportunity event on the *j*th risk and opportunity event and W_k ($k = 1, 2, \dots, v$ and $\sum_{\mathrm{k}=1}^{\mathrm{v}} W_k = 1$) is the importance weight of the kth expert.

Step 4: Construct the normalized fuzzy direct-relation matrix ($\tilde{Z}$).

The normalized fuzzy direct-relation matrix ($\tilde{Z}$) is constructed using Eqs. (7)–(8), and it is defined in Eq. (9).

$$\tilde{Z} = \frac{\tilde{X}^C}{\lambda} = \frac{\tilde{x}_{ij}^C}{\lambda} = \left(\frac{\bar{l}_{ij}}{\lambda}, \frac{\bar{m}_{ij}}{\lambda}, \frac{\bar{u}_{ij}}{\lambda}\right) \qquad (7)$$

$$\lambda = \max_{1 \le i \le n} \sum_{j=1}^{n} \bar{u}_{ij} \qquad (8)$$

$$\tilde{Z} = \left[\tilde{z}_{ij}\right]_{nxn} = \begin{bmatrix} 0 & \tilde{z}_{12} & \cdots & \tilde{z}_{1n} \\ \tilde{z}_{21} & 0 & \cdots & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \cdots & 0 \end{bmatrix} \qquad (9)$$

where $\tilde{z}_{ij}$ $(i, j = 1, 2, \dots, n)$, defined by a triplet $\left(l'_{ij}, m'_{ij}, u'_{ij}\right)$, denotes the normalized degree of causal influence of the *i*th risk and opportunity event on the *j*th risk and opportunity event.

Step 5: Construct the fuzzy total-relation matrix ($\tilde{T}$).

According to the classical DEMATEL method, the crisp total-relation matrix (T) can be generated by raising the crisp normalized direct-relation matrix (Z) to an infinite power, which guarantees the continuous decline of indirect influence of factor *i* on factor *j* and the convergence of the crisp total-relation matrix (T) to the inverse matrix shown in Eq. (10), where I is the identity matrix.

$$T = \lim_{m \to \infty} (Z + Z^2 + \cdots + Z^m) = \sum_{m=1}^{\infty} Z^m = Z(I - Z)^{-1} \qquad (10)$$

In order to adapt the classical DEMATEL method and construct the fuzzy total-relation matrix ($\tilde{T}$), three crisp direct-relation matrices, Z_l, Z_m, and Z_u, are first extracted from the normalized fuzzy direct-relation matrix ($\tilde{Z}$) based on the triplets $(l'_{ij}, m'_{ij}, u'_{ij})$ of the triangular fuzzy numbers. Then, the crisp total-relation matrices, T_l, T_m, and T_u, are determined based on the corresponding crisp direct-relation matrices, Z_l, Z_m, and Z_u, using Eq, (10). Finally, the fuzzy total-relation matrix ($\tilde{T}$) defined by Eq. (11) is constructed using elements of the crisp total-relation matrices T_l, T_m, and T_u as the triplets $\left(l''_{ij}, m''_{ij}, u''_{ij}\right)$ of the corresponding triangular fuzzy number in the fuzzy total-relation matrix ($\tilde{T}$).

$$\tilde{T} = \left[\tilde{t}_{ij}\right]_{nxn} = \begin{bmatrix} 0 & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & 0 & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & 0 \end{bmatrix} \qquad (11)$$

where $\tilde{t}_{ij}$ $(i, j = 1, 2, \dots, n)$, defined by a triplet $\left(l''_{ij}, m''_{ij}, u''_{ij}\right)$, represents the total degree of causal influence of the *i*th risk and opportunity event on the *j*th risk and opportunity event and I is the identity matrix.

Step 6: Construct the CLDs.

First, the fuzzy total-relation matrix ($\tilde{T}$) is defuzzified using the COA method to acquire the corresponding defuzzified total-relation matrix (T^{Def}). Second, a threshold value is set for the defuzzified total-relation matrix (T^{Def}) to filter out negligible causal relations among risk and opportunity events and to keep the complexity of the CLDs to a manageable level. Third, CLDs of the work packages are constructed based on the defuzzified total-relation matrix (T^{Def}). Then, the flows and stocks used in the FSD model are identified. Finally, the qualitative FSD model of the project is created using simulation software (i.e., AnyLogic® 8.2.3).

Constructing the Quantitative FSD Model

The mathematical procedure used in the FSD model to determine the work package and project contingency by analyzing the impact of interrelated risk and opportunity events are described as follows.

Step 1: Identify the FSD model parameters and variables as objective and subjective (i.e., fuzzy) variables.

First, the parameters and variables involved in the FSD model are identified as objective and subjective (i.e., fuzzy) variables based on the adopted scales of measure. Objective variables have quantitative metrics and are readily quantifiable. They are defined by crisp numbers or probability distributions to capture randomness (i.e., probabilistic uncertainties). In the FSD model, objective variables are quantified using crisp numbers. Subjective (i.e., fuzzy) variables are defined by membership functions to capture the subjective uncertainties resulting from linguistic approximation. The risk and opportunity events are considered subjective (i.e., fuzzy) variables in the FSD model and are represented by fuzzy arrays. A fuzzy array representing a given risk and opportunity event in a work package ($\tilde{R}_{ib}$) is defined with two dimensions: risk and opportunity event attributes ($\tilde{P}_{R_{ib}}$, $\tilde{I}_{R_{ib}}$, $\tilde{S}_{R_{ib}}$, $\tilde{P}_{O_{ib}}$, $\tilde{I}_{O_{ib}}$, $\tilde{S}_{O_{ib}}$, C_{ib}, t_{ij}^{Def}) and their respective fuzzy membership function parameters (l_{ib}, m_{1ib}, m_{2ib}, u_{ib}). The advantage of using an array is that it can represent a large number of fuzzy variables with several attributes (i.e., dimensions) while keeping the FSD model compact and efficient.

Step 2: Define the relationships between risk and opportunity events and calculate the values of the risk and opportunity event attributes.

A fuzzy weighted average, which considers the degree of causal influence (t_{ij}^{Def}) between the risk and opportunity events obtained from the fuzzy DEMATEL method, is used to define the causal relationships between the risk and opportunity events (Kwan and Leung 2011; Tah and McCaffer 1993). In a causal relationship between risk and opportunity events, the occurrence of predecessor risk and opportunity events has an effect on both the risk probability and the opportunity probability of the posterior risk and opportunity events. The aggregated probability and impact fuzzy numbers determined in the risk assessment and prioritization stage are used as the initial probability and impact values of the risk and opportunity events in the FSD model. A new weighted risk probability ($\tilde{P}^{*}_{R_{jb}}$) and weighted opportunity probability ($\tilde{P}^{*}_{O_{jb}}$), reflecting the effect of the predecessor risk and opportunity events on the posterior risk and opportunity event, are obtained at each time step in the FSD model using Eq. (12).

$$\tilde{P}^{*}_{R_{jb}} = \frac{\tilde{P}_{R_{jb}} \oplus \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def} \otimes \tilde{P}_{R_{ib}}}{1 + \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def}}; \quad \tilde{P}^{*}_{O_{jb}} = \frac{\tilde{P}_{O_{jb}} \oplus \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def} \otimes \tilde{P}_{O_{ib}}}{1 + \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def}} \quad (12)$$

where $\tilde{P}^{*}_{R_{jb}}$ and $\tilde{P}^{*}_{O_{jb}}$ are the weighted risk probability and weighted opportunity probability, respectively, of the jth posterior risk and opportunity event affected by the ith predecessor risk and opportunity event in the bth work package; $\tilde{P}_{R_{jb}}$ and $\tilde{P}_{O_{jb}}$ are the initial aggregated risk probability and opportunity probability, respectively, of the jth posterior risk and opportunity event in the bth work package; $\tilde{P}_{R_{ib}}$ and $\tilde{P}_{O_{ib}}$ are the initial aggregated risk probability and opportunity probability, respectively, of the ith predecessor risk and opportunity event in the bth work package; $t_{(ij)b}^{Def}$ is the degree of causal influence of the ith predecessor risk and opportunity event on the jth posterior risk and opportunity event in the bth work package; and $\oplus$ and $\otimes$ are fuzzy addition and fuzzy multiplication, respectively.

