Hybrid Fuzzy System Dynamics Model for Risk Analysis and Contingency Determination

by

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Abstract

The unique nature of construction projects and the uncertainties encountered during project execution make construction a highly-risk prone industry. Risks on construction projects (especially large-scale projects) are extremely complex and highly dynamic, and substantial interrelationships exist among risks throughout the lifecycle of the project. The dynamic nature of risk and opportunity events and the causal interactions and dependencies between them have a considerable effect on risk analysis and contingency determination; their lack of consideration can lead to overestimation or underestimation of contingency.

System dynamics (SD) is a viable option for modeling and analyzing construction risks to determine work package and project contingency, as it is capable of handling such characteristics. However, conventional SD models do not effectively account for the subjective uncertainties associated with system variables, the imprecise nature of factors that influence the variables, and the vague interdependencies between variables. Therefore, a hybrid fuzzy system dynamics (FSD) model that combines the strengths of both SD and fuzzy logic is developed in this research to analyze the severity of interrelated and interacting risk and opportunity events on work package cost and determine work package and project contingencies.

A systematic review and detailed content analysis of selected articles was conducted to identify, categorize, and rank potential risk and opportunity events affecting construction projects. A fuzzy-based risk assessment procedure, which assesses the probability and impact of both risk and opportunity events and considers the experts' expertise level, was employed to assess and prioritize risk and opportunity events. Linguistic scales, represented by fuzzy numbers, were used to allow experts to use natural language to assess the probability and impact of risk and opportunity events and the causal relationships between them. The alpha-cut method and the extension principle based on drastic t-norm were implemented in the FSD model to carry out fuzzy arithmetic operations whenever a fuzzy variable was involved in a given mathematical equation to determine an intermediary or final output. The comparison of project contingency fuzzy numbers obtained based on the two fuzzy arithmetic methods indicates that the 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. Structural and behavioral validation tests were performed to validate the FSD model. Moreover, the performance of the FSD model was evaluated by implementing it using actual project case study and the results were compared against contingency values obtained from Monte Carlo simulation and Fuzzy Contingency Determinator©.

This research addresses the lack of a systematic review and content analysis of published articles related to risk identification and provides a useful reference on common potential risks affecting construction projects. Moreover, it provides a systematic risk assessment and prioritization procedure. This research provides both researchers and construction industry practitioners with a hybrid FSD modeling approach for understanding the dynamic causal interactions and dependencies among risk and opportunity events and determining their severity on work package and project cost contingency using subjective evaluation and experience. It also provides a structured and systematic method of defining causal relationships among risk and opportunity events and constructing causal loop diagrams in the qualitative FSD model. Additionally, this research provides a basis for the implementation of fuzzy arithmetic methods (both alpha-cut and extension principle) and defuzzification methods in FSD modeling for risk analysis and contingency determination.

Preface

This thesis is an original work by Nasir Bedewi Siraj. The research project, on which this dissertation is based on, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Risk Assessment of Power Projects' Budgets Using Fuzzy Logic", Study ID: Pro00044029, approved on November 12, 2015. This research was funded by the Natural Sciences and Engineering Research Council of Canada Industrial Research Chair in Strategic Construction Modeling and Delivery (NSERC IRCPJ 428226–15), which is held by Dr. Aminah Robinson Fayek.

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Dedication

I dedicate this thesis to my mother, Hawa Shafi, to the memory of my father, Bedewi Siraj, my siblings, and my beloved wife, Muna Naser.

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First and foremost, I would like to express my gratitude to my supervisor, Dr. Aminah Robinson Fayek, for her guidance and unwavering support throughout my time as a graduate student. I have benefited from her great knowledge and expertise during my research, and her meticulous and instructive comments have always been helpful. I also want to extend my thanks to my doctoral committee members: Dr. Simaan Abourizk and Dr. Petr Musilek for their contribution and invaluable input during the course of my research.

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List of Abbreviations and Notations

Abbreviations

AACE	Association for the Advancement of Cost Engineering International
AC	Automation in Construction
AHP	Analytical hierarchical process
ANNs	Artificial neural networks
ANP	Analytic network process
ASCE	American Society of Civil Engineers
B&E	Building and Environment
BBN	Bayesian belief network
CII	Construction Industry Institute
CJCE	Canadian Journal of Civil Engineering
CLDs	Causal loop diagrams
CME	Construction Management and Economics
COA	Center of area
DEMATEL	Decision making trial and evaluation laboratory
DTA	Decision tree analysis
ECAM	Engineering, Construction and Architectural Management
ESA	Expert Systems with Applications

FAHP	Fuzzy analytical hierarchical process
FCD$^{©}$	Fuzzy Contingency Determinator$^{©}$
FCM	fuzzy cognitive maps
FMEA	Failure mode and effect analysis
FRBS	Fuzzy rule-based systems
FSD	Fuzzy system dynamics
FTA	Fault tree analysis
FWISM	Fuzzy weighted interpretive structural modeling
H	High
IJCM	International Journal of Construction Management
IJPM	International Journal of Project Management
IRM	Influence relation map
ISM	Interpretive structural modeling
ISO	International Organization for Standardization
JCCE	Journal of Computing in Civil Engineering
JCEM	Journal of Construction Engineering and Management
JCiEM	Journal of Civil Engineering and Management
JIS	Journal of Infrastructure Systems
JME	Journal of Management in Engineering

JRUES	Journal of Risk and Uncertainty in Engineering Systems
L	Low
LOM	Largest of maxima
M	Medium
MCS	Monte Carlo simulation
MF	Membership function
MOM	Middle of maxima
MW	Megawatt
N/A	Not applicable
P–I	probability–impact
PMI	Project Management Institute
RBS	Risk breakdown structure
SD	System dynamics
SMAPE	Symmetric mean absolute percentage error
SOM	Smallest of maxima
SWOT	Strengths, weaknesses, opportunities, and threats
T/A/K	Title, abstract, and keyword
TPPP	Transnational public-private-partnership
VH	Very high

VL	Very low

Notations

A_b	Forecasted monthly progress percentage of the bth work package
$\tilde{C}$	Fuzzy vector representing sum of columns of the fuzzy total-relation matrix
$\tilde{c}_j$	Effect of all other risk and opportunity events have on the jth risk and opportunity event
$C_{ib}^{(k)}$	Percentage of the bth work package cost affected by the ith risk and opportunity event assessed by the kth expert
C_{ib}	Aggregated percentage of the bth work package cost affected by the ith risk and opportunity event
D_b	Forecasted total work package cost of the bth work package
F_b	Forecasted monthly progress in dollars of the bth work package
I	Identity matrix
$\tilde{I}_{O_{ib}}^{(k)}$	Fuzzy number representing the opportunity impact of he ith risk and opportunity event on the bth work package assessed by the kth expert
$\tilde{I}_{O_{ib}}$	Aggregated fuzzy number representing the opportunity impact of he ith risk and opportunity event on the bth work package
$\tilde{I}_{R_{ib}}^{(k)}$	Fuzzy number representing the risk impact of he ith risk and opportunity event on the bth work package assessed by the kth expert

$\tilde{I}_{R_{ib}}$	Aggregated fuzzy number representing the risk impact of he ith risk and opportunity event on the bth work package
K_b	Relative weight of the work package in terms of its share to the total project cost
$\widetilde{NCD}^{PR}$	Net contingency in dollars of the project
$\widetilde{NCD}_b^{WP}$	Net contingency in dollars of the bth work package
$\widetilde{NCD}_{eb}^{RC}$	Net contingency in dollars of the eth risk category in the bth work package
$\widetilde{NS}_i$	Overall net severity percentage of the ith risk and opportunity events on a project
NS_i^{Def}	Defuzzified overall net severity percentage of the ith risk and opportunity events on a project
$\widetilde{NS}_{ib}$	Net severity percentage of the ith risk and opportunity event on the bth work package
NS_{ib}^{Def}	Defuzzified net severity percentage of the ith risk and opportunity event on the bth work package
$\widetilde{NSD}^{PR}$	Net severity in dollars of the project
$\widetilde{NSD}_b^{WP}$	Net severity in dollars of the bth work package
$\widetilde{NSD}_{eb}^{RC}$	Net severity in dollars of the eth risk category in the bth work package
$\widetilde{OCD}^{PR}$	Opportunity contingency in dollars of the project
$\widetilde{OCD}_{eb}^{RC}$	Opportunity contingency in dollars of the eth risk category in the bth work package
$\widetilde{OSD}^{PR}$	Opportunity severity in dollars of the project

$\widetilde{OSD}_b^{WP}$	Opportunity severity in dollars of the bth work package
$\widetilde{OSD}_{eb}^{RC}$	Opportunity severity in dollars of the eth risk category in the bth work package
$\tilde{P}_{O_{ib}}^{(k)}$	Fuzzy number representing the opportunity probability of he ith risk and opportunity event on the bth work package assessed by the kth expert
$\tilde{P}_{O_{ib}}$	Aggregated fuzzy number representing the opportunity probability of he ith risk and opportunity event on the bth work package
$\tilde{P}_{O_{jb}}^{*}$	Weighted opportunity probability of the jth posterior risk and opportunity event affected by the ith predecessor risk and opportunity events in the bth work package
$\tilde{P}_{R_{ib}}^{(k)}$	Fuzzy number representing the risk probability of he ith risk and opportunity event on the bth work package assessed by the kth expert
$\tilde{P}_{R_{ib}}$	Aggregated fuzzy number representing the risk probability of he ith risk and opportunity event on the bth work package
$\tilde{P}_{R_{jb}}^{*}$	Weighted risk probability of the jth posterior risk and opportunity event affected by the ith predecessor risk and opportunity events in the bth work package
Q_t	Defuzzified net project contingency predicted by the fuzzy system dynamics model
$\tilde{R}$	Fuzzy vector representing sum of rows of the fuzzy total-relation matrix
$\tilde{r}_i$	Total causal influence of the ith risk and opportunity event has on all other risk and opportunity events

$\tilde{R}_{ib}$	Fuzzy array representing the ith risk and opportunity event in the bth work package
$\widetilde{RCD}^{PR}$	Risk contingency in dollars of the project
$\widetilde{RCD}_{b}^{WP}$	Opportunity contingency in dollars of the bth work package
$\widetilde{RCD}_{b}^{WP}$	Risk contingency in dollars of the bth work package
$\widetilde{RCD}_{eb}^{RC}$	Risk contingency in dollars of the eth risk category in the bth work package
$\widetilde{RSD}^{PR}$	Risk severity in dollars of the project
$\widetilde{RSD}_{b}^{WP}$	Risk severity in dollars of the bth work package
$\widetilde{RSD}_{eb}^{RC}$	Risk severity in dollars of the eth risk category in the bth work package
$\tilde{S}_{O_{ib}}$	Opportunity severity of the ith risk and opportunity event on the bth work package
$\tilde{S}_{O_{jb}}^{*}$	Weighted opportunity severity of the jth posterior risk and opportunity event affected by the ith predecessor risk and opportunity events in the bth work package
$\tilde{S}_{R_{ib}}$	Risk severity of the ith risk and opportunity event on the bth work package
$\tilde{S}_{R_{jb}}^{*}$	Weighted risk severity of the jth posterior risk and opportunity event affected by the ith predecessor risk and opportunity events in the bth work package
T	Crisp total-relation matrix
$\tilde{T}$	Fuzzy total-relation matrix
t_d	Drastic *t*-norm
T^{Def}	Defuzzified total-relation matrix

$\tilde{t}_{ij}$	Total degree of causal influence of the ith risk and opportunity event on the jth risk and opportunity event
t_{ij}^{Def}	Defuzzified total degree of causal influence of the ith risk and opportunity event on the jth risk and opportunity event
$t_{(ij)b}^{Def}$	Defuzzified degree of causal influence of the ith predecessor risk and opportunity events on the jth risk and opportunity event in the bth work package
T_l	Crisp total-relation matrix of the lower bound values (l)
t_{Luk}	Lukasiewicz (bounded difference) t-norm
T_m	Crisp total-relation matrix of the mode values (m)
t_{min}	Minimum t-norm
t_{prod}	Product t-norm
T_u	Crisp total-relation matrix of the upper bound values (u)
V_t	The P50 and P95 project contingency estimated by Monte Carlo simulation or the defuzzified project contingency predicted by Fuzzy Contingency Determinator©
W_k	Importance weight of the kth expert
$\tilde{X}^{(k)}$	Initial fuzzy matrix assessed by the kth expert
$\tilde{X}^{C}$	Aggregated fuzzy direct-relation matrix
$\tilde{x}_{ij}^{(k)}$	Degree of causal influence of the ith risk and opportunity event on the jth risk and opportunity event as assessed by the kth expert

$\tilde{x}_{ij}^{C}$	Aggregated degree of causal influence of the *i*th risk and opportunity event on the *j*th risk and opportunity event
Z	Crisp normalized direct-relation matrix
$\tilde{Z}$	Normalized fuzzy direct-relation matrix
$\tilde{z}_{ij}$	Normalized degree of causal influence of the *i*th risk and opportunity event on the *j*th risk and opportunity event
Z_l	Crisp normalized direct-relation matrix of the lower bound values (l)
Z_m	Crisp normalized direct-relation matrix of the mode values (m)
Z_u	Crisp normalized direct-relation matrix of the upper bound values (u)
$\ominus$	Fuzzy subtraction
$\oplus$	Fuzzy addition
$\otimes$	Fuzzy multiplication

Chapter 1 Introduction[1]

1.1 Background

Studies confirm that construction is a highly risk-prone industry because of certain distinctive characteristics of construction projects (El-Sayegh and Mansour 2015; Zeng et al. 2007). Construction projects are characterized by their varying degrees of uniqueness and complexity, the active involvement of multiple stakeholders, capital intensiveness, dynamic environments, long production durations, and exposure to external environment and weather conditions (Taroun 2014). Such characteristics contribute significantly to the existence of high uncertainty and risk in construction projects. Risks and uncertainties are indeed inherent in every construction project from initiation through to completion—and even during the operation phase of the constructed facility—regardless of the size, nature, complexity, and location of the project. Failure to deal sufficiently with potential risks and uncertainties throughout the project life cycle can often have detrimental consequences on project objectives. Risk management, therefore, should be applied as an integral part of project management for the successful delivery of construction projects in terms of time, cost, quality, safety, and environmental sustainability (Zou et al. 2007).