The corresponding weighted risk severity ($\tilde{S}^*_{R_{jb}}$) and weighted opportunity severity ($\tilde{S}^*_{O_{jb}}$) are determined by multiplying $\tilde{P}^*_{R_{jb}}$ and $\tilde{P}^*_{O_{jb}}$ with $\tilde{I}_{R_{jb}}$ and $\tilde{I}_{O_{jb}}$, respectively. Thus, the posterior risk and opportunity event affected by the predecessors is described by the risk and opportunity event attributes ($\tilde{P}^*_{R_{jb}}$, $\tilde{I}_{R_{jb}}$, $\tilde{S}^*_{R_{jb}}$, $\tilde{P}^*_{O_{jb}}$, $\tilde{I}_{O_{jb}}$, $\tilde{S}^*_{O_{jb}}$, C_{jb}, $t^{Def}_{(ij)b}$) and their respective membership function parameters (l^*_{jb}, m^*_{1jb}, m^*_{2jb}, l^*_{jb}) at each time step.

Step 3: Calculate the values of flow and stock variables at the risk and opportunity event category, work package, and project levels.

The forecasted monthly progress in dollars (F_b), which is the product of the forecasted monthly progress percentage (A_b) and the forecasted total work package cost (D_b), is multiplied by the affected percentage of the work package cost (C_{ib}) and the weighted risk severity ($\tilde{S}^*_{R_{ib}}$) percentage to determine the risk severity in dollars of the ith risk and opportunity event on the bth work package. The opportunity severity in dollars is determined in a similar fashion using the weighted opportunity severity ($\tilde{S}^*_{O_{ib}}$). The net severity in dollars is determined for each risk and opportunity event by subtracting its opportunity severity in dollars from its risk severity in dollars. Then, the values of the flow variables (i.e., *risk severity in dollars* ($\widetilde{RSD}$), *opportunity severity in dollars* ($\widetilde{OSD}$), and *net severity in dollars* ($\widetilde{NSD}$)) for each risk and opportunity event category, work package, and project, are determined at each time step (i.e., monthly) using Eqs. (13)–(21), as provided in Table 2. The accumulation of each of the flow variables results in the corresponding contingency values of the stock variables at each time step, namely *risk contingency in dollars* ($\widetilde{RCD}$), *opportunity contingency in dollars* ($\widetilde{OCD}$), and *net contingency in dollars* ($\widetilde{NCD}$), as defined in Eqs. (22)–(30) in Table 2.

Table 2. Mathematical equations of flow and stock variables in FSD.

Level of aggregation	Flow variables		Stock variables	
	Description	Equation	Description	Equation
Risk and opportunity event category ($1 \leq e \leq h$)	Risk severity in dollars ($\widetilde{RSD}_{eb}^{RC}$)	$\widetilde{RSD}_{eb}^{RC} = \sum_{i=1}^{n} C_{ib}\, F_b \otimes \tilde{S}_{R_{ib}}^{*}$ (13)	Risk contingency in dollars ($\widetilde{RCD}_{eb}^{RC}$)	$\widetilde{RCD}_{eb}^{RC} = \int_{t_0}^{t} \widetilde{RSD}_{eb}^{RC}\,(t)dt$ (22)
	Opportunity severity in dollars ($\widetilde{OSD}_{eb}^{RC}$)	$\widetilde{OSD}_{eb}^{RC} = \sum_{i=1}^{n} C_{ib}\, F_b \otimes \tilde{S}_{O_{ib}}^{*}$ (14)	Opportunity contingency in dollars ($\widetilde{OCD}_{eb}^{RC}$)	$\widetilde{OCD}_{eb}^{RC} = \int_{t_0}^{t} \widetilde{OSD}_{eb}^{RC}\,(t)dt$ (23)
	Net severity in dollars ($\widetilde{NSD}_{eb}^{RC}$)	$\widetilde{NSD}_{eb}^{RC} = \widetilde{RSD}_{eb}^{RC} \ominus \widetilde{OSD}_{eb}^{RC}$ (15)	Net contingency in dollars ($\widetilde{NCD}_{eb}^{RC}$)	$\widetilde{NCD}_{eb}^{RC} = \int_{t_0}^{t} \widetilde{NSD}_{eb}^{RC}\,(t)dt$ (24)
Work package ($1 \leq b \leq g$)	Risk severity in dollars ($\widetilde{RSD}_{b}^{WP}$)	$\widetilde{RSD}_{b}^{WP} = \sum_{e=1}^{h} \widetilde{RSD}_{eb}^{RC}$ (16)	Risk contingency in dollars ($\widetilde{RCD}_{b}^{WP}$)	$\widetilde{RCD}_{b}^{WP} = \int_{t_0}^{t} \widetilde{RSD}_{b}^{WP}\,(t)dt$ (25)
	Opportunity severity in dollars ($\widetilde{OSD}_{b}^{WP}$)	$\widetilde{OSD}_{b}^{WP} = \sum_{e=1}^{h} \widetilde{OSD}_{eb}^{RC}$ (17)	Opportunity contingency in dollars ($\widetilde{RCD}_{b}^{WP}$)	$\widetilde{RCD}_{b}^{WP} = \int_{t_0}^{t} \widetilde{OSD}_{b}^{WP}\,(t)dt$ (26)
	Net severity in dollars ($\widetilde{NSD}_{b}^{WP}$)	$\widetilde{NSD}_{b}^{WP} = \widetilde{RSD}_{b}^{WP} \ominus \widetilde{OSD}_{b}^{WP}$ (18)	Net contingency in dollars ($\widetilde{NCD}_{b}^{WP}$)	$\widetilde{NCD}_{b}^{WP} = \int_{t_0}^{t} \widetilde{NSD}_{b}^{WP}\,(t)dt$ (27)
Project	Risk severity in dollars ($\widetilde{RSD}^{PR}$)	$\widetilde{RSD}^{PR} = \sum_{b=1}^{g} \widetilde{RSD}_{b}^{WP}$ (19)	Risk contingency in dollars ($\widetilde{RCD}^{PR}$)	$\widetilde{RCD}^{PR} = \int_{t_0}^{t} \widetilde{RSD}^{PR}\,(t)dt$ (28)
	Opportunity severity in dollars ($\widetilde{OSD}^{PR}$)	$\widetilde{OSD}^{PR} = \sum_{b=1}^{g} \widetilde{OSD}_{b}^{WP}$ (20)	Opportunity contingency in dollars ($\widetilde{OCD}^{PR}$)	$\widetilde{OCD}^{PR} = \int_{t_0}^{t} \widetilde{OSD}^{PR}\,(t)dt$ (29)
	Net severity in dollars of ($\widetilde{NSD}^{PR}$)	$\widetilde{NSD}^{PR} = \widetilde{RSD}^{PR} \ominus \widetilde{OSD}^{PR}$ (21)	Net contingency in dollars ($\widetilde{NCD}^{PR}$)	$\widetilde{NCD}^{PR} = \int_{t_0}^{t} \widetilde{NSD}^{PR}\,(t)dt$ (30)

Where:

C_{ib} is the percentage of the bth work package cost affected by the ith risk and opportunity event;

F_b ($F_b = A_b D_b$) is the forecasted monthly progress in dollars of the bth work package, which is the product of the forecasted monthly progress percentage (A_b) and the forecasted total work package cost (D_b) at each time step; and

$\otimes$ and $\ominus$ are fuzzy multiplication and fuzzy subtraction, respectively.

The summations in the equations are carried out using fuzzy addition.

Dynamic Simulation of the FSD Model and Output Determination

Having constructed the quantitative FSD model, the cumulative and concurrent impact of risk and opportunity events on work packages and project cost were quantified by simulating the quantitative model over the total project duration. Fuzzy arithmetic was utilized in the FSD model instead of classical arithmetic to carry out the algebraic operations whenever a fuzzy variable was involved in a given mathematical expression. In this paper, the α-cut method and the drastic t-norm were implemented to carry out fuzzy arithmetic operations involving both triangular and trapezoidal fuzzy numbers in the FSD model. A horizontal discretization method proposed by Hanss (2005) was adopted in the FSD model to implement fuzzy arithmetic based on the drastic t-norm. The final output (fuzzy numbers) of the FSD model that represents the work package and project contingency values in terms of cost were represented as a single crisp value using different defuzzification methods, such as the COA, smallest of maxima (SOM), middle of maxima (MOM), and largest of maxima (LOM). A fuzzy arithmetic class was developed using the Java programming language and imported to the quantitative FSD model in AnyLogic® for performing fuzzy arithmetic operations using the α-cut method and the drastic t-norm as well as for determining contingency values using defuzzification methods.

Construction Application and Model Validation: Case Study

The proposed modeling approach was applied to develop an FSD model for analyzing risk and opportunity events and determining contingency on the construction of 99-megawatt (MW) wind farm power generation project in North Dakota. The forecasted total project cost was approximately $145 million (USD) and the planned project duration was 12 months. The project involved eight construction work packages ranging in cost from approximately $900,000 to $84 million. The construction work packages were grouped into three main project work packages: civil, structural, and electrical.

Identification, Assessment, and Prioritization of Risk and Opportunity Events

A heterogeneous group consisting of four experts (E_1, E_2, E_3, and E_4) who were directly involved in the project was formed. The experts had an average of 23 total years of experience in construction and an average of 12 years of experience specifically in risk management. The expertise levels of the experts in risk management were assessed based on qualitative and quantitative qualification attributes belonging to the seven criteria mentioned in the methodology section. Then, the importance weights (W_k) of the four experts (W_1, W_2, W_3, and W_4) were calculated using the FAHP weight-assigning method proposed by Monzer et al. (2019). The importance weights of the four experts were 0.25, 0.27, 0.22, and 0.26, respectively.

The experts assessed the probability of occurrence of the risk and opportunity events and their respective impacts on civil, structural, and electrical work packages using the linguistic terms and their associated fuzzy numbers presented in Table 3. The experts also determined the percentage of the work packages' costs impacted by each risk and opportunity event. The experts' assessments were aggregated by taking into account the importance weights of the experts (W_k), and the net severity percentage ($\widetilde{NS}_{ib}$) of each of the risk and opportunity events for the three work packages were calculated as discussed in the methodology section. Then, the risk and opportunity events were ordered based on defuzzified net severity percentage (NS_{ib}^{Def}) from largest to smallest, and the risk and opportunity events to be considered in the FSD model were chosen based on the 75th percentile. As a result, 35 risk and opportunity events were selected for each work package. The prioritized list of risk and opportunity events for a civil work package is provided in Table S1 (see Supplemental Data) as an example.

Table 3. Linguistic terms and fuzzy numbers for assessing the probability and impact of risk and opportunity events (Elbarkouky et al. 2016).

Linguistic term	Fuzzy Number			
	Risk probability	Risk impact	Opportunity probability	Opportunity Impact
Very low	(0.00 0.00 27.50)	(0.00 0.00 20.83)	(0.00 0.00 20.83)	(0.00 0.00 20.83)
Low	(0.00 23.53 45.00)	(0.00 9.66 45.35)	(0.00 12.30 38.42)	(0.00 5.03 60.74)
Medium	(21.11 37.78 55.00 80.00)	(4.46 16.09 41.27 55.35)	(11.63 30.65 40.13 84.91)	(0.00 26.61 48.50 71.55)
High	(49.36 75.00 97.73)	(12.47 50.99 111.10)	(21.88 79.98 97.46)	(5.29 64.14 92.03)
Very high	(65.79 100.00 100.00)	(44.51 200.00 200.00)	(64.58 97.55 100.00 100.00)	(63.20 100.00 100.00)

Qualitative FSD Model Development

The fuzzy DEMATEL survey described earlier was completed by three of the experts who were involved in the risk assessment and prioritization stage. The linguistic assessments of the experts were converted to fuzzy numbers and three 35x35 initial fuzzy matrices ($\tilde{X}_k$) were obtained for each work package. The fuzzy DEMATEL steps discussed in the methodology section were applied for each work package to construct the CLDs in the qualitative model development stage. For the sake of brevity, only the results of the civil work package and the whole project are presented and discussed in this paper. Table 4 depict part of the defuzzified total-relation matrix (T^{Def}) of the civil work package, respectively.

Table 4. Defuzzified total-relation matrix (T^{Def}) of risk and opportunity events in the civil work package.

Risk ID	R1_1	R1_3	R1_4	R1_5	…	R11_1	R11_12	R11_14
R1_1	0.050	**0.075**	**0.077**	0.050	…	**0.075**	**0.072**	**0.073**
R1_3	0.065	0.057	**0.083**	0.063	…	**0.086**	**0.082**	**0.081**
R1_4	0.066	0.060	0.053	0.053	…	0.063	0.065	0.065
R1_5	**0.075**	0.054	0.066	0.036	…	0.058	0.056	0.055
…	…	…	…	…	…	…	…	…
R11_1	0.063	0.065	0.065	0.051	…	0.048	0.054	0.053
R11_12	0.065	**0.076**	**0.078**	0.054	…	**0.083**	0.049	0.063
R11_14	0.065	**0.073**	0.063	0.051	…	**0.077**	**0.074**	0.046

Note: The bold values represent the relationships depicted in the CLDs.

The CLDs were constructed based on the defuzzified total-relation matrix values (Table 4). A threshold value of 0.070, which is the 75th percentile of the defuzzified total-relation matrix (T^{Def}), was set for the civil work package so only the strongest causal relationships would be depicted, reducing the complexity of the resulting CLDs. The directions of the causal relationships were established from Table 4 in such a way that the risk and opportunity events in the row affect the risk and opportunity events in the column ($i \rightarrow j$, e.g., R1_5→R1_1). For better clarity and representation, a CLD was created for each risk and opportunity event category. The CLD of a given risk and opportunity event category shows the causal relationships among the risk and opportunity events within the category as well as the causal influence of risk and opportunity events from other categories on the given category. The CLDs of management risk and opportunity event category for the civil work package are shown as an example in Fig. 2. When the number of risk and opportunity events in a given category or the number of causal relationships in a category are too few, the CLDs for two or more closely related risk and opportunity event categories were combined. The CLDs of the other risk and opportunity event categories for civil work package are shown in Fig. S1–S5 (see Supplemental Data).

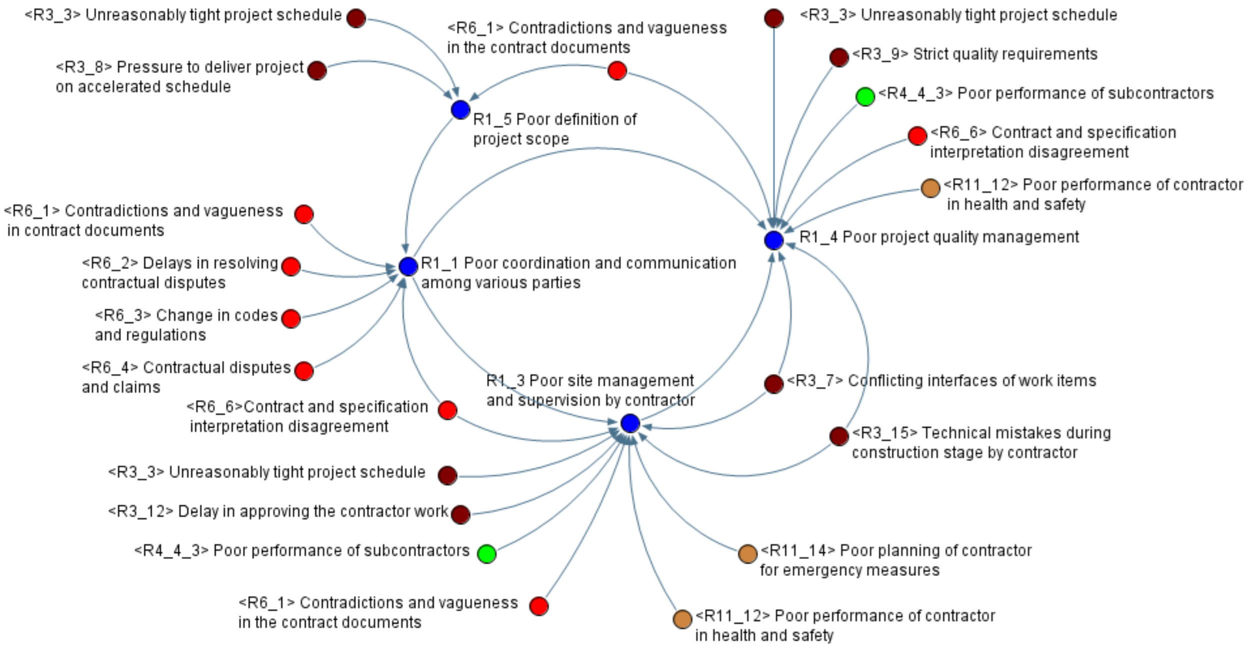


Fig. 2. Causal loop diagram of the management risk and opportunity event category for a civil work package.

After the CLDs were constructed for each work package, the corresponding flow and stock diagrams were developed for the risk and opportunity event categories, work packages, and project. The FSD model is structured in such a way that the severity and contingency values of the flow and stock variables at the category level are aggregated to obtain the severity and contingency values at the work package level, and then the severity and contingency values at the work package level are aggregated to determine the severity and contingency values at the project level. Figs. 3–5 depict the flow and stock diagrams of the management risk and opportunity event category, the civil work package, and the wind farm project, respectively.