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There are several definitions of risk in the literature, and the definitions vary based on the industry and context in which they are used. Risk is often defined in terms of uncertain events and their impact on project objectives. The Project Management Institute (PMI 2013) defines risk as “an uncertain event or condition that, if it occurs, has a positive or negative effect on a project’s objectives.” Most definitions of risk in the literature focus on the negative effect or risks (threats) and overlook the positive effect (opportunity). In this thesis, the definition proposed by PMI is adopted and the term “risk and opportunity event” is used to show both the positive and negative effects. While risk and uncertainty are considered distinct terms and concepts by some authors, others consider them to be synonymous. The International Organization for Standardization (ISO) defines uncertainty as the “state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood” (ISO 2009). In this thesis, risk is considered a concern if and only if an event or its effect is associated with a certain degree of uncertainty. According to Al-Bahar and Crandall (1990) and Lam et al. (2007), risk is characterized by three components: the risk event (what might happen to the detriment or in favor of the project), the uncertainty of the event (the chance of the event occurring), and the potential loss or gain (the consequence of the event happening).

The Association for the Advancement of Cost Engineering International (AACE International 2007) defines contingency as "an additional cost added to an estimate to allow for items, conditions, or events for which the state, occurrence, or effect is uncertain and that experience shows will likely result." The definition provided by AACE International, specifically focuses on a single project objective, i.e., cost that needs to be added on the base estimate. On the other hand, contingency is defined by Project Management Institute (PMI 2013) as “the amount of funds, budget, or time needed above the estimate to reduce the risk of overruns of project objectives to a level acceptable to the organization." For defined risks (known unknowns), contingency take the form of risk budget (risk allowance); whereas the unforeseen risks (unknown unknowns) are covered with "true contingency" (Hillson 1999). Despite the distinction between these two types of contingency, they are commonly used interchangeably. Contingency estimation, allocation, and management are vital for mitigating the risks and enhancing the opportunities associated with construction projects in order to deliver successful outcomes (Salah and Moselhi 2015). Without proper risk analysis and contingency determination, risk management and risk response planning strategies can be compromised; therefore, contingency needs to be accurately estimated, reasonably allocated, and wisely managed over the life of the project (Barraza et al. 2007; Salah and Moselhi 2015).

Risks in construction projects are extremely complex and highly dynamic, especially on large-scale projects. Moreover, substantial interrelationships exist among risks due to the interactions between internal and external environments throughout the lifecycle of the project (Nasirzadeh et al. 2008). The dynamic nature of risk and opportunity events and the causal interactions and dependencies among them have a considerable effect on risk analysis and contingency determination. Failing to account for these factors can lead to inaccurate contingency estimation, resulting in a budget deficit in the case of underestimation or the loss of bids and investment opportunities in the case of overestimation. If contingency is overestimated, there is a potential for mismanagement of excess contingency reserve.

1.2 Problem Statement

Risk identification and risk analysis are the most widely studied stages of risk management in the literature. As a result, various risk identification and risk analysis tools and techniques have been developed. However, there are still some gaps in risk identification and risk analysis research. The current gaps that will be addressed in this research are summarized in this section.

Risk identification is a critical stage in the risk management process, as it provides a basis for subsequent stages and ensures the effectiveness of risk management (Banaitiene and Banaitis 2012; Hwang et al. 2013; Zayed et al. 2008). Published literature is one of the main sources of information for identifying risks (both positive and negative) in construction projects. Researchers have previously identified numerous risks affecting construction projects, and these identified risks have been used for risk assessment, analysis, and modeling purposes. Although much effort has been expended on identifying risks from the literature, existing literature reviews are not exhaustive, they lack systematic analysis, and they are limited to only a few papers. Moreover, a detailed content analysis has not been done on articles that deal with risk identification tools and techniques, classification methods, and common risks in construction management. Thus, the ***first gap*** that will be addressed in this thesis is the lack of systematic review and content analysis of published articles related to risk identification in construction.

Most traditional quantitative risk analysis techniques and contingency determination methods fail to capture the complex interrelationships and causal interactions that exist among risks and do not account for the dynamic nature of construction risks that result from various feedback processes (Wang and Yuan 2017; Boateng et al. 2012; Nasirzadeh et al. 2008). In many studies, risks in a construction system are assessed and analysed 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; Ren 1994). Moreover, the existence of one risk may affect the probability and impact of other risks (Tavakolan and Etemadinia 2017). The cumulative impact of interrelated and interacting risks is different than the sum of the individual impacts of independent risks (Nasirzadeh et al. 2008). The probability of occurrence and impact of risk and opportunity events on work package and project cost change over time. However, traditional risk modeling and analysis approaches tend to focus on a static view of risks rather than considering the time-related behavior of risks. 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 (randomness) and non-probabilistic uncertainties (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. For instance, experts tend to assess the probability of occurrence and impact of risk and opportunity events as well as the causal relationships among them using linguistic terms (e.g., *low* and *high*) instead of using an exact numerical value. The subjective uncertainties resulting from linguistic approximation and measurement imprecision in risk assessment are best addressed with fuzzy logic. Therefore, the ***second gap*** that will be addressed in this thesis is the lack of dynamic risk analysis model capable of capturing the complex interrelationships and interactions among risk and opportunity events and the dynamic aspect of risks, for determining the work package and project contingencies by accounting for subjective uncertainties. A hybrid fuzzy system dynamics (FSD) model that combines the individual strengths of SD and fuzzy logic for analyzing the severity of interrelated and interacting risk and opportunity events and determining work package and project contingencies has been developed in this research. SD captures the interrelationship and interaction among risk factors and consider the highly dynamic nature of risks that results from various feedback processes involved throughout the lifecycle of a project. While, fuzzy logic captures the subjective uncertainty and imprecision of variables and/or parameters involved in risk analysis and contingency determination. Although several efforts have been made to integrate fuzzy logic and SD in various fields, the application of FSD in construction and specifically in risk analysis and contingency determination is limited.

The fundamental purpose of SD and FSD is to capture how the parts in a system interact with one another and how a change in one variable affects the other variable over time (Boateng et al. 2012; Nasirzadeh et al. 2008). Causal loop diagrams (CLDs) are employed in SD and FSD models to map interdependencies and causal structures among model variables. The literature reveals that there is a lack of structured and systematic methods for constructing CLDs to capture the causal relationships among risk and opportunity events. CLDs in SD and FSD models for risk analysis and contingency determination are commonly constructed based on modelers' assumptions and experts' verification (Wang and Yuan 2017; Boateng et al. 2012) or, alternatively, the conceptual foundations of the models are borrowed from other fields and modified to make them applicable for construction projects (Nasirzadeh et al. 2008; Nasirzadeh et al. 2014). Thus, the ***third gap*** that will be addressed in this research is the lack of structured and systematic method for constructing CLDs to capture the causal relationships among risk and opportunity events.

The variables involved in FSD models are categorized as objective and subjective (fuzzy) variables (Coyle 2000; Sterman 2000). Objective variables (e.g., remaining time, work done, production, etc.) have quantitative metrics and are readily quantifiable (Coyle 2000). Objective variables are defined by crisp numbers or probability distributions to capture randomness (probabilistic uncertainties). Subjective variables (e.g., familiarity with new techniques, workmanship of workers, crew motivation, adequacy of maintenance program, haul road condition, etc.) do not have numerical metrics or are qualitative in nature and better expressed linguistically (Coyle 2000; Sterman 2000). Subjective variables can be best described using membership functions, which characterize linguistic terms. Subjective variables represented by membership functions are incorporated in SD through the use of different approaches (Liu et al. 2011; Nasirzadeh et al. 2008; Sabounchi et al. 2011). However, these approaches are not practical when the number of subjective variables involved are large. Thus, the ***fourth gap*** that will be addressed in this research is the lack of methods for representing a large number of subjective (fuzzy) variables in FSD models for risk analysis and contingency determination.

In FSD, mathematical equations can contain both objective and subjective variables. Fuzzy arithmetic is utilized in FSD models instead of the classical arithmetic to carry out algebraic operations in a given mathematical equation to determine an intermediate or final output whenever a subjective (fuzzy) variable is involved, such as multiplying the probability and impact of a risk and opportunity event, both of which are expressed as a fuzzy number, to determine its severity. Basically, there are two methods for carrying out the fuzzy arithmetic operations: the alpha-cut (α-

cut) method and the extension principle method (based on *t*-norms). The type of fuzzy arithmetic method and choice of fuzzy operators such as *t*-norm have a considerable effect on the output of FSD model. The α-cut method is the most commonly used arithmetic method in FSD models. However, the α-cut method is based on interval arithmetic, which can lead to phenomenon of accumulating fuzziness (due to growth of the support) and the overestimation of the uncertainty in FSD model (Chang et al. 2006). Recently, Gerami Seresht and Fayek (2018) explored the implementation of fuzzy arithmetic operations by both the α-cut and extension principle methods in FSD model to determine the multi-factor productivity of equipment intensive activities. Implementing the extension principle method in FSD models for risk analysis and contingency determination helps to address the over estimation of uncertainty due to the use of α-cut method. Therefore, the ***fifth gap*** that will be addressed in this research is the lack of research on implementation of fuzzy arithmetic by the extension principle method in FSD models for risk analysis and contingency determination.

1.3 Research Objectives

The hypothesis of this research is as follows:

Construction risks and opportunities can effectively be modeled and analysed using FSD to determine work package and project contingency by accounting for causal interactions between risks and opportunities, dynamic nature of risks and opportunities that results from various feedback processes, and subjective uncertainty of experts in assessing risks and opportunities.

The main objective of this research is to develop a hybrid FSD model to analyse the severity of interrelated and interacting risk and opportunity events on work package cost and determine work package and project contingency. The detailed objectives of this research are grouped under the following five main categories:

1. To examine common risk identification tools and techniques, risk classification methods, and common risks affecting construction projects through systematic review and detailed content analysis.

2. To provide a systematic fuzzy-based risk assessment and prioritization procedure, which incorporates opportunity in the assessment and accounts for differing levels of expertise in risk management based on a comprehensive set of expert qualification attributes.

3. To provide a hybrid FSD modeling approach for capturing the causal interactions and dependencies among risk and opportunity events and quantifying their severity on work package and project cost.

4. To offer a risk analysis and contingency determination approach based on subjective evaluation and experience, which is complementary to traditional deterministic and probabilistic methods, and to demonstrate how risk analysis can be improved using fuzzy logic and SD.

1.4 Expected Contributions

The expected contributions of this research are categorized as academic contributions and industrial contributions based on their relevance to academic researchers and construction industry practitioners, respectively.

1.4.1 Academic Contributions

The expected academic contributions of this research are as follows:

1. Providing a systematic and in depth content analysis of published articles related to risk identification in construction; and a useful reference on common potential risks affecting construction projects for future risk identification, analysis, and modeling purposes.
2. Providing a systematic fuzzy-based risk assessment and prioritization procedure, which uses linguistic scales represented by fuzzy numbers to assess probability and impact of risks; incorporates opportunity in the assessment; allows risk assessment at the work package level; and accounts for differing levels of expertise in risk management based on a comprehensive set of expert qualification attributes.
3. Providing an approach, using hybrid FSD modeling, that can consider the dynamic causal interactions and dependencies between risks (opportunities) and quantify their severity on work package cost and consequently determine work package and project contingency by using expert judgement, linguistic scales, and fuzzy numbers.
4. Contributing to the advancement of the state of the art in FSD modeling for risk analysis and contingency determination by
    a) providing a structured and systematic method that uses linguistic terms for constructing CLDs;
    b) providing a method for handling subjective uncertainty in FSD;
    c) implementing fuzzy arithmetic methods (both α-cut and extension principle based on drastic *t*-norm) in FSD to carry out algebraic operations in mathematical equations involving fuzzy variables.

1.4.2 Industrial Contributions

The expected industrial contributions of this research are as follows:

1. Providing a useful reference on common potential risks affecting construction projects for future risk identification, analysis, and modeling purposes through systematic review and content analysis of published articles.
2. Providing a risk modeling and analysis approach that allows construction industry practitioners to assess risks and opportunities by using subjective evaluation and experience.
3. Providing a hybrid FSD modeling approach to understand the dynamic causal interactions and dependencies among risks; quantify and track their severity on work package cost; and determine work package and project contingency.

1.5 Research Methodology

A brief description of the four main stages followed in this research to achieve the objectives listed in Section 1.3 are provided in this section.

1.5.1 The First Stage

The research commenced by conducting comprehensive state of the art review on processes entailed in risk management in general, with a specific focus on risk identification and risk analysis. Past studies focusing on hybrid fuzzy techniques, SD, and FSD for risk analysis and contingency determination were closely examined to identify the research gaps outlined in Section 1.2. After conducting the literature review, the main theoretical framework of the research and rationale for selecting the FSD modeling approach for risk analysis and contingency determination were established.

1.5.2 The Second Stage

In the second stage of this research, a systematic review and detailed content analysis of 130 selected articles from 14 well-regarded academic journals in construction engineering and management published between 1990 and 2017 was conducted. Common risk identification tools and techniques and risk classification methods used in the construction risk management process were investigated. A comprehensive and structured classification method is proposed based on the existing category names in the selected articles. Also, common potential risks that affect construction projects were identified from the selected articles; categorized based on the nature of the risks; and ranked based on their frequencies, i.e., the total number of references (hits) each risk had.

1.5.3 The Third Stage

In the third stage of this research, data collection forms were designed to determine the expertise level of the research participants in risk management based on certain qualification attributes; to assess the project and work package characteristics; to identify and assess potential risks/opportunities affecting the selected work packages; and to establish causal relationship among prioritized risks/opportunities. A candidate project and work packages were selected for the research through a meeting in the presence of senior management staff from the participating company. Then, data collection was carried out initially and at different percentage completion of the work packages. A systematic risk assessment and prioritization procedure was established and the identified risks were then assessed and prioritized based on their net severity percentage.

1.5.4 The Fourth Stage

In the fourth stage, the FSD model was developed in two phases: (i) development of CLDs and the qualitative model to establish the causal interactions and dependencies among risk and opportunity events and (ii) development of the quantitative model to quantify the severity of prioritized risk and opportunity events on work package and project cost contingency. A structured and systematic method, based on fuzzy DEMATEL (decision making trial and evaluation laboratory) (Jalal and Shoar 2017; Can and Toktas 2018; Ghassemi and Darvishpour 2018), was used to construct the CLDs from the experts' causal relationship assessments. In developing the quantitative model, the objective and subjective (fuzzy) variables of the FSD model was identified. The subjective variables of the FSD model were represented using membership functions. Mathematical equations were developed to define the relationships between risk and opportunity events and to calculate the values of flow and stock variables in the FSD model. Methods for incorporating both α-cut method and extension principle based on drastic *t*-norm in FSD model were explored to carry out fuzzy arithmetic operations in mathematical equations involving fuzzy variables. The qualitative and quantitative FSD models were implemented using AnyLogic® simulation software. A fuzzy arithmetic class was developed using the Java programing language and imported to the quantitative FSD model in AnyLogic® for performing fuzzy arithmetic operations as well as for determining the contingency values using defuzzification methods and confidence levels. Finally, the qualitative and quantitative FSD models were validated by conducting structural and behavioral validations. 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 behavioral validation, the performance of The FSD model was evaluated by implementing it using actual project case study and the results were compared against contingency values obtained from Monte Carlo simulation (MCS) and Fuzzy Contingency Determinator© (FCD©) (Elbarkouky et al. 2016), both of which determine project contingency by considering risk events to be independent and static.