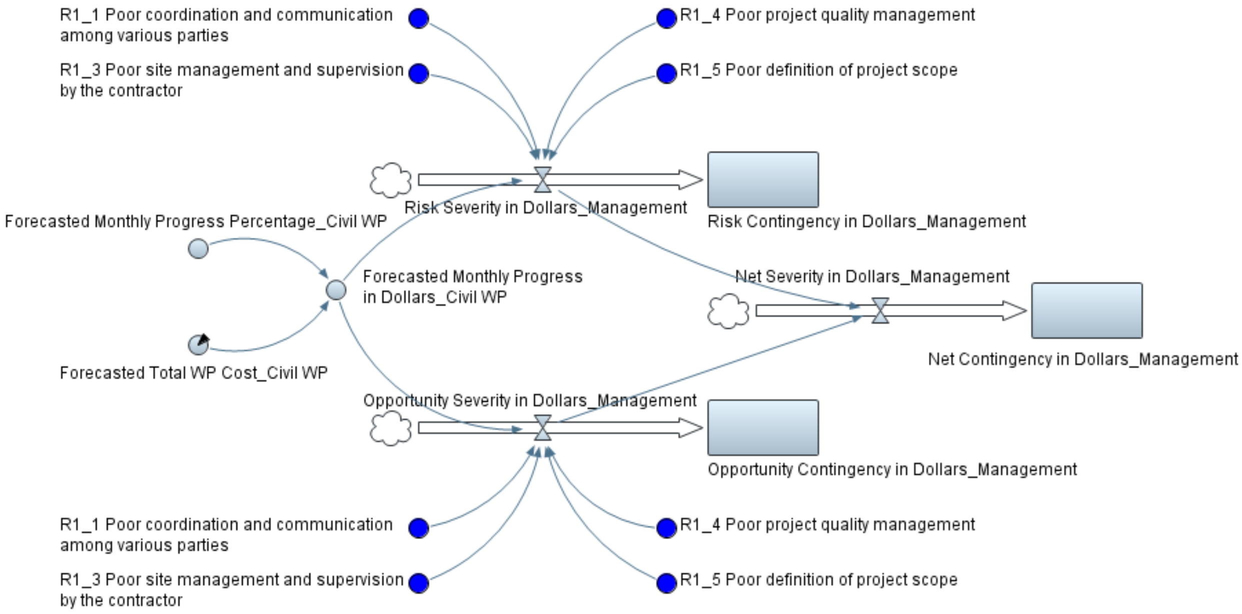


Fig. 3. Flow and stock diagram of the management risk and opportunity event category for a civil work package.

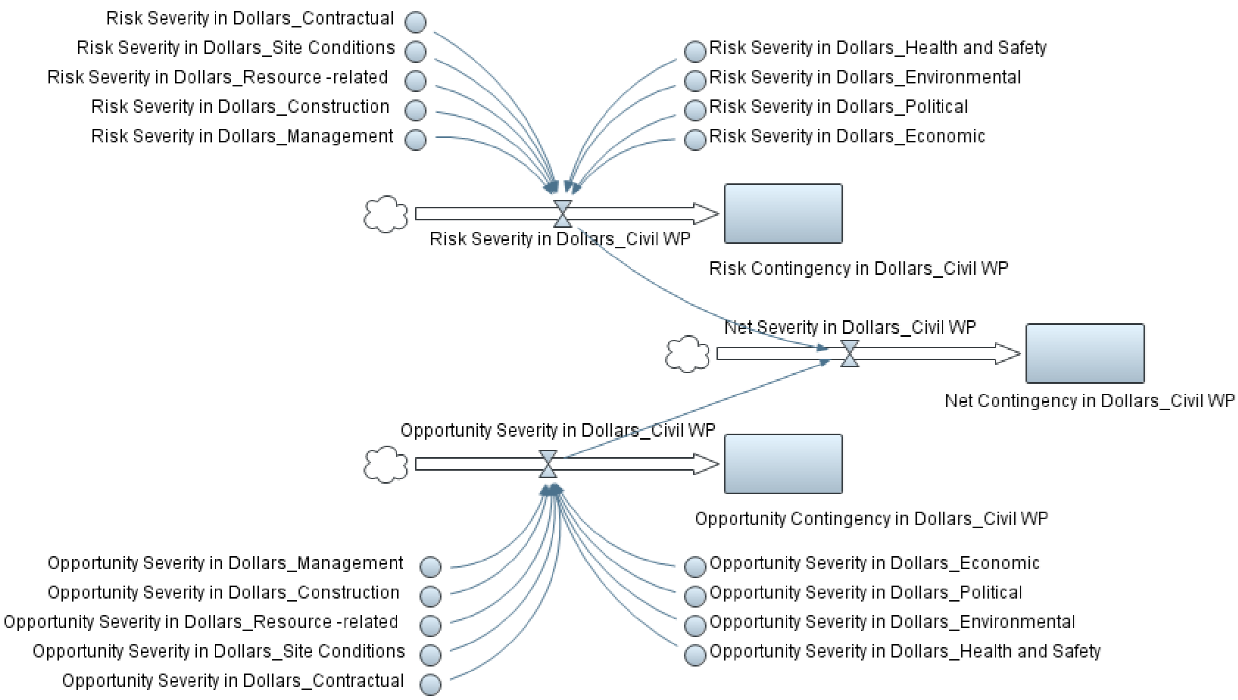


Fig. 4. Flow and stock diagram of a civil work package.

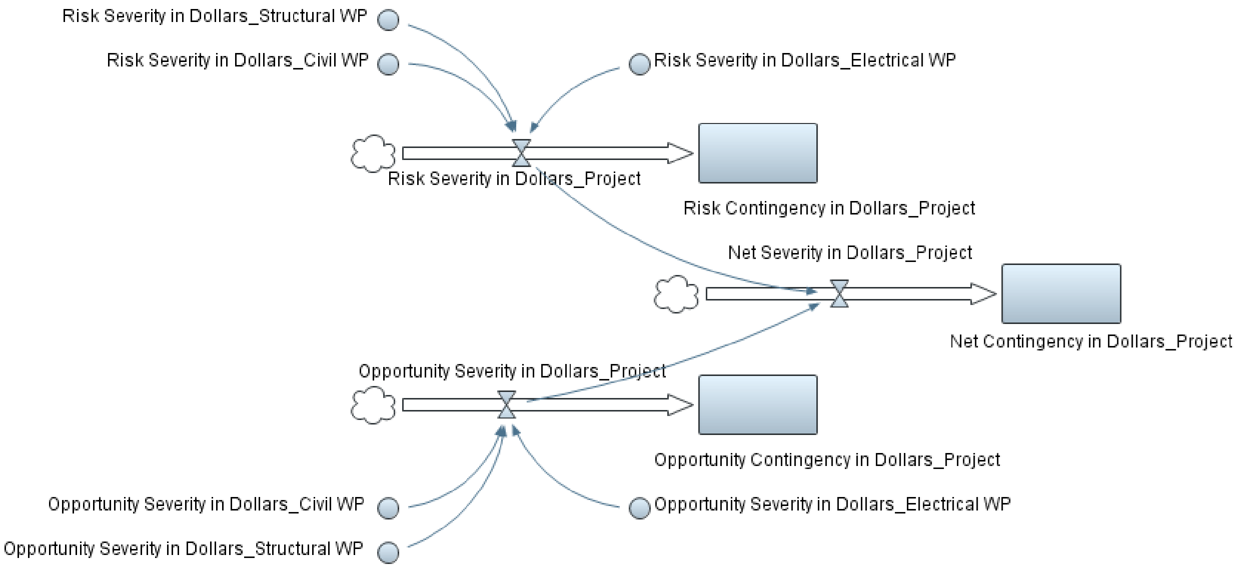


Fig. 5. Flow and stock diagram of the wind farm project.

Quantitative FSD Model Development

In developing the quantitative FSD model of the wind farm project, the objective and subjective (i.e., fuzzy) parameters and variables were first identified as described in the methodology section. Each risk and opportunity event was modeled as a dynamic fuzzy array defined by the risk and opportunity event attributes and their corresponding fuzzy membership function parameters. Among the risk and opportunity event attributes, the affected percentage of work package cost (C_{ib}) and the degree of causal influence of risk and opportunity event i on risk and opportunity event j (t_{ij}^{Def}) were expressed by crisp values, whereas the rest of the attributes were represented by triangular or trapezoidal fuzzy numbers. The other objective variables in the FSD model were the forecasted monthly progress percentage (A_b), forecasted total work package cost (D_b), and forecasted monthly progress in dollars (F_b). All the flow and stock variables in the FSD model were fuzzy variables as the risk severity and opportunity severity used in the equations were fuzzy numbers. Finally, the mathematical procedures described in the methodology section were followed to analyse the severity of risk and opportunity events on work package cost and determine work package and project contingencies.

Dynamic Simulation of the FSD Model and Output Determination

The contingency values of the work packages and the project were determined by simulating the quantitative FSD model over the project duration (i.e., 12 months). The fuzzy arithmetic calculation in the FSD model was carried out using the α-cut method and the drastic t-norm and the work packages' and project's contingencies were determined as fuzzy numbers represented by a tuple (l_b^*, m_{1b}^*, m_{2b}^*, l_b^*) and (l^*, m_1^*, m_2^*, u^*), respectively. The plots of the fuzzy numbers representing the net project contingency based on the α-cut and drastic t-norm are shown in Fig. 6.

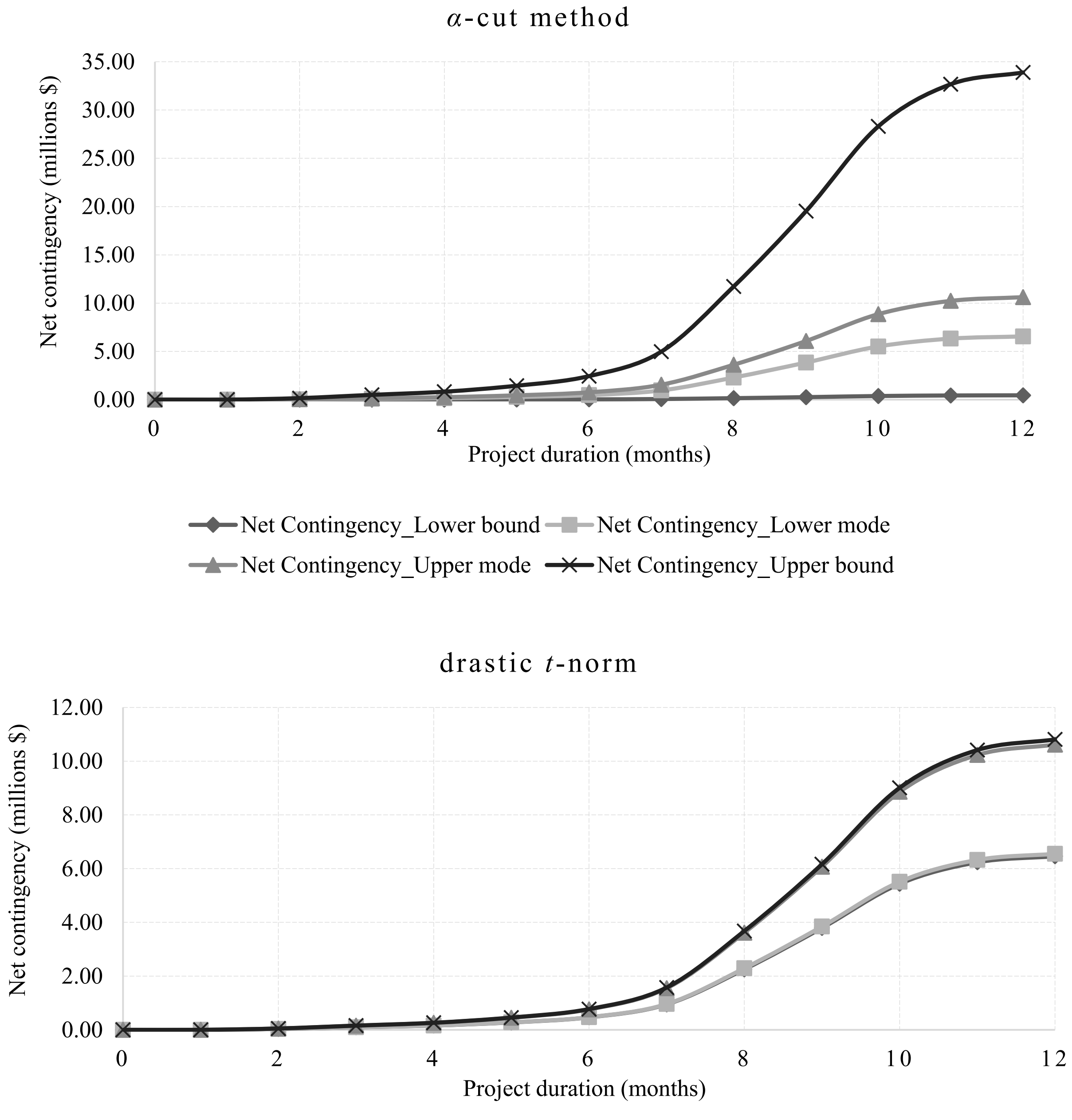


Fig. 6. Civil work package net contingency based on the α-cut method and the drastic t-norm.

When the α-cut method is used in the FSD model, the supports of the fuzzy numbers grow rapidly, contributing to the overestimation of uncertainty. For example, the support of the net project contingency fuzzy number at the end of the project duration (shown in Fig. 6) is [450,300.61

33,892,516.73] for the α-cut method. In order to observe the accumulation of fuzziness phenomenon in the two arithmetic methods, the length of the support was calculated. The length of the support is the distance between the lower bound and upper bound of the support of a fuzzy number. Table 5 shows a comparison of the length of the support of the net project contingency fuzzy numbers over the project duration when the two arithmetic methods are used in the FSD model. The reduction rate (%) in the length of the support achieved by employing the drastic t-norm instead of the α-cut method is also summarized in Table 5. The excessive accumulation of fuzziness and overestimation of uncertainty encountered in the FSD model was significantly reduced by using the drastic *t*-norm instead of the α-cut method. Based on these results, it can be concluded that the α-cut method and the drastic *t*-norm provide a pessimistic and conservative net project contingency range estimate, respectively.

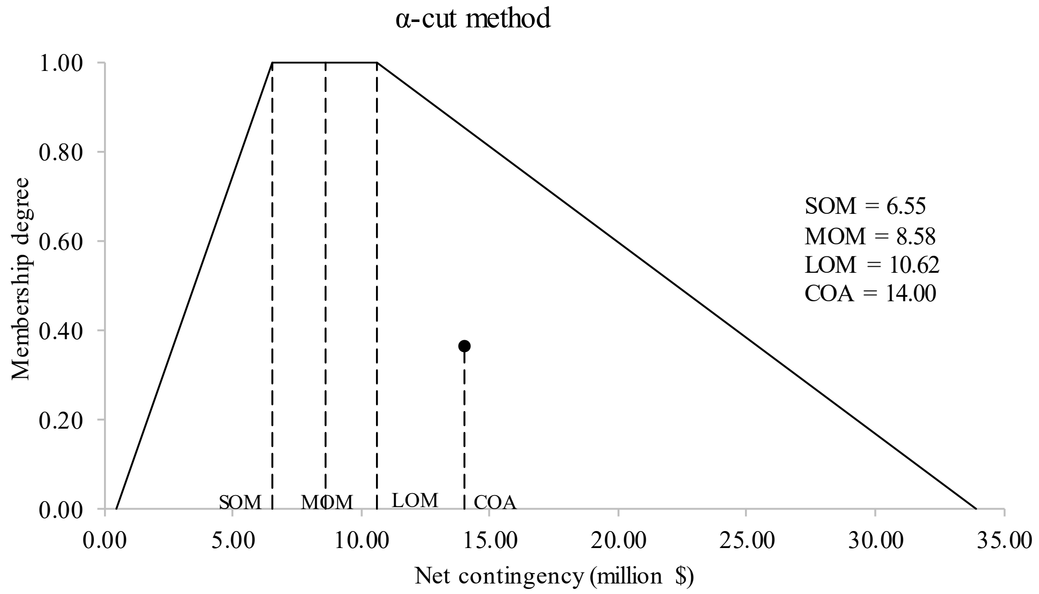
Table 5. Comparison of the length of support of the net project contingency fuzzy numbers for the α-cut method and the drastic *t*-norm.

Project duration	Length of support		Reduction rate (%) = [((1)–(2))/(1)]*100
	α-cut method (1)	drastic *t*-norm (2)	
0	0.00	0.00	0.00
1	0.00	0.00	0.00
2	156,700.09	20,423.22	86.97
3	491,570.69	64,255.34	86.93
4	815,868.58	104,689.54	87.17
5	1,425,401.23	181,324.53	87.28
6	2,405,163.85	307,932.26	87.20
7	4,912,017.38	626,435.32	87.25
8	11,567,913.74	1,425,288.81	87.68
9	19,266,750.08	2,373,897.54	87.68
10	27,932,561.82	3,573,392.53	87.21
11	32,237,520.17	4,177,089.14	87.04
12	33,442,216.12	4,346,346.92	87.00

The net project contingency fuzzy numbers in dollars (450,300.61, 6,550,070.15, 10,615,179.05, 33,892,516.73) and (6,460,369.29, 6,550,070.15, 10,615,179.05, 10,806,716.21) at the end of the project duration (t=12 months), shown in Fig. 7, represent the total net contingency of the wind farm project based on the α-cut method and the drastic t-norm, respectively. The fuzzy numbers were defuzzified using the SOM, MOM, LOM, and COA methods to obtain representative crisp values. Since the core of the net contingency fuzzy numbers obtained based on the α-cut method and the drastic t-norm are equal, the defuzzified net contingency values of the project determined using the SOM (\$6,550,070.15), MOM (\$8,582,624.60), and LOM (\$10,615,179.05) are the same for both fuzzy arithmetic methods (Fig. 7). The defuzzified net contingency values of the project based on the COA method are \$13,998,190.00 and \$8,608,360.00 for the α-cut method and the drastic t-norm, respectively (Fig. 7). The SOM, MOM, and LOM defuzzification methods are simple to implement. However, they always give the same result irrespective of the fuzzy arithmetic method used and they do not take into account the shape of the fuzzy number in determining the defuzzified value. The COA method is more realistic in representing the output fuzzy number, as it averages the membership values of the entire domain range. However, in general, difficulty of implementation and an increase in simulation runtime are major drawbacks of the COA method.