1.6 Thesis Organization

Chapter 1 presents a brief background of the research, the problem statement, and objectives of this research. The expected academic and industrial contributions and the research methodology are also provided in this chapter. The rest of this thesis is organized as follows.

Chapter 2 presents an overview of processes entailed in risk management and the conventional risk analysis and contingency determination techniques commonly used in construction domain with their advantages and drawbacks. In addition, state of the art review on hybrid fuzzy risk analysis and contingency determination methods, SD, and FSD is presented and limitations are identified.

Chapter 3 presents the methodology, results, and discussions of a systematic review and detailed content analysis of 130 articles related to risk identification published in 14 well-regarded academic journals in construction engineering and management between 1990 and 2017. This chapter also presents the proposed comprehensive and structured risk classification method and a list of systematically categorized and ranked common risks affecting construction projects based on the content analysis of the selected articles. The proposed classification method and the identified risks were used as input to develop the data collection forms and the qualitative and quantitative FSD models in the subsequent chapters.

Chapter 4 presents the overall methodology and the detailed steps for developing the hybrid FSD model to analyse the severity of prioritized risk and opportunity events on work package cost and determine work package and project contingencies. This chapter, describes the method adopted to assess the experts' expertise level and determine importance weight of experts. Also, a systematic risk assessment and prioritization procedure is presented. This chapter discusses the fuzzy DEMATEL method proposed to construct the CLDs in the qualitative model development stage. Moreover, the mathematical procedure used in the FSD model to determine the work package and project contingency as well as implementation of the fuzzy arithmetic methods are described.

Chapter 5 describes the application of the proposed FSD modelling methodology for analyzing the risk and opportunity events and determining the work package and project contingencies of a selected case study. The work package and project cost contingency results of the dynamic simulation of the FSD model based on α-cut method and drastic *t*-norm are presented and discussed. The structural and behavioral validation tests used for validating the FSD models are also presented in this chapter.

Chapter 6 presents the conclusions, contributions, and limitations of this research along with recommendations for future research.

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Chapter 2 Literature Review[2]

2.1 Introduction

This chapter aims to provide the background and pertinent information related to this research by conducting state of the art review on processes entailed in risk management, with a specific focus on risk identification and risk analysis. Also, this chapter presents the main theoretical framework of the research and the rationale for selecting the proposed risk analysis and contingency determination method. In the following sections, a brief background on risk management is provided. An overview of risk identification process is presented, along with a review of tools and techniques used for risk identification and methods employed for risk classification in construction projects. A background on deterministic, probabilistic, and fuzzy-based risk analysis and contingency determination is provided and limitations are identified. Some of the hybrid fuzzy methods available for risk analysis and contingency determination in construction are discussed and their limitations are established. The concept of system dynamics (SD) and fuzzy system dynamics (FSD) and their applications in construction risk management is presented. Moreover,

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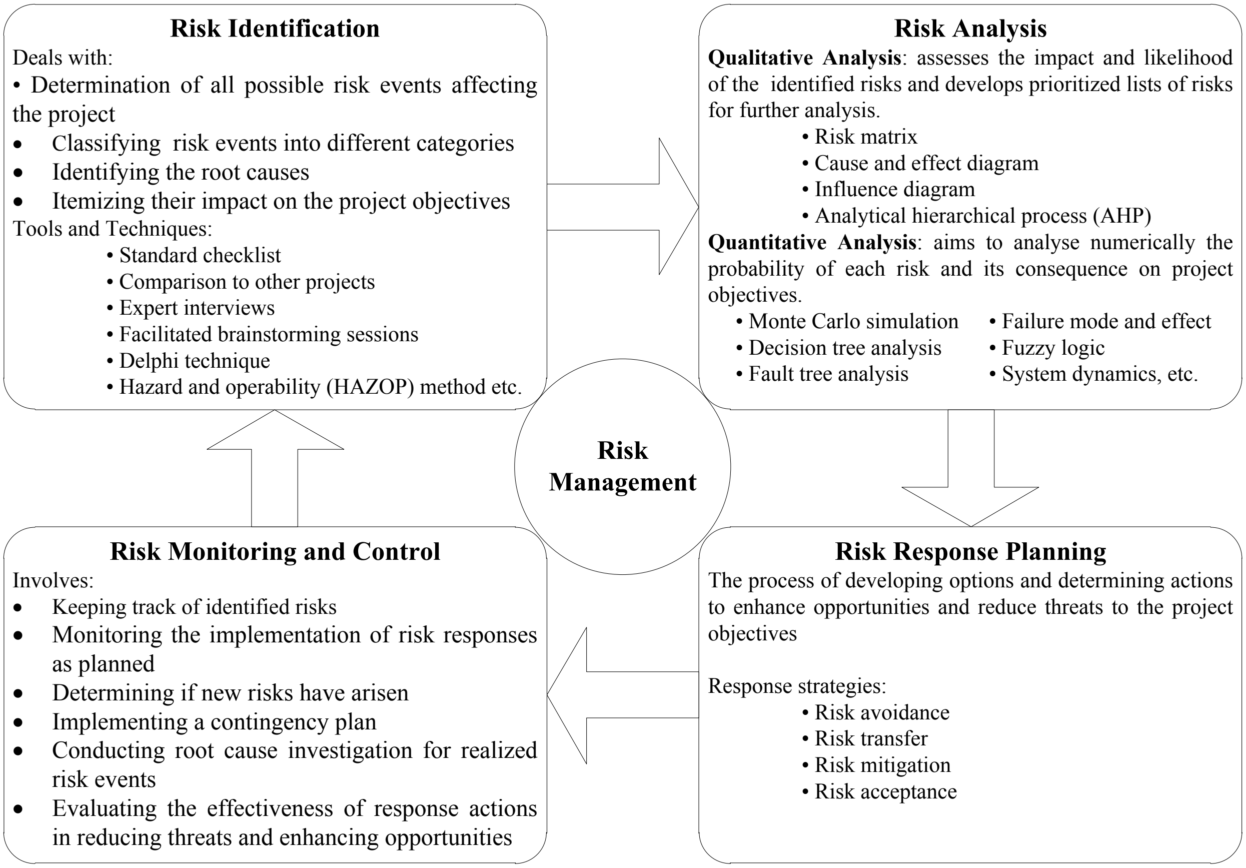
the limitations of conventional SD and FSD models for risk analysis and contingency determinations are highlighted.

2.2 Risk Management

Risk management is an important and integral part of project management that aims to identify the source of risks and uncertainties, quantify their likelihood of occurrence and effects, and manage them to prevent harmful effects and maximize opportunities to achieve project objectives such as cost, time, quality, and safety (Gray and Larson 2003). Wide range of standards, guidelines and best practices are currently available for risk management around the world. The most widely known, distributed, and used guidelines and approaches for risk management include Project Management Institute's (PMI) PMBOK® Guide; Construction Industry Institute's (CII) Implementation Resource 280-2; International Organization for Standardization's (ISO) 3100:2009; and Association for the Advancement of Cost Engineering International's (AACE International) guide to contingency. Despite the presence of several approaches to risk management procedures, risk management process generally entails a framework for risk identification, risk analysis, risk response planning, and risk monitoring and control (Figure 2.1). Project risk management is an iterative process: the process is beneficial when it is implemented in a systematic manner throughout the lifecycle of a construction project, from the planning stage to completion (Banaitiene and Banaitis 2012). Figure 2.1 depicts the processes in risk management.



Risk Identification

Deals with:

- Determination of all possible risk events affecting the project
- Classifying risk events into different categories
- Identifying the root causes
- Itemizing their impact on the project objectives

Tools and Techniques:

- Standard checklist
- Comparison to other projects
- Expert interviews
- Facilitated brainstorming sessions
- Delphi technique
- Hazard and operability (HAZOP) method etc.

Risk Analysis

Qualitative Analysis: assesses the impact and likelihood of the identified risks and develops prioritized lists of risks for further analysis.

- Risk matrix
- Cause and effect diagram
- Influence diagram
- Analytical hierarchical process (AHP)

Quantitative Analysis: aims to analyse numerically the probability of each risk and its consequence on project objectives.

- Monte Carlo simulation
- Decision tree analysis
- Fault tree analysis
- Failure mode and effect
- Fuzzy logic
- System dynamics, etc.

Risk Management

Risk Monitoring and Control

Involves:

- Keeping track of identified risks
- Monitoring the implementation of risk responses as planned
- Determining if new risks have arisen
- Implementing a contingency plan
- Conducting root cause investigation for realized risk events
- Evaluating the effectiveness of response actions in reducing threats and enhancing opportunities

Risk Response Planning

The process of developing options and determining actions to enhance opportunities and reduce threats to the project objectives

Response strategies:

- Risk avoidance
- Risk transfer
- Risk mitigation
- Risk acceptance

Figure 2.1. Project risk management process (adapted from Abourizk 2008)

Risk identification is the process of systematically and continuously identifying possible risks and their potential consequences on a project using different risk identification tools and techniques, classifying the risks into different categories, identifying their root causes, and documenting the characteristics of each risk (Banaitiene and Banaitis 2012; Al-Bahar and Crandall 1990). In some cases, primary risk responses may also be identified at the risk identification stage. Risk identification tools and techniques and risk classification methods used in construction projects are discussed in section 2.3.

Abourizk (2008) described risk analysis as "*the process of quantifying the factors of identified risks to estimate the likelihood and magnitude of their impact or consequence*," in order to plan the proper risk responses and allocate proper contingency values to the project's cost elements or work packages. Risk analysis is an essential link between systematic identification of potential risks and rational management of the critical risks. Risk analysis generally can be carried out using qualitative and/or quantitative analysis depending on the information available and the level of detail required. Qualitative risk analysis assesses the likelihood and impact of identified risks based on descriptive or nominal scales and develops prioritized lists of risks for further analysis or direct mitigation (Banaitiene and Banaitis 2012; PMI 2013). Qualitative analysis is mainly used in an initial evaluation of risks or for a quick assessment. Risk matrix, influence diagrams, probability-impact risk rating tables, and analytical hierarchical process (AHP) are some of the specialised techniques available to examine risks in this manner (Abdelgawad 2011; Banaitiene and Banaitis 2012). In quantitative risk analysis, the frequency of risks and the magnitude of their severity are quantified using different techniques, such as Monte Carlo simulation (MCS), decision tree analysis (DTA), fault tree analysis (FTA), failure mode and effect analysis (FMEA), fuzzy logic, and system dynamics (SD). Better decision-making abilities are attained by using quantitative analysis when dealing with uncertainty. Further discussion on risk analysis and contingency determination methods is provided in section 2.4.

Risk response planning is "*the process of developing options and determining actions to enhance opportunities and reduce threats to the project objectives*" (PMI 2013). Risk response planning ensures that suitable actions are taken and the identified risks are properly addressed. The response strategies are assigned based on the nature and potential consequences of the key identified risks and the party best able to manage the risks (Al-Bahar and Crandall 1990). The alternative response strategies are determined by conducting workshop sessions or from historical data. Risk avoidance, risk transfer, risk mitigation, and risk acceptance are the most widely used alternative strategies in treating risks in construction projects (Banaitiene and Banaitis 2012). Risk avoidance deals with eliminating uncertainty associated with risk events, based on the source of risk. Risk transfer is concerned with shifting the consequences of a risk event and responsibility for its management to another party through insurance or contracts. Risk mitigation deals with reducing the probability and/or impact of an adverse risk event to an acceptable level, i.e., acceptability threshold (PMI 2013). Risk acceptance is the last resort available for residual risks that remain after the other response strategies have been taken. Most of the standards, guidelines and best practices commonly used for risk management do not incorporate response strategy for addressing opportunity (positive risk). Hillson (2001) presented structured response strategies for opportunity such as exploit, share, enhance, and ignore, which are extended from the four common risk response strategies.

Risk monitoring and control, the final stage of risk management, is vital to keep a rigorous check on the implementation of risk identification, risk analysis, and risk responses. Risk monitoring and control involves keeping track of the identified risks and monitoring the implementation of risk responses as planned. Risk monitoring and control is an ongoing process throughout the life of the project and determines if new and secondary risks have arisen. It also involves implementing a contingency plan and conducting root cause investigation for realized risk events. Moreover, it requires evaluating the effectiveness of response actions in reducing threats and enhancing opportunities and ensuring that risk policies and procedures are followed (Abdelgawad 2011; ISO 2009; PMI 2013). Tools and techniques frequently employed for risk monitoring and control include risk reassessment, risk response audits, periodic project risk reviews, earned value analysis, reserve analysis, and technical performance measurement (PMI 2013).

2.3 Risk Identification

2.3.1 Background on Risk Identification Process

Risk identification is the first and possibly the most important stage in the risk management process because subsequent stages can only be performed on potential risks that have been identified (Banaitiene and Banaitis 2012; Hwang et al. 2013; Zayed et al. 2008). Risk identification is an iterative and continuous process. It should be carried out rigorously on a regular basis throughout the project life cycle, as new risks may appear and previously identified risks may cease to exist (PMI 2013). The risk identification process should equally focus on the identification of positive risks or opportunities, which have beneficial effects on project objectives (Hillson 2002). However, common practice is to concentrate more on the identification and management of negative risks, and opportunities tend to be overlooked or addressed reactively (Hillson 2002). El-Sayegh (2008) pointed out that attempting to identify all potential risks for a construction project is laborious, counterproductive, and impractical. Hence, the focus should be on the identification of the most critical and frequently occurring risks.

Risk identification is a process of discovery, and thus it calls for creative thinking, imagination, and leveraging project team experience and knowledge (Chapman and Ward 2003). According to Mojtahedi et al. (2010) and PMI (2013), the identification of risks in construction projects requires the participation of project stakeholders, project team members, the risk management team (if assigned), subject matter experts who are not members of the project team, project managers of other projects, and risk management experts, depending on the type of project. Involving the project team in the risk identification process can develop and maintain a sense of ownership and responsibility for identified risks and their respective response strategies (PMI

2013). In addition to the involvement of combinations of experts and stakeholders, inputs and sources of information such as historical project data, published literature on risk, standard checklists, risk breakdown structures, and risk registers facilitate the identification of risks and contribute to the comprehensiveness of the risk identification process. Tools and techniques and classification methods involved in the risk identification process for construction projects are discussed below.

2.3.2 Risk Identification Tools and Techniques

In the literature, risk identification is one of the most widely studied stages of risk management. As a result, a wide array of tools and techniques exist for risk identification. These tools include documentation reviews; information-gathering techniques (brainstorming, the Delphi technique, interviewing, root cause analysis, questionnaires, risk workshops); checklist analysis; assumption analysis; diagramming techniques (cause-and-effect diagrams, system or process flow charts, influence diagrams); strengths, weaknesses, opportunities, and threats (SWOT) analysis; expert judgment; fault tree analysis; decision tree analysis; and failure mode and effect analysis (Grimaldi et al. 2012; Marle and Gidel 2012; PMI 2013). Hillson (2002) suggested that an appropriate combination of tools and techniques should be employed in risk identification, as there is no single "best method." The selection of appropriate tools and techniques for risk identification requires taking into account criteria such as project phase; complexity of the project; availability of skilled personnel familiar with the risk identification tools and techniques; risk maturity of the organization; the approach (analogical, heuristic, or analytic) to be applied for risk identification; and simplicity of use, interaction considerations, and completeness of the tools and techniques (Grimaldi et al. 2012; Marle and Gidel 2012). Despite the availability of several risk identification tools and techniques, only a few are frequently used in the construction industry. Based on an investigation conducted by Lyons and Skitmore (2004), brainstorming, case-based approaches, and checklists are the most commonly used risk identification techniques. Irrespective of the tools and techniques used to identify risks on a project, the main outputs of the identification process are presented in the risk register. The risk register contains detailed information on the identified risks, and it can help the project team assess, review, track, mitigate, and control project risks periodically throughout the project life cycle. Additionally, a well-documented risk register can be a useful reference for future risk identification and the main source of information for developing a risk knowledge database.

2.3.3 Risk Classification Methods

Risk classification (or categorization) is an integral part of risk identification. It helps the project team structure the diverse and varied risks that may affect a construction project. The structured classification of risks contributes to the effectiveness and quality of the risk identification process and creates a better understanding of the nature of risks and their sources (Bu-Qammaz et al. 2009). Moreover, a logical and structured classification of risks assists in the reduction of redundancy and ambiguity in the risk identification stage and provides for easier management of risks in the later stages of risk management. In the literature, various approaches have been recommended for classifying risks on construction projects. Some of the approaches adopt a broad categorization, while others use categories that are more detailed. Risks can be categorized based on their source, nature, occurrence at different stages of the project, impact on project objectives, the party who might be the originator of the risk, and a three-level meta-classification approach (macro-, meso-, and micro-level).

Using the initial source of risks as a basis, Al-Sabah et al. (2014), El-Sayegh and Mansour (2015), and Tah and Carr (2000) classified risks into two main categories: internal risks (those that are project-related and that usually fall under the control of the project management team) and external risks (those risks that are beyond the control of the project management team). Each author partitioned these main categories (internal and external) into detailed subcategories according to the nature and type of the projects. Several researchers, including Boateng et al. (2012), Elbarkouky et al. (2016), and Tavakolan and Etemadinia (2017), used the nature of risks as the criteria for classifying risks into distinct groups. For example, Tavakolan and Etemadinia (2017) classified risks into nine groups: financial, contractual, design, health and safety, management, construction, social/political, external, and procurement/supply. Goh et al. (2013), Lee and Schaufelberger (2014), and Li and Zou (2011) categorized risks based on the project stage at which the risks would occur. For example, Goh et al. (2013) categorized risks into five groups: planning, design, procurement, construction, and hand over stage risks. Zou et al. (2007) categorized risks into five groups based on their respective impact on project objectives: cost-, time-, quality-, environment-, and safety-related risks. Such categorization may result in redundancy, as a single risk may have an impact on more than one project objective. According to the party who might be the originator of the risk, Wang and Yuan (2017) classified risks into five groups: client-, designer-, contractor-, subcontractor-, and authority-related risks. Bing et al. (2005) and Hwang et al. (2013) adopted a three-level meta-classification approach and grouped risks into macro-level risks (risks beyond the system boundaries of the project), meso-level risks (risks within the system boundaries of the project and directly related to the nature of the project), and micro-level risks (risks that are project party-related, that is, risks associated with the relationships between the parties involved in the project).

According to Ebrahimnejad et al. (2010), the classification of risks based on either the source or the nature of those risks are the most widely used methods for risk identification on construction projects. Risk classification methods selected for construction projects may differ based on the type of project, the type of procurement method employed, and the project party conducting the risk identification and assessment. Regardless of the categorization scheme adopted, the various categories of risks are organized and presented using a risk breakdown structure (RBS). According to PMI (2013), an RBS is defined as "a hierarchically organized depiction of the identified project risks arranged by risk category and subcategory that identifies the various areas and causes of potential risks." RBSs show the risk categories and sub-categories within which risks may arise as well as the risks at the lowest level for risk identification, assessment, mitigation, and reporting purpose.

2.4 Overview of Risk Analysis and Contingency Determination Methods

Currently available methods for analyzing risk and estimating contingency can be categorized into four groups: deterministic, probabilistic, fuzzy-based, and hybrid methods (Salah and Moselhi 2015). The selection of risk analysis and contingency determination methods depend on type and size of the project; project phase; availability of information; level of detail and accuracy required; the cost and time available for risk analysis; the extent of innovation and ultimate use of the risk analysis; experience and availability of risk analyst; and simplicity of use, interactions considerations, and completeness of the risk analysis and contingency determination method to be used (Goh and Abdul-Rahman 2013; Grimaldi et al. 2012; Marle and Gidel 2012).

A deterministic figure or value which comprises of the base estimate and a certain percentage addition for contingency has been adopted for long in the construction industry for cost budgeting purpose without detail investigation of risks and uncertainties that could occur in the project (Mak and Picken 2000). Deterministic methods, such as the probability-impact matrix proposed by the Construction Industry Institute (CII) (2012), assess the probability and impact of risks using a single-point estimate or linguistic expressions, and the risks are categorized based on risk severity. Deterministic methods are known for their simplicity and transparency, but they fail to account for subjective and probabilistic uncertainties, resulting in a low degree of accuracy in contingency estimation (CII 2012; Elbarkouky et al. 2016).

Probabilistic methods capture the uncertainties associated with risk and opportunity events using probability theory instead of adopting deterministic values. These methods comprise Monte Carlo simulation (MCS), decision tree analysis (DTA), fault tree analysis (FTA), failure mode and effect analysis (FMEA), and Bayesian belief network (BBN) (Islam et al. 2017). MCS is the most widely used probabilistic method for risk analysis and contingency determination in the construction domain (Salah and Moselhi 2015; Sadeghi et al. 2010). Despite their wide application and easy implementation, probabilistic methods heavily rely on large historical data sets to define probability density functions and are incapable of modelling subjective uncertainty (Salah and Moselhi 2015).

Fuzzy-based risk analysis and contingency estimation methods rely on fuzzy logic, which deals with reasoning that is approximate rather than exact or precise. The basis of fuzzy logic is fuzzy set theory, wherein an object belongs to different classes/subsets of the universal set with unsharp boundaries, and membership is a matter of degree of belongingness in the set. In fuzzy set theory, the partial belongingness to a set is described numerically using a membership function (MF), which assumes values between 0 and 1, inclusively, for each element in the set. Moreover, the MFs can be represented by linguistic terms to signify a given concept (e.g., “very high” or “low”). Linguistic variables are widely used in fuzzy logic to capture the imprecision, vagueness, and subjectivity inherent in human cognitive processes. Fuzzy logic is therefore suitable to assess the probability and impact of risk events and to capture the interrelationship between risk events using linguistic terms in the absence of historical data. Thus, it addresses the data reliance challenges of probabilistic methods and deals with the adoption of imprecise crisp values to assess risk and opportunity events in deterministic methods (Islam et al. 2017; Elbarkouky et al. 2016). Complexity, long processing times associated with soliciting expert opinions and establishing membership functions and rules, and the difficulty of choosing appropriate fuzzy arithmetic operations and defuzzification methods are some of the drawbacks of fuzzy-based methods (Shaheen et al. 2007; Elbarkouky et al. 2016; Abdelgawad 2011).

Hybrid methods combine the strengths of two or more methods to overcome the shortcomings associated with deterministic, probabilistic, and fuzzy-based methods when used alone. Hybrid fuzzy methods are combinations of fuzzy and other methods. In this chapter, only fuzzy hybrid methods that integrate fuzzy logic with methods capable of determining the root causes of risks or methods capable of capturing the interrelationships and interactions among risks are discussed. A more detailed discussion on other types of hybrid fuzzy methods for risk analysis can be found in Islam et al. (2017).

Abdelgawad and Fayek (2011) and Ardeshir et al. (2014) integrated fuzzy logic and fault tree analysis (FTA). FTA provides an excellent visual representation of the events that lead to risks and offers a proactive tool for identifying and controlling their root causes (Abdelgawad and Fayek 2011; Ardeshir et al. 2014). In other studies, efforts have been made to combine fuzzy logic and failure mode effect analysis (FMEA) for analyzing risks on construction projects (Abdelgawad and Fayek 2010; Mohammadi and Tavakolan 2013). FTA and FMEA determine the root causes of risks and their effects; however, both techniques focus on single risks and are unable to model the complex interactions among different risks, nor do they support a cyclic graph structure (Fang and Marle 2012). Moreover, FTA and FMEA are only used to prioritize risk events for corrective actions and do not quantify the contingency amount.

In an effort to overcome the drawbacks of traditional analytic network process (ANP) in risk analysis, Lin and Jianping (2011) and Valipour et al. (2015) hybridized ANP with fuzzy logic. In fuzzy ANP, pairwise comparison between risk categories and among risks in a category is conducted using fuzzy linguistic terms or fuzzy numbers and a network model showing interdependency is constructed (Islam et al. 2017). The lengthy and laborious pairwise comparison process, computational complexity, and the inability to intoduce new information into the risk structure are the major drawbacks of fuzzy ANP. In a recent study, Islam and Nepal (2016) proposed a method based on the combination of Bayesian belief network (BBN) and fuzzy logic for risk assessment on power plant projects. Fuzzy BBN can model interdependent risks, deal with uncertainty and subjective judgements, and update probabilistic information in the risk network when new data become available. Nonetheless, fuzzy BBN is not capable of modeling feedback loops as it is inherently acyclic (Fang and Marle 2012).

Case and Stylios (2016) developed a model based on fuzzy cognitive map (FCM) to evaluate overall project success by considering the causal relationships among key risks on construction projects. FCM modeling captures the complex causal relationships between risks that involve feedback, possesses learning capabilities, and helps to capture mental models of experts

(Lazzerini and Mkrtchyan 2011). However, classic FCM modelling suffers from drawbacks such as the lack of a time concept (dynamism), the assumption of linear causal relations between risks, and the inability to model uncertainty, and it is incapable of representing conditional relationships or rule-based knowledge (Lazzerini and Mkrtchyan 2011). Tavakolan and Etemadinia (2017) proposed fuzzy weighted interpretive structural modeling (FWISM) to explore the influence of and dependence among risk factors in construction. The FWISM method systematically and efficiently models the interactions among risks in a category and uses linguistic terms represented by triangular fuzzy numbers to assess the degree of interaction. However, the FWISM method does not quantify the impact of risks on project objectives, does not consider the interactions among risks that belong in different risk categories, and is unable to deal with the dynamic and time-related behaviour of risks. Table 2.1 presents advantages and drawbacks of hybrid fuzzy risk analysis and contingency determination methods.

Table 2.1. Advantages and drawbacks of hybrid fuzzy risk analysis and contingency determination methods

Method and References	Advantages	Drawbacks
Fuzzy FTA Abdelgawad and Fayek (2011); Ardeshir et al. (2014)	▪ Easy with prioritizing risks for effective mitigation strategies ▪ Good visual representation ▪ Easy to control root causes before occurrence of risk events ▪ Allows expert to assess probability of occurrence using linguistic terms	▪ Tedious to construct fault tree for large systems ▪ Difficult to capture all scenarios ▪ Later changes impact the entire tree ▪ Subjective decisions for the level of detail and completeness ▪ Difficult to model correlation between risks ▪ Does not support cyclic graph structure
Fuzzy FMEA Abdelgawad and Fayek (2010); Mohammadi and Tavakolan (2013)	▪ Helps to take necessary and timely corrective actions ▪ Allows systematic and comprehensive establishment of relationship between failure	▪ Inability to deal with multiple failure scenarios ▪ Significant effort is needed to establish clearly defined terms ▪ Trivial cases might be considered

Method and References	Advantages	Drawbacks
	causes and effects ▪ The failure modes are determined based on three dimensions ▪ Linguistic terms are used to assess input and output parameters	▪ Large number of rules required to determine the risk probability number ▪ Only used for prioritizing risks for corrective actions ▪ Does not support cyclic graph structure
Fuzzy ANP Lin and Jianping (2011); Valipour et al. (2015)	▪ Easy to understand ▪ Captures relationships between risk events belonging in different risk categories ▪ Captures both subjective and objective measures	▪ Lengthy and laborious pairwise comparison process ▪ Computational complexity ▪ Inability to update new information into the risk structure ▪ Does not support cyclic graph structure
Fuzzy BBN Islam and Nepal (2016); Fang and Marle 2012	▪ Capture complex and uncertain relationships between risks ▪ Deals with uncertainty and subjective judgements ▪ Captures both subjective and objective measures ▪ Updates probabilistic information in the risk network when new data becomes available	▪ Not capable of modeling feedback loops ▪ Fail to consider the dynamic nature of risks
FCM Case and Stylios (2016); Lazzerini and Mkrtchyan (2011)	▪ Models complex causal relationships between risks involving feedbacks ▪ Possesses learning capability ▪ helps to capture mental model of experts	▪ Lack of time concept (dynamism) ▪ Assumption of linear causal relations between risks ▪ Inability to model uncertainty ▪ Inability to represent conditional relationships or rule-based knowledge
FWISM Tavakolan and Etemadinia (2017)	▪ Models the interactions among risks in a category ▪ Uses linguistic terms to assess the degree of interactions ▪ Allows grouping of risks into independent, linkage, dependent, and autonomous clusters ▪ Good visual representation	▪ Does not quantify the impact of risks on project objectives ▪ Does not consider the interactions among risks belonging in different risk categories ▪ Unable to deal with the dynamic and time-related behaviour of risks

With exception of FCMs, the hybrid fuzzy methods discussed above are incapable of modeling the causal loops (i.e., feedback loops) that exist among risk and opportunity events because these methods are inherently tree-like or acyclic graph structures. These methods also fail to fully capture the complex causal relationships and time-varying interactions among interdependent variables and multiple feedback processes in a system. To address these shortcomings, efforts have been made to integrate fuzzy logic and SD, which are discussed in the following section.