Model Validation

The qualitative and quantitative FSD models were validated by conducting structural and behavioral validations (Sterman 2000; Lee et al. 2005). Structural validation, which comprises structural verification, parameter verification, and dimensional consistency, was carried out on the CLDs, flow and stock diagrams, and mathematical equations. For behavior validation, the FSD model was checked to see if it reproduced the anticipated behavior in the system. The performance of the FSD model was evaluated by implementing it using an actual project case study and the results were compared against contingency values obtained from Monte Carlo simulation (MCS).



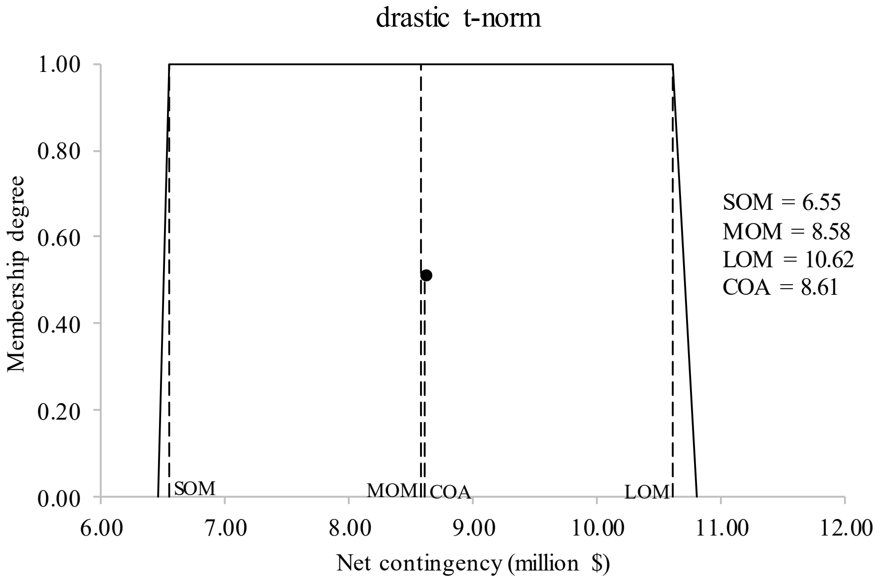


Fig. 7. Defuzzified values of the net project contingency fuzzy numbers.

The defuzzified net project contingency values determined using the the α-cut method and the drastic *t*-norm from the FSD model at the end of the project duration (t=12 months) were compared with the P50 (confidence level of 0.5) and P95 (confidence level of 0.95) project contingency values obtained through MCS. The symmetric mean absolute percentage error (SMAPE) was used to calculate the error and evaluate the degree of agreement between the FSD model and MCS in predicting the net project contingency. The SMAPE overcomes the shortcomings, such as asymmetry and impact of outliers, associated with other error measurements, including the mean absolute error and the root mean square error (Willmott and Matsuura 2005). The SMAPE is expressed as shown in Eq. (31).

$$SMAPE = \frac{100\%}{n}\sum_{\mathrm{t=1}}^{\mathrm{n}}\frac{|Q_t - V_t|}{(|Q_t| + |V_t|)/2} \qquad (31)$$

where Q_t is the defuzzified net project contingency predicted by the FSD model and V_t is the P50 or P95 project contingency estimated by MCS. The value of the SMAPE ranges from 0% to 200%, where a value of 0% implies a perfect agreement between the contingency results of the FSD model and MCS.

Table 6 presents the SMAPE results calculated based on the P50 and P95 project contingency output of MCS. The comparison between the FSD net project contingency results and MCS P50 shows that the lowest SMAPE was observed for the COA (8.67%) defuzzification method when the drastic *t*-norm was used. The comparison between the FSD net project contingency results and MCS P95 indicates that the lowest SMAPE was achieved for the COA (5.15%) defuzzification method when the α-cut method was used. The SMAPE results obtained for the SOM, MOM, and LOM defuzzification methods were the same regardless of which arithmetic method was adopted. The net project contingency results obtained from FSD are comparable to the MCS P50 and P95 project results. The FSD modeling approach addresses the limitations of MCS, such as a reliance on historical data to develop probability distributions, by using expert judgment, linguistic scales, and fuzzy numbers. Moreover, the causal relationships that exist among risk and opportunity events were taken into account when determining the net project contingency in FSD; MCS, on the other hand, considers risks to be causally independent.

Furthermore, FSD estimates the net project contingency continuously throughout the project duration, while MCS estimates project contingency at a specific time (e.g., quarterly).

The defuzzified net project contingency values determined by the FSD model at the end of the project duration (t=12 months) were also compared with the defuzzified contingency values obtained by employing the α-cut method and the drastic *t*-norm in Fuzzy Contingency Determinator© (FCD©) software (Elbarkouky et al. 2016). The SMAPE defined in Eq. 31, where V_t is the defuzzified project contingency predicted by FCD©, was used to evaluate the degree of agreement between FSD and FCD©. The SMAPE results are summarized in Table 7. Overall, the degree of agreement between the net contingency estimated by the FSD model and FCD© varied between 2.63% and 98.90%. A better degree of agreement (2.63%) was achieved when the α-cut method/drastic *t*-norm and LOM defuzzification method was employed in the FSD model, and the resulting net project contingency was compared with the contingency result obtained from FCD© by using the α-cut method/drastic *t*-norm and the COA defuzzification method. Although both FSD and FCD© use linguistic terms represented by fuzzy numbers and fuzzy arithmetic procedures to determine project contingency, FCD© fails to consider the causal interactions that exist among risk and opportunity events and only estimates project contingency at specific time.

Table 6. SMAPE: FSD net project contingency results compared to MCS P50 and P95 project contingency results.

Fuzzy system dynamics (FSD)		Symmetric mean absolute percentage error (SMAPE) (%)	
Fuzzy arithmetic method	Defuzzification methods	MCS P50	MCS P95
α-cut method	SOM	37.16	76.93
	MOM	10.57	52.79
	LOM	10.67	32.52
	COA	37.88	5.15
Drastic *t*-norm	SOM	37.16	76.93
	MOM	10.57	52.79
	LOM	10.67	32.52
	COA	10.27	52.51

Table 7. SMAPE: FSD net project contingency results compared to FCD$^{\copyright}$ project contingency results.

		Symmetric mean absolute percentage error (SMAPE) (%)							
		Fuzzy Contingency Determinator (FCD$^{\copyright}$)							
Fuzzy system dynamics (FSD)		α-cut method				Drastic *t*-norm			
		SOM	MOM	LOM	COA	SOM	MOM	LOM	COA
α-cut method	SOM	**32.17**	5.94	33.30	44.88	32.17	5.94	33.30	6.16
	MOM	57.78	**21.01**	6.59	18.57	57.78	21.01	6.59	20.79
	LOM	76.61	41.72	**14.64**	2.63	76.61	41.72	14.64	41.51
	COA	98.90	67.28	41.71	**30.06**	98.90	67.28	41.71	67.08
Drastic *t*-norm	SOM	32.17	5.94	33.30	44.88	**32.17**	5.94	33.30	6.16
	MOM	57.78	21.01	6.59	18.57	57.78	**21.01**	6.59	20.79
	LOM	76.61	41.72	14.64	2.63	76.61	41.72	**14.64**	41.51
	COA	58.06	21.30	6.29	18.28	58.06	21.30	6.29	**21.09**

Note: The bold values represent SMAPE values for similar arithmetic and defuzzification methods.

The project contingencies estimated by FSD need to be compared with the final actual cost variances of several projects to determine if FSD offers better predictive capability than MCS and FCD$^{\copyright}$. The selection of arithmetic and defuzzification methods depends on different factors such as project scale, project context, and the preferences of decision makers.