2.5 Fuzzy System Dynamics

2.5.1 General Background on System Dynamics

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 behaviour of complex social systems in the industrial domain (Sterman 2000). Since its introduction, SD has been widely applied to model the dynamics of complex and non-linear systems in various fields of research. SD enables decision- and policy-makers in various fields to solve complex problems, improve decision making, examine different strategies, and formulate policies. Alzraiee et al. (2015) stated that SD is well suited for modeling problems that are broad in details, holistic in perspective, continuous in behaviour, and qualitative and quantitative in nature. As a top-down modeling approach, SD first models the system at the macro-level of abstraction and subsequently identifies interrelated variables influencing the state of the system. SD focuses on capturing time-varying interactions among interdependent variables and multiple feedback processes in a system (Nasirzadeh et al. 2008). SD modeling in general requires constant iterations, continual testing, and refinement.

SD uses modeling elements such as causal loop diagrams (CLDs), delays, and flows (rates) and stocks (Figure 2.2) to determine the dynamic behaviour of complex systems over time (Sterman 2000). In SD, variables are connected by causal links with polarities forming CLDs. The polarities (either positive “+” or negative “-”) denote the causal influence among system variables. A positive link implies that the variables change in the same direction, while the negative link indicates the variables change in opposite direction. CLDs are very practical to elicit mental models of experts, capture causalities, and communicate important feedback loops in the system. The feedback loops are of two types: positive (reinforcing) and negative (balancing). Positive loops amplify changes whereas negative loops tend to self-correct and seek equilibrium (Boateng et al., 2012). A delay, usually indicated by a double line perpendicular to the causal link, is used in SD to model the time that elapses between cause and effect (Boateng et al., 2012). Development of SD models also involves the mapping of variables in CLDs to flows and stocks. Stocks (levels), accumulation or depletion due to differences between inflows and outflows, represent the state or condition of the system at any point in time and provide the basis for any decisions and actions to be taken (Sterman 2000). Flows represent the rates (units per time period) at which the stock changes over time. SD is an appropriate simulation technique when the main points of interest for the modeller are assessing the changes of variables in the system over time, and identifying the effects of influencing factors on the system’s variables. The effects of a change in a given variable on the other variables in the loop can be traced by increasing or decreasing its value and observing the changes.

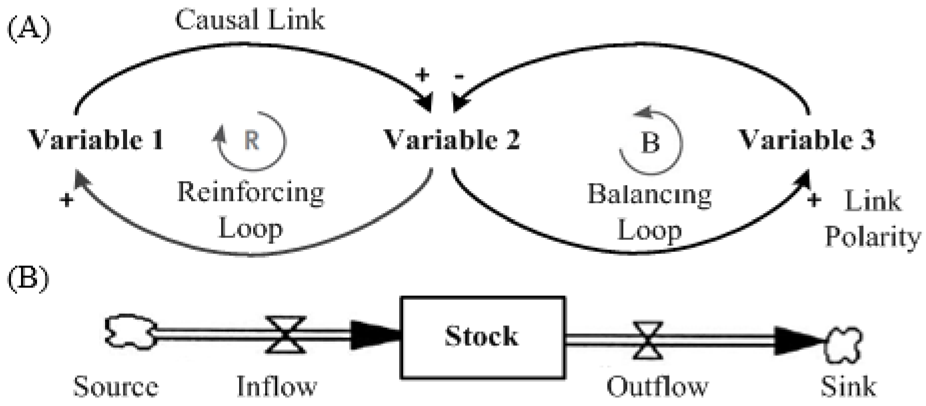


Figure 2.2. Components of system dynamics: (A) Causal loop diagrams and (B) Flow and stock diagrams

2.5.2 Application of System Dynamics in Construction

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 modelling construction management processes in general and risk and contingency in particular. Han et al. (2014) stated that relatively little attention has been given to SD modelling in construction compared to the other industries. 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 (Park 2005; Tatari et al. 2008); project performance (Leon et al. 2018; Moradi et al. 2015); planning and control (Alzraiee et al. 2015; Lee et al. 2006; Peña-Mora and Li 2001); productivity (Gerami Seresht and Fayek 2018; Khanzadi et al. 2018; Nojedehi and Nasirzadeh 2017); rework and change (Forcada et al. 2014; Lee and Peña-Mora 2007; Lee et al. 2006; Love et al. 2002), delay and disruption analysis (Jalal and Shoar 2017; Eden et al. 2000);

claim assessment (Howick 2005; Williams et al. 2003); Bidding and pricing (Lo and Yan 2009; Lo et al. 2007); constructability (Ford et al. 2004); sustainability (Hong et al. 2011; Zhang et al. 2014); rehabilitation (Hwang et al. 2016; Rashedi and Hegazi 2016); dispute resolution (Menassa and Peña-Mora 2010; Ng et al. 2007); health and safety (Lingard et al. 2017; Nasirzadeh et al. 2018), and others (Raoufi et al. 2018).

2.5.3 Application of System Dynamics for Risk Analysis and Contingency Determination

The use of SD for modeling and analysing risk and contingency 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 analyse the impact of different response strategies for identified risks on project cost, quality, and schedule. Ford (2002) adopted 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. Using a similar approach, De Marco et al. (2016) developed a dynamic contingency management model to simulate decision-making scenarios for effective management of the contingency budget during the lifecycle of a design-build (DB) project.

2.5.4 Integrating Fuzzy Logic and System Dynamics

Traditional SD models do not effectively account for non-probabilistic (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 is 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 (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.

2.5.5 Application of Fuzzy System Dynamics in Construction

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. Gerami Seresht and Fayek (2018) developed an FSD model to predict the multifactor productivity of equipment-intensive activities in construction projects. Nojedehi and Nasirzadeh (2017) integrated fuzzy logic and SD to capture the imprecision and subjective uncertainty associated with factors affecting labor productivity. Nasirzadeh et al. (2013) proposed a dynamic quality management system based on FSD to simulate the impact of quality defects on project cost and schedule and to evaluate the effectiveness of alternative mitigation strategies prior to implementations. Khanzadi et al. (2012) presented an integrated FSD model to determine the concession period in build-operate-transfer (BOT) projects. Karavezyris et al. (2002) integrated SD with fuzzy logic to develop a waste management model for forecasting municipal solid waste disposal needs. Marzouk and Hamdy (2013) developed a framework that comprises historical records database, analytical fuzzy model, and SD model to quantify the impact of weather on formwork shuttering and removal operation.

2.5.6 Application of Fuzzy System Dynamics for Risk Analysis and Contingency Determination

There is very little literature on the application of FSD to risk modeling and analysis. Nasirzadeh et al. (2008) adopted a fuzzy-based system dynamics approach to integrated risk management processes on construction projects. Uncertain input factors affecting the magnitude of risk events (e.g., haul road conditions, maintenance programs, and equipment life) were represented by fuzzy numbers and a fuzzy rule-based system (if-then rules) was used to determine the magnitude of risk events (e.g., the probability of machinery breakdown). The impacts of risk events on project cost and schedule were quantified as fuzzy numbers based on the α-cut method, which uses interval arithmetic. The proposed model also evaluates the effectiveness of alternative response strategies by considering the secondary risks that may arise due to implementation of the response strategies. 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. SD was used to model the interrelationships among factors affecting the risk allocation process while fuzzy logic was used to account for the non-probabilistic uncertainties of input parameters and variables in the model. In both approaches, very few fuzzy variables were considered in the FSD models. The impact 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.

2.6 Chapter Summary

This chapter provided a brief literature review on processes entailed in construction project risk management. An overview of risk identification process, common risk identification tools and techniques, and risk classification methods employed in construction projects were presented. Despite availability of wide array of tools and techniques for risk identification, only few are commonly used in construction industry. The risk identification process in construction mainly focuses on identification of negative risks and opportunities are overlooked or addressed reactively. The review of existing classification methods revealed that there is no standard or consensus on the categorization of risks in the construction industry. Also, the literature review indicated that there is a lack of systematic review and content analysis of published articles related to risk identification in construction.

In this chapter, different methods for risk analysis and contingency determination—categorized as deterministic, probabilistic, fuzzy-based, and hybrid—were discussed and their respective advantages and drawbacks were presented. Fuzzy logic addresses imprecisions, vagueness, and subjectivity in assessing risks and opportunities and determining contingency. Fuzzy logic alone or in combination with other techniques have been widely used to address problems associated with conventional quantitative risk analysis techniques. Previous studies which have used hybrid fuzzy methods for risk analysis and contingency determinations were reviewed and their limitations have been identified. Even though, several endeavors have been made to integrate fuzzy logic with methods capable of determining root causes of risks (FTA and FMEA) or capturing interrelationship and interactions between risks (ANP, BBN, and ISM), most of the hybrid fuzzy methods fail to deal with dynamic and time-related behaviour of risk and opportunity events and do not support feedback loops.

SD is a viable option to capture dynamic nature of risks and complex interrelationship and interaction among risk and opportunity events. Basic concepts related to SD were introduced and the application of SD in construction management overall as well as specifically in risk analysis and contingency determination were reviewed. Conventional SD models do not effectively account for subjective uncertainties associated with risk and opportunity events and do not capture vague interrelationships and dependencies among them. Thus, efforts made to integrate fuzzy logic and SD in construction were examined and limitations were established. Some limitations of existing hybrid FSD models are: only few fuzzy variables were considered in the FSD models; problem of the growing support of fuzzy outputs due to the use of α-cut method; the defuzzification methods used in the models are limited to only COA and LOM; there are no structured methods for developing causal loop diagrams; and expertise level of experts are not considered when aggregating their opinions. The next chapter presents results of systematic review and content analysis of common risk identification tools and techniques, risk classification methods, and common risks in construction projects.

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Chapter 3 Risk Identification Process and Common Risks in Construction: Systematic Review and Content Analysis[3]

3.1 Introduction

The identification of possible sources of risk is an essential stage in the risk management process because it allows project parties to discern specific instances of uncertainty; thereby, the potential impact of these uncertainties can be analyzed and appropriate strategies for mitigating their effects can be developed (Zayed et al. 2008). Furthermore, structured and detailed risk identification provides a basis for later stages and ensures risk management effectiveness (Banaitiene and Banaitis 2012). Published literature is one of the main sources of information for identifying risks (both positive and negative) in construction projects. Researchers have previously identified numerous risks affecting construction projects, and these identified risks have been used for risk assessment, analysis, and modeling purposes. Although much effort has been expended on identifying risks from the literature, existing literature reviews are not exhaustive, they lack systematic analysis, and they are limited to only a few papers. Moreover, a detailed content analysis has not been done on articles that deal with risk identification tools and techniques, classification methods, and common risks in construction management. The objectives of this

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chapter are threefold. The first objective is to address the lack of a systematic review and content analysis of published articles related to risk identification in construction, identify research gaps, and suggest directions for future research. The second objective is to perform a critical examination of common risk identification tools and techniques and risk classification methods employed in construction risk management processes. The third objective is to identify, systematically categorize, and prioritize potential risks affecting construction projects through a literature review and detailed content analysis of articles published in academic journals specializing in civil engineering, construction engineering and management, and project management. The common risks in construction projects that will be identified, categorized, and prioritized in this chapter will be used to design the risk identification and assessment interview survey form and subsequently rank the risks that will be considered in developing the FSD model for risk analysis and contingency determination.

The rest of this chapter is organized as follows. First, a summary of previous reviews conducted on risk-related topics is presented. Second, the research methodology adopted in this chapter is briefly discussed. Third, the results of the content analysis of the common risk identification tools and techniques, risk classification methods, and common risks in construction projects are presented. Finally, a summary of this chapter is provided.

3.2 Previous State of the Art Reviews Conducted on Risk-Related Topics

Despite the abundance of published articles focusing on risk-related topics in construction, only a few are dedicated to bibliometric or content analysis. Edwards and Bowden (1998) carried out an analytical review of construction and project risk management literature published between 1960 and 1997 to identify gaps in research and practice and to determine potential areas for future research. Taroun (2014) presented a review of risk modeling and assessment literature published between 1983 and 2012 in academic journals specializing in the construction industry, project management, risk analysis, and management science. Islam et al. (2017) provided a comprehensive review of current research trends and application areas of fuzzy and fuzzy hybrid methods applied in the risk assessment of construction projects based on content analysis of 82 articles published between 2005 and 2017 in leading construction and engineering management journals. Yu et al. (2018) conducted a systematic review of 37 articles published in construction management journals between 1991 and 2015 to study research trends and identify critical risk factors of transnational public-private-partnership (TPPP) project.

The studies by Edwards and Bowden (1998), Taroun (2014), and Islam et al. (2017) focused on either the entire risk management process or specifically on risk modeling and assessment. Although Yu et al. (2018) reviewed the identification of critical risk factors in previous studies, their review was limited to a particular type of project (i.e., TPPP). This chapter specifically focuses on the risk identification process and common risks in construction and addresses the lack of a systematic review and content analysis of literature on these topics. The scope and objectives of this chapter are different than the aforementioned studies, thereby resulting in new findings.

3.3 Research Methodology

A three-stage process (Figure 3.1) was adopted in this chapter to achieve the research objectives. These stages are described in the following subsections.

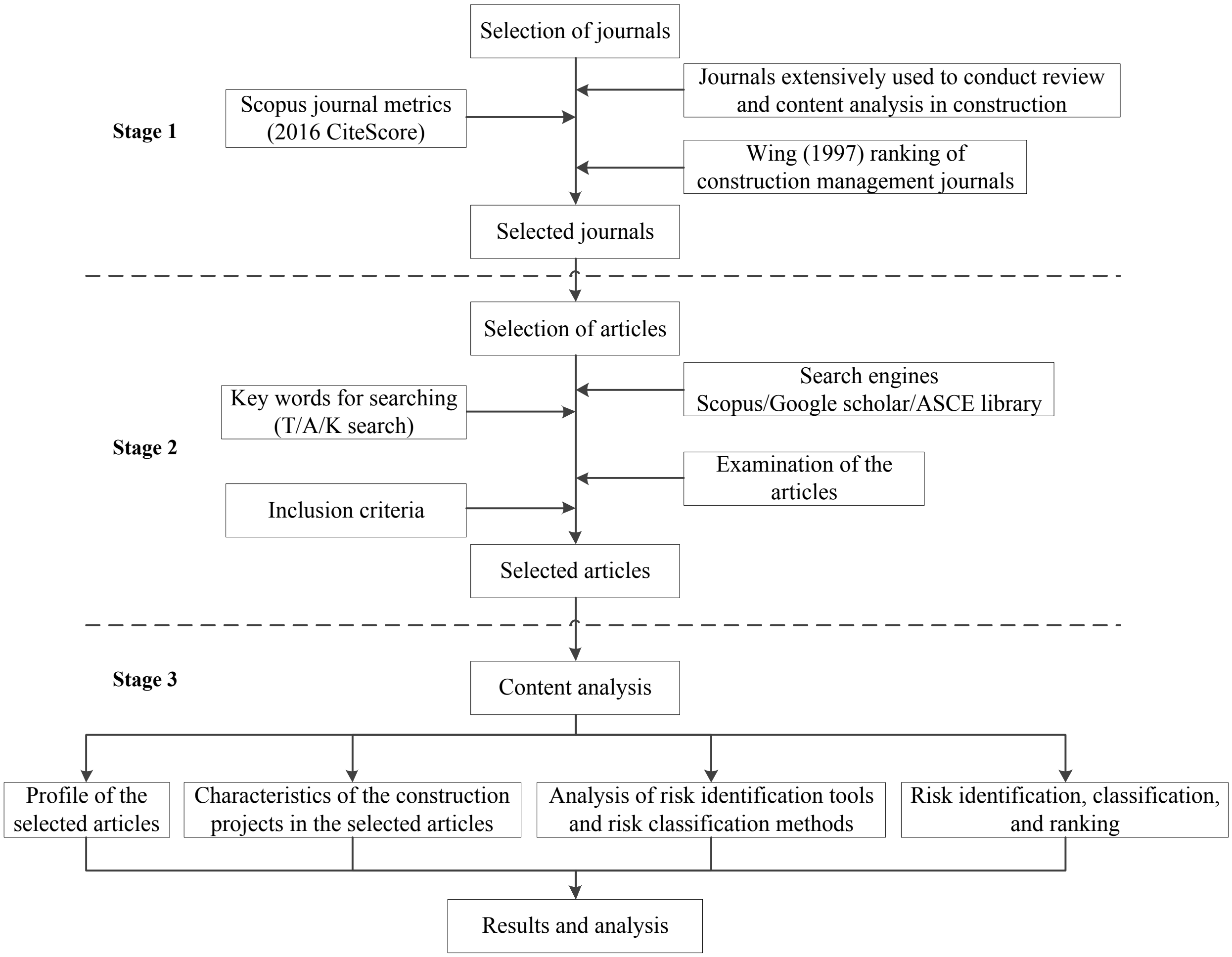

Figure 3.1. Research methodology for article selection and content analysis

3.3.1 Journal Selection

The literature review and content analysis is focused only on peer-reviewed articles published in academic journals; thus, conference papers, books, historical project data, risk registers, standard checklists, handbooks, and other sources of information were not considered. In stage 1, journals that have an important impact and prominent position in the research community of construction engineering and management were selected. The selection of journals was based on purposive/selective sampling (Xiong et al. 2015); that is, those journals extensively used to conduct literature review and content analysis specifically on risk-related topics in construction engineering and management by different authors (Islam et al. 2017; Taroun 2014; Yu et al. 2018) were considered. Also, the 2016 Scopus journal metrics (CiteScore) and the research conducted by Wing (1997) on the ranking of construction management journals were referred to when choosing the journals. Journals that have a CiteScore of 0.70 and above based on the 2016 Scopus journal metrics were considered. Only those journals that published at least three papers related to the topic of this study between 1990 and 2017 were chosen. The following 14 journals were selected: *Expert Systems with Applications* (ESA), *Automation in Construction* (AC), *International Journal of Project Management* (IJPM), *Building and Environment* (B&E), *Journal of Construction Engineering and Management* (JCEM), *Journal of Computing in Civil Engineering* (JCCE), *Journal of Management in Engineering* (JME), *Journal of Infrastructure Systems* (JIS), *Construction Management and Economics* (CME), *Journal of Civil Engineering and Management* (JCiEM), *Engineering, Construction and Architectural Management* (ECAM), *Canadian Journal of Civil Engineering* (CJCE), *International Journal of Construction Management* (IJCM), and *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A:Civil Engineering* (JRUES). The selected journals were ordered from high to low based on their CiteScore. Even though the last journal in the list (JRUES) is not included in the Scopus database and does not have a CiteScore, it was selected for this research because of its relevance.

3.3.2 Article Selection

In stage 2, searches for relevant articles were performed using Scopus (Elsevier's abstract and citation database), Google Scholar, and American Society of Civil Engineers (ASCE) library search engines. Keywords used for searching the articles included risk identification, risk assessment, risk analysis, risk management, construction risk, project risk, uncertainty analysis, and project uncertainty. The keywords were selected from previously published articles (Islam et al. 2017; Taroun 2014) that conducted a review on risk-related topics, and they were based on an initial examination of common keywords used in risk management-related articles published in the construction domain. The search was conducted using the title, abstract, and keyword (T/A/K) field of the aforementioned search engines. The search was restricted to articles published from 1990 to 2017 (inclusive). As a result, 484 articles were initially retrieved from the selected journals. The contents of the articles were further examined, and the number of articles was reduced to 130. The following inclusion criteria were used to select the articles: (1) the article should be specifically related to risks in the construction industry; (2) the article should mention, discuss, or list potential risks affecting construction projects in the main text, tables, or figures; (3) the article should use at least one technique for identifying risks; and (4) the article should use a specific classification method for categorizing risks or simply mention, discuss, or list the risks in the main text, tables, or figures.

3.3.3 Content Analysis

In stage 3, once the articles were identified, detailed content analysis was carried out in order to (1) profile the selected articles based on type of journal, year of publication, and the number of authors per article; (2) characterize the construction projects considered for risk identification in the selected articles based on region and type; (3) examine common risk identification tools and techniques, risk classification methods, and category names used for classifying risks in the selected articles; and (4) systematically identify, categorize, and rank common construction project risks identified from the selected articles. Content analysis is a research technique for determining major facets of and valid inferences from written, verbal, or visual communication messages, either qualitatively or quantitatively, depending on the nature of the project and the issues to be addressed in the research (Chan et al. 2009; Krippendorff 2013). Content analysis is a powerful technique for collecting and organizing information and for examining trends and patterns in documents (Krippendorff 2013). Qualitative content analysis focuses on grouping data into categories, while quantitative content analysis determines the numerical values of categorized data (i.e., frequencies, ratings, and rankings) by simply counting the number of times a topic is mentioned (Chan et al. 2009). In this chapter, a combination of both qualitative and quantitative content analysis was adopted.

3.4 Results and Discussion

The complete list of selected articles used for the content analysis is provided in Appendix A. The percentage values indicated in the discussion, figures, and tables were determined based on the number of references over the total number of articles considered in the content analysis (i.e., 130 articles).

3.4.1 Profile of the Selected Articles

The selected articles considered for content analysis were profiled based on journal, year of publication, and the number of authors per article. Figure 3.2 depicts the percentage of the selected articles published in each journal. Close to 60% of the selected articles were published in five journals: JCEM (17.69%), IJPM (16.92%), CME (9.23%), JME (7.69%), and JCiEM (7.69%). The remaining 40% of the selected articles were published in the other nine journals. The number of selected articles by journal and year is shown in Figure 3.3. The selected articles were published between 1990 and 2017; among these, 109 articles (73.84%) were published between 2005 and

2017. The number of selected articles published in the span of 2010–2014 is considerably greater than any other publication period.

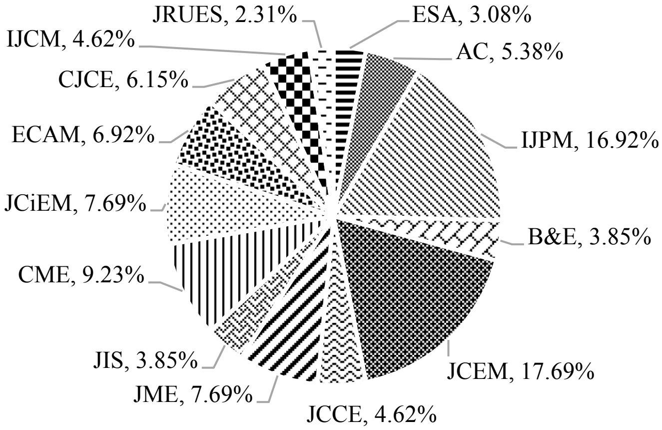

Figure 3.2. Percentage of the selected articles published in each journal

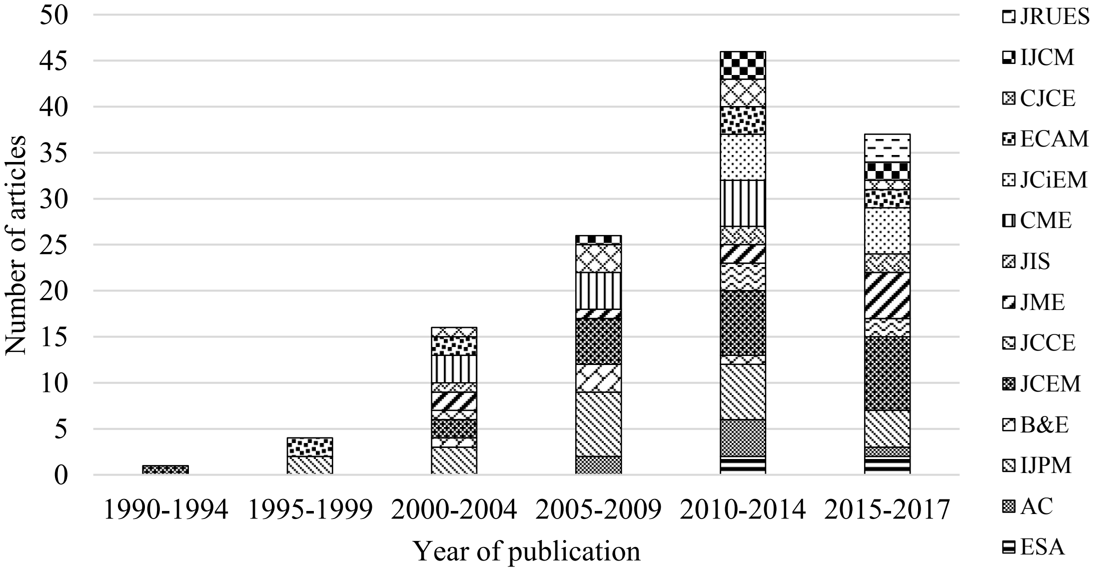

Figure 3.3. Number of selected articles by journals and year

In terms of the number of authors per article, 7.69% of the selected articles were authored by a single author; 92.31% were authored by two or more authors, of which 35.38% had two authors; 26.92% had three authors; and 30.00% had four or more authors. To determine the contribution of authors in the selected articles, a scoring method [Eq. (1)] widely used in previous studies was adopted (Yi and Chan 2014; Yu et al. 2018). The scoring method considers the order of the authors in multi-authored articles to determine each author's proportional credit.

$$Score = \frac{1.5^{n-i}}{\sum_{i=1}^{n} 1.5^{n-i}} \tag{3.1}$$

where n is number of authors of the article and i is the order of the specific author. For example, if an article is authored by three authors, the first, second, and third author will each have a score of 0.47, 0.32 and 0.21, respectively. The total score of an author is determined by adding the scores that the author has from all articles. Table 3.1 shows the ten most contributing authors in the selected articles based on their total score, the number of articles each has authored, and their respective affiliation. The three most contributing authors in the selected articles (according to their total score) are: I. Dikmen (3.35) from Middle East Technical University, Turkey; P.X.W. Zou (2.47) from University of New South Wales, Australia; and A.P.C. Chan (2.37), from the Hong Kong Polytechnic University, Hong Kong.

Table 3.1. Contribution of authors in the selected articles

Author	Affiliation	Country	Number of Articles	Total Score
I. Dikmen	Middle East Technical University	Turkey	9	3.35
P.X.W. Zou	University of South Wales	Australia	5	2.47
A.P.C. Chan	Hong Kong Polytechnic University	Hong Kong	9	2.37
X. Jin	Deakin University	Australia	3	2.20
M. Birgonul	Middle East Technical University	Turkey	9	2.17
Y. Ke	Tsinghua University	China	7	1.95
A. Oztas	University of Gaziantep	Turkey	3	1.60
S. M. El-Sayegh	American University of Sharjah	UAE	2	1.60
J. H. M. Tah	South Bank University	United Kingdom	4	1.50
B. Hwang	National University of Singapore	Singapore	3	1.42

3.4.2 Profile of the Projects in the Selected Articles

The construction projects considered for risk identification in the selected articles were profiled based on type and geographical region. The selected articles encompassed risk identification on various construction projects located in different geographical regions. The various construction projects in the selected articles were grouped into five categories according to the type of construction work: building projects (residential, office, commercial, mixed development, hospitals, etc.), infrastructure projects (highways, mass transit systems, tunnels, bridges, drainage systems, sewage treatment plants, etc.), power and energy projects (hydroelectric plants, solar energy, wind power, nuclear energy, etc.), heavy industrial projects (chemical, refineries, oil sands installations, etc.), and multiple combinations thereof. As shown in Table 3.2, most of the construction project types considered for risk identification in the selected articles were infrastructure projects (41.54%), followed by a combination of two or more project types (37.69%), and building projects (11.54%).

A higher percentage is attributed to articles related to infrastructure projects, because a wide range of projects are subset of this project category. Moreover, infrastructure development plays a key role in the economic growth and social development of both developed and developing countries. As a result, infrastructure projects are high on governments' agendas and often have large budget allocations (Yu et al. 2018). Large infrastructure projects often suffer from cost overruns, delays, failed procurement, and lack of availability of finances, which contribute to the existence of wide variety of risks and uncertainties (Vickerman 2007; Yu et al. 2018). Hence, it is important to identify and manage risks for successful completion of infrastructure projects.