Conclusions and Recommendations for Future Work

In this paper, a hybrid FSD model was developed to analyze the impact of dynamic and interacting risk and opportunity events on work package costs and determine work package and project contingencies. The main contributions of this paper can be grouped into three areas. First, the paper provides a systematic risk assessment and prioritization procedure that uses linguistic scales represented by fuzzy numbers to assess the probability and impact of risk and opportunity events. Second, the paper provides a hybrid FSD modeling approach that accounts for the dynamic causal interactions and dependencies among risk and opportunity events and quantifies their impact on work package and project cost contingencies. Third, the paper contributes to the advancement of the state of the art in FSD modeling for risk analysis and contingency determination by (1) providing a structured and systematic method that uses linguistic terms for constructing CLDs, (2) providing a method for handling subjective uncertainty in FSD, and (3) implementing fuzzy arithmetic methods (the α-cut method and the drastic *t*-norm) in FSD to carry out algebraic operations in mathematical equations involving fuzzy variables.

In the future, this study will be extended to develop an FSD model to determine the concurrent and cumulative impact of risk and opportunity events on two or more project objectives (e.g., cost, schedule, quality, and safety and health). In particular, the FSD model will be extended to determine the severity of risk and opportunity events in terms of not only cost but also impact on the project schedule, including extensions of time. The FSD model developed in this paper only deals with subjective uncertainties. Thus, this study will be extended to provide the ability to account for both probabilistic (i.e., random) and subjective uncertainties in FSD. Moreover, future research will focus on developing an FSD model that is capable of incorporating response strategies for critical risks along with their associated secondary risks to determine their impact on work package and project contingency and evaluate the effectiveness of response strategies prior to their implementation. Future research will also explore the application of machine learning techniques, such as data-driven fuzzy rule-based systems, artificial neural networks, fuzzy neural networks, and neuro-fuzzy systems, to define the relationships between system variables in FSD automatically from data.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

Acknowledgments

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Supplemental Data

Table S1 and Figs. S1–S5 are available online in the ASCE Library (www.ascelibrary.org) [and at the end of this post-print document].

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Supplemental Data

Table S1 and Figs. S1–S5 are included in this supplemental data.

Table S1. Prioritized list of risk and opportunity events for a civil work package.

Risk ID	Description of risk and opportunity event	Risk and opportunity event category	Net severity percentage ($\widetilde{NS}_{i1}^{Def}$)	Rank
R3_1	Delays and interruptions causing a cost increase to the work package/project	Construction	3.55	1
R10_1	Adverse weather conditions (continuous rainfall, snow, temperature, wind)	Environmental	1.29	2
R7_5	Change in tax regulation	Economic and financial	1.22	3
R3_9	Strict quality requirements	Construction	1.17	4
R1_4	Poor project quality management including inadequate quality planning, quality assurance, and quality control	Management	1.14	5
R3_8	Pressure to deliver project on an accelerated schedule	Construction	1.07	6
R5_10	Finding historical objects during the excavation process	Site conditions	1.07	6
R1_3	Poor site management and supervision by the contractor	Management	1.02	8
R4_1_5	Higher workforce attrition rates	Resource-related	0.87	9
R11_1	Accidents occurring during construction	Health and safety	0.87	9
R4_3_1	Unavailability or shortage of expected equipment	Resource-related	0.84	11
R4_3_2	Equipment breakdown	Resource-related	0.82	12
R9_1	Changes in government laws, regulations, and policies affecting the project	Political	0.79	13
R4_4_3	Poor performance of subcontractors	Resource-related	0.74	14
R6_4	Possibility of contractual disputes and claims	Contractual and legal	0.72	15
R10_2	Force majeure (natural and man-made disasters that are beyond the firm's control)	Environmental	0.71	16
R6_2	Delays in resolving contractual disputes and litigations	Contractual and legal	0.70	17
R3_12	Delays in approving contractor work by consultant or owner of the project	Construction	0.69	18

Risk ID	Description of risk and opportunity event	Risk and opportunity event category	Net severity percentage ($\widetilde{NS}_{i1}^{Def}$)	Rank
R6_6	Contract and specification interpretation disagreement	Contractual and legal	0.69	18
R3_3	Unreasonably tight project schedule causing a cost increase to the work package/project	Construction	0.68	20
R6_1	Contradictions and vagueness in contract documents	Contractual and legal	0.68	20
R6_3	Change in codes and regulations	Contractual and legal	0.68	20
R3_15	Technical mistakes during construction stage by contractor	Construction	0.67	23
R3_7	Conflicting interfaces of work items	Construction	0.64	24
R1_1	Poor coordination and communication among various parties involved in the project	Management	0.62	25
R10_6	Changes in environmental permitting	Environmental	0.59	26
R1_5	Poor or incomplete definition of project scope	Management	0.58	27
R4_1_1	Unavailability of sufficient amount of skilled labor in project region	Resource-related	0.52	28
R5_12	Unexpected underground utilities encounters	Site conditions	0.51	29
R5_5	Late construction site possession	Site conditions	0.48	30
R11_12	Poor performance of contractor in health and safety of work	Health and safety	0.45	31
R10_4	Pollution associated with construction activities (dust, harmful gases, noise, solid and liquid wastes, etc.)	Environmental	0.43	32
R10_5	Strict environmental regulations and requirements	Environmental	0.43	32
R11_14	Poor planning of contractor for emergency measures	Health and safety	0.29	34
R9_4	Delay or refusal of project approval and permit by government departments	Political	0.26	35

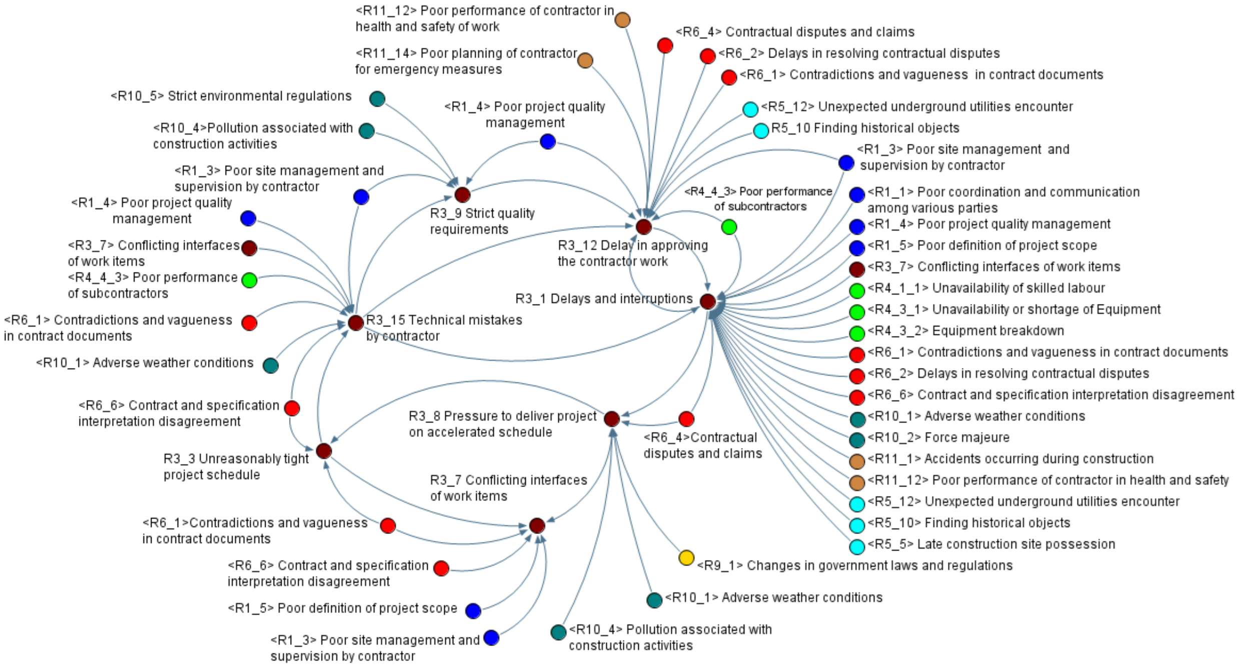

Fig. S1 Causal loop diagram of the **construction** risk and opportunity event category for the civil work package