The majority of the selected articles dealt with risk identification of construction projects located in Asian countries (56.92%), of which 39.19 % were in China and 13.51% were in Iran; followed by European countries (16.92%), of which 50.00% were in Turkey and 27.27% were in the United Kingdom. The geographical distribution of the projects used in risk identification in the selected articles reflect the growing demand for research on risk-related topics in those regions. Construction companies in developed countries apply systematic risk management, have better risk management maturity, and benefit from well-established risk management standards compared to construction companies in developing countries (Hosseini et al. 2016). The risk management practice in developing countries has been found to be inadequate, unstructured, and inconsistently used (Choudhry and Iqbal 2013; Hosseini et al. 2016; Tadayon et al. 2012). For example, an empirical study conducted on risk management practices by Tang et al. (2007) revealed that the risk management systems applied in the Chinese construction industry tend to be "informal, which are inadequate to manage project risks". The rapid economic growth of China has contributed to large expenditures in infrastructure development, thus creating one of the largest construction markets in the world (Tang et al. 2007). A higher percentage of the projects in the selected articles were therefore focused on Asian countries (mainly China) as opposed to Europe and North America, to highlight the growing demand for research on risk-related topics in countries like China.

Table 3.2. Profile of the projects in the selected articles

Feature	Category	Number of articles	Percentage of articles
Project type	Building projects	15	11.54
	Infrastructure projects	54	41.54
	Power and energy projects	9	6.92
	Heavy industrial projects	3	2.31
	Combination of two or more project types	49	37.69
	Total	130	100.00
Geographical region of projects	Africa	4	3.08
	Asia	74	56.92
	Australia	6	4.62
	Europe	22	16.92
	North and Central America	9	6.92
	South America	1	0.77
	General*	14	10.77
	Total	130	100.00

*The geographical regions of the projects are not stated in the selected articles or the projects are located in more than one geographical location

3.4.3 Risk Identification Tools and Techniques Used in the Selected Articles

A wide variety of tools and techniques were used for risk identification in the selected articles (Table 3.3). In the selected articles, the use of combinations of two risk identification tools and techniques (53.08%) was more popular than the use of a single tool or technique (26.92%) and a combination of three or more tools and techniques (20.00%). The three most frequently used risk identification tools and techniques, regardless of whether they were used alone or in combination, were literature review (66.92%), questionnaire surveys (46.92%), and expert interviews (29.23%). Detailed analysis of the selected articles that used a combination of two or more tools and techniques indicated that the use of a literature review combined with a questionnaire survey was the most prevalent (29.47%), followed by a combination of literature review, expert interview, and questionnaire survey (15.79%), and a combination of literature review and expert interview

(9.47%). The findings of the content analysis indicate that information-gathering tools and techniques (e.g., literature review, questionnaire survey, expert interview) were more widely used than diagramming tool and techniques (e.g., influence diagrams, cause-and-effect diagrams, system or process flow charts) for risk identification. Diagramming tools and techniques were rarely used in the selected articles, as most articles focused only on the identification of risks and their impact on the project objectives without considering the root causes of risks and their interdependencies. None of the analysis-based tools and techniques (e.g., fault tree analysis, decision tree analysis, failure and mode effect analysis) were used in the selected articles, perhaps because analysis-based tools and techniques are more often used in risk analysis, even though they are also applicable for risk identification.

Table 3.3. Risk identification tools and techniques used in the selected articles

Category	Number of articles	Percentage of articles	Rank
Combination of tools and techniques			
Single tool or technique	35	26.92	2
Two tools and techniques	69	53.08	1
Three or more tools and techniques	26	20.00	3
Total	130	100.00	
Tools and techniques regardless of being used alone or in combination			
Checklist	3	2.31	10
Documentation review	13	10.00	6
Brainstorming	5	3.85	7
Delphi technique	5	3.85	7
Expert interview	38	29.23	3
Questionnaire survey	61	46.92	2
Risk workshop	4	3.08	9
Literature review	87	66.92	1
Influence diagram	1	0.77	11
Expert judgment/panel	21	16.15	4
Past projects/ historical project data	21	16.15	4
Combination of two or more tools and techniques (top 3)			
Literature review and questionnaire survey	28	29.47	1
Literature review, expert interview, and questionnaire survey	15	15.79	2
Literature review and expert interview	9	9.47	3

Of the information-gathering tools and techniques, literature review is predominantly used in the selected articles mainly because it is easily implemented and helps to assess knowledge and historical information accumulated from previous projects. Since most risks in literature are identified for a specific context, the user should consider risks that do not appear in the literature but are highly relevant to a specific project. Questionnaire survey helps to capture the perception of large (diversified) groups and encourages broad thinking to identify risks. The success of questionnaire survey depends on the quality of the questions, mode of questionnaire administration, sample size, burden on respondents (length of questions), response rate, and quality of responses (Rostami 2016; Baumann et al. 2016). Expert interview is an interactive method that makes use of past experience of project managers, subject matter experts, and experienced project participants to identify potential risks through structured questions. The results of expert interview depend on the experience and expertise of each interviewee and the quality of the interview process. Contrary to the other two information-gathering tools and techniques, expert interview is resource-intensive and time consuming (Rostami 2016; Baumann et al. 2016). Tools and techniques that employ diversified groups of subject matter experts are better for risk identification than tools and techniques that rely on an individual assessment (Baumann et al. 2016). According to Hillson (2002), an appropriate combination of tools and techniques (especially those that complement each other) guarantees better results in identifying potential risks, as there is no single best risk identification tool and technique.

The review conducted on the selected articles reflects that there is a lack of guidelines and systematic criteria for selecting appropriate risk identification tools and techniques for construction projects, as the selected articles did not provide such guidelines or provide a rationale for selecting a specific risk identification tool or technique based on specific criteria. Also, studies that focus specifically on systematic approaches/models for evaluating the maturity level of risk identification practices are scarce in the selected articles. Groups of experts with different levels of knowledge, experience, and expertise are often involved in risk identification processes. However, the group-based risk identification tools and techniques used in the selected articles do not take into account the expertise level of experts in risk management. In most of the selected articles, the experts are assumed to have equal weights, or the weights of experts are simply determined based on experts' years of experience, which calls for further research on methods of distinguishing experts based on a more comprehensive set of qualifications.

3.4.4 Risk Classification Methods Used in the Selected Articles

Table 3.4 presents the risk classification (categorization) methods adopted in the selected articles. A majority of the selected articles (38.46%) classified risks based on their nature. Classification based on the initial source of the risk (internal or external) was the second most favored classification method and was used in 15.38% of the articles. Classification based on the occurrence of the risk at different stages of the project (6.15%) and three-level meta-classification (6.15%) were considerably less common in the selected articles. Classification based on the impact of risks on project objectives (2.31%) and classification based on the project party who might be the originator of the risk (1.54%) were very rarely used in the selected articles. A considerable proportion of the selected articles (30.00%) did not use any of the classification methods; rather, the risks were simply listed. A large proportion of the selected articles (48.46%) used a two-level RBS (i.e., main category and list of risks). Another 21.54% of the articles used a three-level RBS comprised of main category, sub-category, and risks at the lowest level, and 30.00% of the articles just listed the risks without categorizing them. Further analysis carried out on the categories (main and sub) indicated that numerous category names have been adopted in the selected articles for classifying risks based on their nature. The top 20 risk category names used in the selected articles for classifying risks based on their nature are shown in Table 3.5, which was later used as the basis for the proposed classification method adopted in this chapter. The most popular category names used in the selected articles were economic (24.62%), political (24.62%), construction (22.31%), financial (21.54%), and management (20.00%).

The review of existing classification methods in the selected articles reveals that there is no standard or consensus on how to categorize risks in the construction industry. In addition, there is a lack of clarity and consistency in the definition of risk categories. The categories in most risk classification methods adopted in the selected articles do not capture the broad variety of risks. Furthermore, the available classification methods are suitable for specific project types or project stakeholders. These limitations highlight the need for a structured and comprehensive risk classification method. Therefore, a comprehensive and structured classification method is proposed in this chapter based on the existing category names in the selected articles (Table 3.5), as discussed in the next section.

Table 3.4. Risk classification methods and level of RBS used in the selected articles

Category	Number of articles	Percentage of articles	Rank
Risk classification methods			
Classification based on initial source of risks (internal and external)	20	15.38	3
Classification based on nature of risks	50	38.46	1
Classification based on occurrence of risks at different stages of the project	8	6.15	4
Classification based on impact of risks on project objectives	3	2.31	6
Classification based on the project party who might be the originator of the risk	2	1.54	7
Three-level meta-classification	8	6.15	4
No classification (just listing of risks)	39	30.00	2
Total	130	100.00	
Level of risk breakdown structure (RBS)			
Three levels	28	21.54	3
Two levels	63	48.46	1
Single level (just listing)	39	30.00	2
Total	130	100.00	

Table 3.5. Top 20 risk category names used in the selected articles for classifying risk based on their nature

Category name	Number of articles	Percentage of articles	Category name	Number of articles	Percentage of articles
Economic	32	24.62	Legal	15	11.54
Political	32	24.62	Site conditions	13	10.00
Construction	29	22.31	Market	10	7.69
Financial	28	21.54	Natural	9	6.92
Management	26	20.00	Health and safety	8	6.15
Environmental	23	17.69	Labor	8	6.15
Design	23	17.69	Equipment	7	5.38
Contractual	22	16.92	Resources	7	5.38
Technical	19	14.62	Acts of God	7	5.38
Social	18	13.85	Geological	7	5.38

3.4.5 Identification, Classification, and Ranking of Common Risks from the Selected Articles

In this chapter, the risks identified from the selected articles were categorized based on their nature, as it is the most widely used classification approach in the selected articles. The risks identified from the selected articles were grouped into eleven categories: management, technical, construction, resource-related, site conditions, contractual and legal, economic and financial, social, political, environmental, and health and safety. These category names were chosen from the top 20 category names identified from the selected articles (Table 3.5). Some of the category names had to be combined to avoid redundancy in risk identification and categorization (e.g., economic and financial, contractual and legal). In the case of category names that were commonly used interchangeably, the one that was more general and inclusive of the other was used (e.g., the category name “technical” was chosen over “design” and “engineering,” and the category name “resource-related” was chosen as it incorporates “material,” “labor,” “equipment,” and “subcontractor”). Such classification is intended to illustrate the diversity of risks and thereby assist in examining the full breadth of exposure to possible risks so that project parties do not focus on specific risks and overlook others (Al-Bahar and Crandall 1990; Bu-Qammaz et al. 2009). Since the proposed classification method is comprehensive, it can be adopted for classifying risks for different types of construction projects and project stakeholders. Broader and comprehensive categorization facilitates both risk identification processes and subsequent risk management processes. Grouping risks of similar nature is essential to avoid duplication, identify risk interdependencies and interactions, and identify root causes of risks. Moreover, such categorization helps to identify effective risk response strategies and allocate risks to the most appropriate contracting party.

Each of the risks identified from the selected articles were categorized in a unique category. Because of the categorization method adopted in this chapter, identified risks may fall under a different category than their original category in the selected article. A total of 571 risks were identified after conducting a literature review and content analysis on the selected articles. Table 3.6 shows the number of risks identified under each category.

Table 3.6. Number of identified risks in each category in the selected articles

Risk category	Number of identified risks	Percentage of identified risks
Management	72	12.61
Technical	63	11.03
Construction	59	10.33
Resource-related	68	11.91
Site conditions	38	6.65
Contractual and legal	65	11.38
Economic and financial	67	11.73
Social	38	6.65
Political	46	8.06
Environmental	24	4.20
Health and safety	31	5.43
Total	571	100.00

The risks in each category were ranked solely based on their frequencies, that is, the total number of references (hits) each risk had (Table 3.7). The frequencies reflect how common the risks are in the construction industry or how frequently they are identified in the selected articles. The ranking does not show the probability of occurrence, impact, or severity of the identified risks on project objectives. The probability, impact, and severity or risks are very project- and context-specific and can not be generalized. The top 10 risks in each category are shown in Table 3.7.

Table 3.7. Top ten risks in each category identified from the selected articles

Description of risks	Number of articles	Percentage of articles	Rank
Management			
Poor coordination among various parties involved in the project	29	22.31	1
Lack of experience and project management skills of the project team	26	20.00	2
Inadequate or poor project planning and budgeting	24	18.46	3
Unavailability of sufficient professionals and managers	23	17.69	4
Poor communication among various parties involved in the project	23	17.69	4
Poor site management and supervision by the contractor	16	12.31	6
Poor relationships among various parties involved in the project	16	12.31	6
Inadequate project organization structure	15	11.54	8
Poor project quality management, including inadequate quality planning, quality assurance, and quality control	14	10.77	9
Poor capability of owner in project management	12	9.23	10
Technical			
Design errors and poor engineering	61	46.92	1
Unanticipated engineering and design changes	48	36.92	2
Unclear and inadequate details in design drawings and specifications	22	16.92	3
Inadequate study and insufficient data before design (errors in feasibility studies)	22	16.92	3
Unproven or immature engineering techniques	16	12.31	5
Delay in design (design process takes longer than anticipated)	14	10.77	6
Incomplete design	10	7.69	7
Technology changes	8	6.15	8
Complexity of design	7	5.38	9

Description of risks	Number of articles	Percentage of articles	Rank
Poor constructability	7	4.62	9
Construction			
Poor workmanship and construction errors leading to rework	50	38.46	1
Delays and interruptions causing a cost increase to the work package/project	36	27.69	2
Unreasonably tight project schedule causing a cost increase to the work package/project	15	11.54	3
Complexity of proposed construction methods/techniques	12	9.23	4
Contractors' incompetence in executing the work package/project	12	9.23	4
Changes in construction methods/techniques	11	8.46	6
Adoption of improper, poor, or unproven construction methods/techniques	11	8.46	6
Contractor's lack of experience in similar projects	8	6.15	8
Conflicting interfaces of work items	6	4.62	9
Pressure to deliver project on accelerated schedule (pressure to crash project duration)	6	4.62	9
Resource-related			
Unavailability of a sufficient amount of skilled labor in the project region	53	40.77	1
Unavailability or shortage of expected materials	48	36.92	2
Unavailability or shortage of expected equipment	31	23.85	3
Delay in materials delivery	27	20.77	4
Defective or non-conforming materials that do not meet the standard	22	16.92	5
Low labor productivity of local workforce	22	16.92	5
Subcontractors' failure; default of subcontractors	15	11.54	7
Unavailability of qualified subcontractors	15	11.54	7
Low productivity and efficiency of equipment	14	10.77	9
Equipment breakdown	13	10.00	10
Site conditions			
Unpredicted adverse subsurface conditions	54	41.54	1
Differing and unforeseen site conditions	35	26.92	2
Lack of readily available utilities on site (e.g., water, electricity, etc.) and unavailability of supporting infrastructure	20	15.38	3
Inadequate site investigations (soil tests and site survey)	17	13.08	4
Difficulties of access and work on site due to specific geographical constraints of the region	15	11.54	5
Late construction site possession	13	10.00	6