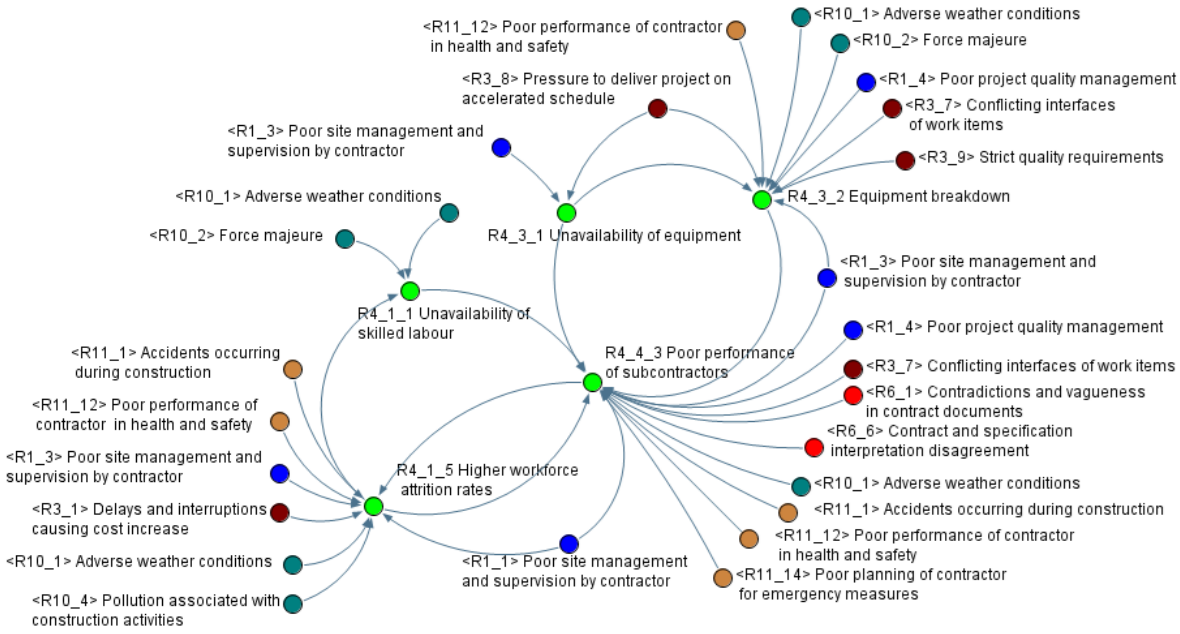

Fig. S2 Causal loop diagram of the **resource-related** risk and opportunity event category for the civil work package

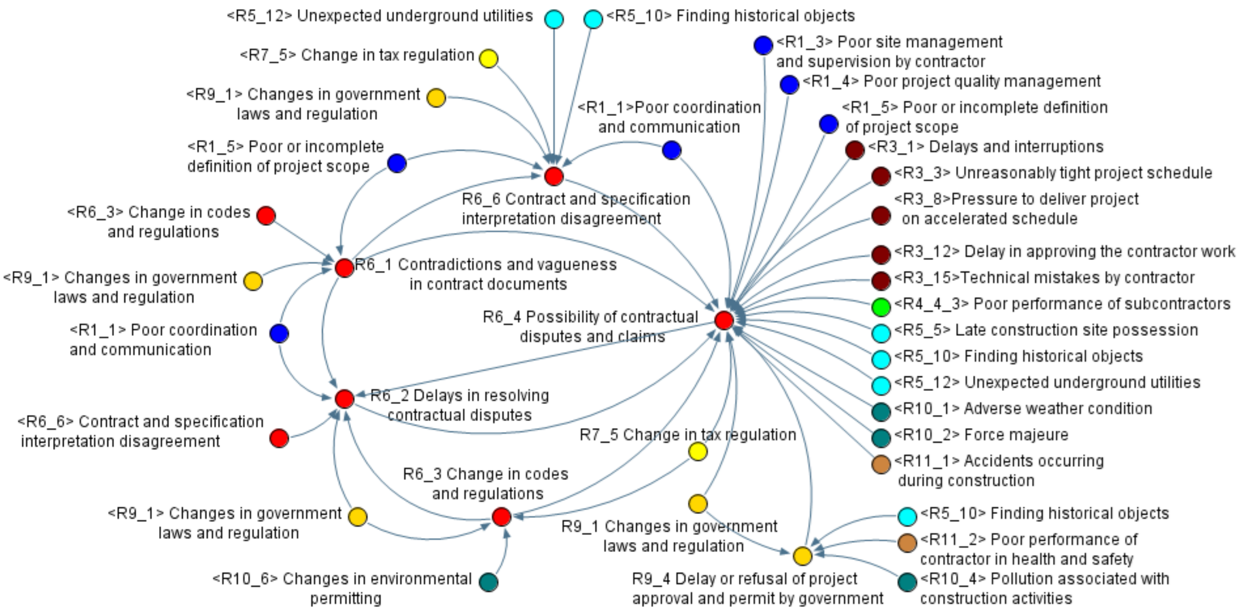

Fig. S3 Causal loop diagram of the **contractual and legal**, **economic and financial**, and **political** risk and opportunity event categories for the civil work package.

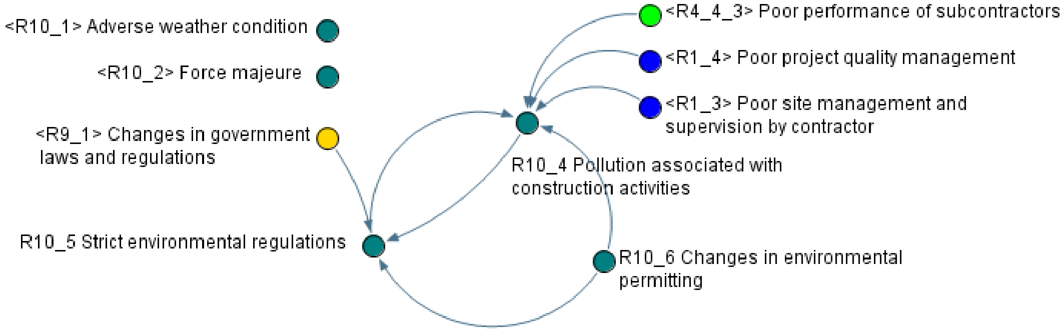

Fig. S4 Causal loop diagram of the **environmental** risk and opportunity event category for the civil work package

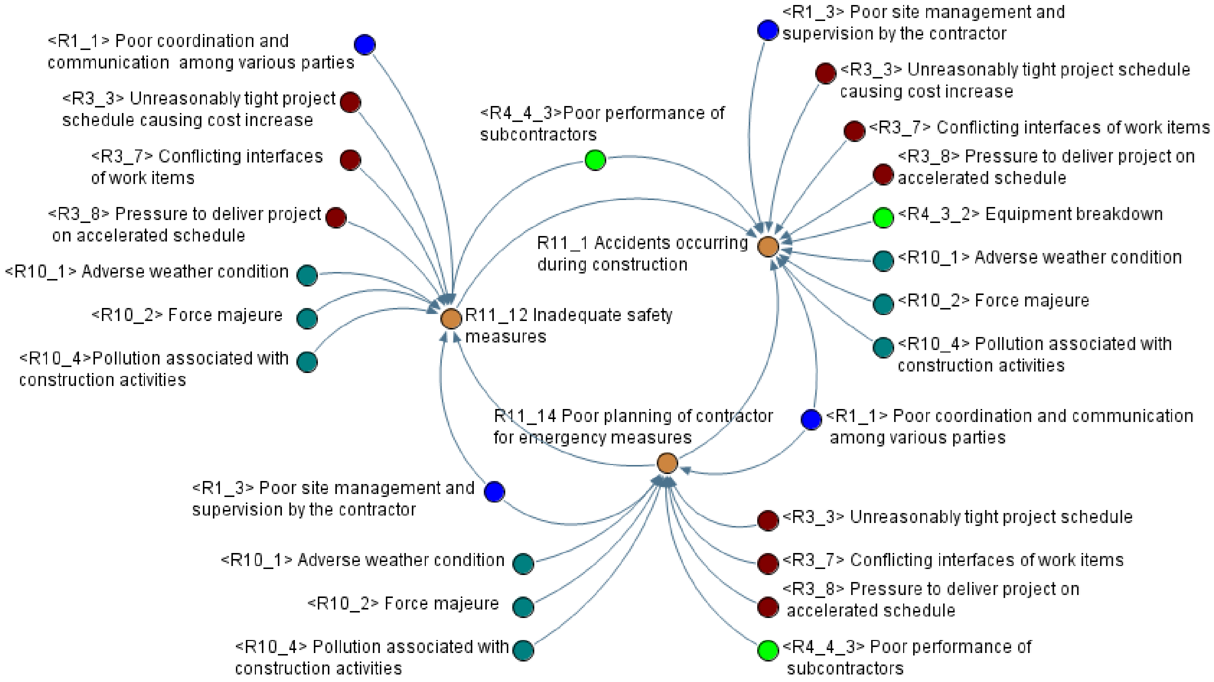

Fig. S5 Causal loop diagram of the **health and safety** risk and opportunity event category for the civil work package