Description of risks	Number of articles	Percentage of articles	Rank
Unexpected underground utilities encounters	10	7.69	7
Delays in the right-of-way process	8	6.15	8
Ineffective control and management of traffic	8	6.15	8
Improper selection of project location	7	5.38	10
Contractual and legal			
Contradictions and vagueness in contract documents	41	31.54	1
Changes in project scope	22	16.92	2
Immaturity and/or unreliability of the legal system	21	16.15	3
Delays in resolving contractual disputes and litigations	20	15.38	4
Possibility of contractual disputes and claims	17	13.08	5
Frequent change orders	12	9.23	6
Change in codes and regulations	12	9.23	6
Excessive contract variation	10	7.69	8
Intense competition at the tender stage	8	6.15	9
Unclear roles and responsibilities of project stakeholders	8	6.15	9
Economic and financial			
Unpredicted changes in the inflation rate	64	49.23	1
Project-funding problems	48	36.92	2
Fluctuations in currency exchange and/or difficulty of convertibility	43	33.08	3
Unpredicted changes in interest rates	33	25.38	4
Escalation of material prices	29	22.31	5
Delay in payments	29	22.31	5
Changes in tax regulation	25	19.23	7
Poor financial market or unavailability of financial instrument resulting in difficulty of financing	24	18.46	8
Unfavorable economic situations in the country (instability of economic conditions)	22	16.92	9
Market demand changes	16	12.31	10
Social			
Land acquisition and compensation problems (the cost and time for land acquisition exceeds the original plans)	28	21.54	1
Public opposition to the project (public objections, social grievances)	23	17.69	2
Differences in social, cultural, and religious backgrounds	21	16.15	3
Insecurity and crime (theft, vandalism, and fraudulent practices)	14	10.77	4
Strikes and labor disputes	14	10.77	4
Poor public relations with local contacts	10	7.69	6

Description of risks	Number of articles	Percentage of articles	Rank
Unfavorable social environment	8	6.15	7
Societal conflict and/or public unrest	8	6.15	7
Poor public decision-making process	7	5.38	9
Disturbances to public activities	5	3.85	10
Political			
Changes in government laws, regulations, and policies affecting the project	60	46.15	1
Political instability of the government (unfavorable political environment)	34	26.15	2
Delay or refusal of project approval and permit by government departments (excessive approval procedures)	32	24.62	3
Outbreak of hostilities (wars, revolution, riots, and terrorism)	26	20.00	4
Corrupt local government officials demand bribes or unjust rewards	24	18.46	5
High level of bureaucracy of the authority	16	12.31	6
Expropriation and nationalization of assets/facilities without reasonable compensation	16	12.31	6
Government's improper intervention during construction	15	11.54	8
Poor relations with related government departments	11	8.46	9
Government restrictions on foreign companies (e.g. import/export restrictions, mandatory technology transfer, differential taxation of foreign firms, etc.)	10	7.69	10
Environmental			
Adverse weather conditions (continuous rainfall, snow, temperature, wind)	60	46.15	1
Force majeure (natural and man-made disasters which are beyond the firm's control, e.g. floods, thunder and lightning, landslide, earthquake, hurricane, etc.)	52	40.00	2
Adverse environmental impacts of the project	30	23.08	3
Pollution associated with construction activities (dust, harmful gases, noise, solid and liquid wastes, etc.)	16	12.31	4
Strict environmental regulations and requirements	12	9.23	5
Poor environmental regulations and controls	7	5.38	6
Changes in environmental standards and permitting	6	4.62	7
Poor preliminary assessment and evaluation of environmental impacts of the project	5	3.85	8
Prosecution due to unlawful disposal of construction waste	5	3.85	8
Failure to obtain environmental approval	4	3.08	10

Description of risks	Number of articles	Percentage of articles	Rank
Health and Safety			
Accidents occurring during construction	36	27.69	1
Inadequate safety measures or unsafe operations	28	21.54	2
Poor construction safety management	16	12.31	3
Damage to persons or property or materials due to poor safety and health management of the project	9	6.92	4
Failure to comply with HS&E standards or security plan	9	6.92	4
Ineffective protection of surrounding environment (e.g., adjacent buildings and facilities)	7	5.38	6
Epidemic illness	7	5.38	6
Strict health and safety regulations	6	4.62	8
Changed labor safety laws or regulations	6	4.62	8
Fatalities	5	3.85	10

Management risks are those risks related to the management skills and experience of the project team and project parties, the availability of project management professionals, and the relationships and coordination among project parties (Ling and Hoi 2006). As shown in Table 3.7, the most frequently mentioned management risks in the selected articles were poor coordination among various parties involved in the project (22.31%), lack of experience and project management skills of the project team (20.00%), inadequate or poor project planning and budgeting (18.46%), unavailability of sufficient professionals and managers (17.69%), and poor communication among various parties involved in the project (17.69%). Technical risks are risks associated with the technical aspects of the project, such as design, specifications, engineering, and technology (El-Sayegh and Mansour 2015). Among the technical risks identified from the selected articles, design errors and poor engineering (46.92%) and unanticipated engineering and design changes (36.92%) were the most prevalent, followed by unclear and inadequate details in design drawings and specifications (16.92%) and inadequate study and insufficient data before design (16.92%). Construction risks involve issues or concerns associated with construction methods, work tasks, delays and interruptions in construction, cost overruns, and quality of construction (Shrestha et al. 2017). The three most common construction risks identified from the selected articles were poor workmanship and construction errors leading to rework (38.46%), delays and interruptions causing a cost increase to the work package/project (27.69%), and an unreasonably tight project schedule causing a cost increase to the work package/project (11.54%).

Resource-related risks are risks associated with the suitability, condition, availability, quality, and procurement of construction materials and equipment and the availability, skill level, and performance of labor and subcontractors. As shown in Table 3.7, unavailability of a sufficient amount of skilled labor in the project region (40.77%), unavailability or shortage of expected materials (36.92%), unavailability or shortage of expected equipment (23.85%), and delay in materials delivery (20.77%) are very common resource-related risks in the selected articles. The site conditions risk category includes those risks related to the construction project site, including uncertainty regarding subsurface conditions, underground utilities, archaeological finds, accessibility of the site, availability of supporting infrastructure, and security and traffic conditions at the site (El-Sayegh and Mansour 2015). The top three site condition risks identified from the selected articles were unpredicted adverse subsurface conditions (41.54%), differing and unforeseen site conditions (26.92%), and lack of readily available utilities on site and unavailability of supporting infrastructure (15.38%).

Contractual and legal risks arise from poorly tailored contracts, inappropriate distribution of responsibilities, conflicts in contract documents, inadequate claim administration, disputes and litigations, third-party liabilities, immature laws, and complexity in the legal environment (El-Sayegh and Mansour 2015; Shrestha et al. 2017). The most frequently mentioned risks belonging to this category in the selected articles were contradictions and vagueness in contract documents (31.54%), changes in project scope (16.92%), immaturity and/or unreliability of the legal system (16.15%), and delays in resolving contractual disputes and litigations (15.38%). The economic and financial risk category includes risks related to inflation, fluctuations in exchange rates, changes in price, tax rates and economic policies, and also risks arising from financing structures and the financial market as well as challenges in financing the project (Iyer and Sagheer 2010; Shrestha et al. 2017). The most common economic and financial risks in the selected articles were unpredicted changes in the inflation rate (49.23%), project-funding problems (36.92%), fluctuations in currency exchange and/or difficulty of convertibility (33.08%), and unpredicted changes in interest rates (25.38%).

The social risks category involves risks associated with cultural and religious differences, crime and lack of security on project sites, issues or concerns related to social and cultural impacts of the project on the community, and public objections to projects (El-Sayegh 2008; Nielsen 2006). Among the identified risks belonging to this category, the most common were land acquisition and compensation problems (21.54%); public opposition to the project (17.69%); and differences in social, cultural, and religious backgrounds (16.15%). The political risks category includes risks that are dependent on political and regulatory situations as well as the stability of the country where the project is taking place (El-Sayegh and Mansour 2015). Changes in government laws, regulations, and policies affecting the project (46.15%) was the most frequently mentioned political risk in the selected articles, followed by political instability of the government (26.15%), delay or refusal of project approval and permit by government departments (24.62%), and outbreak of hostilities (i.e., wars, revolution, riots, and terrorism) (20.00%).

The environmental risk category includes risks created by nature, impact on the environment caused by the project, and changes in environmental policies and regulations (El-Sayegh and Mansour 2015; Shrestha et al. 2017). The most frequently mentioned environmental risks in the selected articles were adverse weather conditions (46.15%), force majeure (40.00%), and adverse environmental impacts of the project (23.08%). Risks belonging to the health and safety category relate to accidents and injuries due to poor safety conditions and measures on the construction site, health-related issues on the construction site, and health and safety regulations (El-Sayegh and Mansour 2015). The top three health and safety risks identified from the selected articles were accidents occurring during construction (27.69%), inadequate safety measures or unsafe operations (21.54%), and poor construction safety management (12.31%).

The comparison made based on the total number of references for the top ten risks in each category (Figure 3.4) shows that the economic and financial risk category was the most frequent in the selected articles. Potential reasons for this finding is that risks belonging to the economic and financial risk category can affect all project parties, span the entire project life cycle, have significant impact on both cost and schedule, influences risks in other categories, and pose significant threat to both international and local construction companies involved in a project. Health and safety and social risk categories were the least frequent in the selected articles. Empirical studies conducted by different researchers also reflect that health and safety and social risks were the lowest ranked risk categories (Edwards and Bowen, 1998; El-Sayegh, 2008). The overall top ten risks identified from the selected articles are presented in Table 3.8, along with their respective risk category, number of articles, percentage of articles, and overall rank. The results show that unpredicted changes in the inflation rate (49.23%); design errors and poor engineering (46.92%); changes in government laws, regulations, and policies affecting the project (46.15%);

adverse weather conditions (46.15%); and unpredicted adverse subsurface conditions (41.54%) were the most common risks amongst all the risks identified from the selected articles.

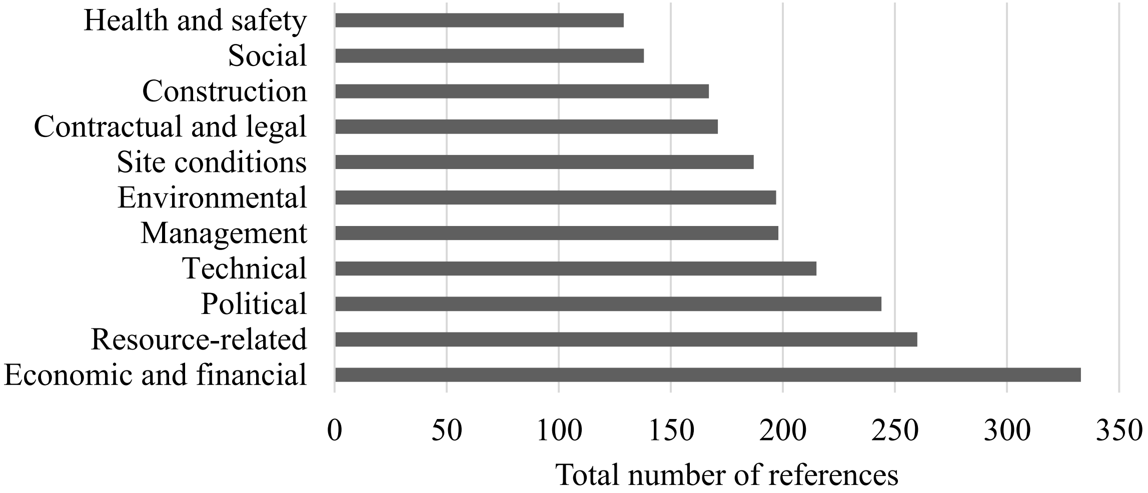

Figure 3.4. Total number of references for the top ten risks in each category

Table 3.8. Overall top ten risks identified from the selected articles

Description of risks	Risk category	Number of articles	Percentage of articles	Overall rank
Unpredicted changes in the inflation rate	Economic and financial	64	49.23	1
Design errors and poor engineering	Technical	61	46.92	2
Changes in government laws, regulations, and policies affecting the project	Political	60	46.15	3
Adverse weather conditions (continuous rainfall, snow, temperature, wind)	Environmental	60	46.15	3
Unpredicted adverse subsurface conditions	Site conditions	54	41.54	5
Unavailability of a sufficient amount of skilled labor in the project region	Resource-related	53	40.77	6
Force majeure (natural disasters that are beyond the firm’s control, e.g. floods, thunder and lightning, landslide, earthquake, hurricane, etc.)	Environmental	52	40.00	7
Poor workmanship and construction errors leading to rework	Construction	50	38.46	8
Unanticipated engineering and design changes	Technical	48	36.92	9
Unavailability or shortage of expected materials	Resource-related	48	36.92	9
Project funding problems	Economic and financial	48	36.92	9

Although interface management was not a common risk category name among the selected papers, risk and opportunity events related to interface management were identified and groped into different categories (e.g., management and technical). The majority of the selected articles concentrated on the identification of negative risks and overlooked opportunities that could have a beneficial effect on achieving project objectives. In addition, the existing tools and techniques available for risk identification are more suitable for identification of negative risks than opportunities (Hillson 2002). Most of the selected articles focused on the identification of risks from the perspective of their impacts on an individual project objective, mainly cost or time, and rarely on quality, safety, and environmental objectives. Overlooking the multifaceted impacts of risks on project objectives in the identification process can lead to underestimation of project contingency allowance (Zou and Zhang 2009). In the majority of the selected articles, risk identification is focused on a specific project phase (predominantly the construction phase), rather than the entire project life cycle. Only a few of the selected articles identified both risks and their respective response strategies. Moreover, secondary risks that may arise due to the implementation of response strategies were given less attention. Additionally, the review conducted on the selected articles indicates that there is a lack of studies that examine critical risks from the perspective of more than one project party. Identifying risks from the perspective of different parties gives a better understanding of the attitude and perception of the project parties on various risks (Zou and Zhang 2009). Consequently, the development of a comprehensive risk identification framework that enables risk identification for multiple project objectives and project phases and from the perspective of different project parties is an area that requires further investigation.

3.5 Chapter Summary

This chapter discussed a systematic review and detailed content analysis of 130 articles related to risk identification published in 14 well-regarded academic journals in construction engineering and management between 1990 and 2017. The selected articles encompassed risk identification on various types of construction projects located in different geographical locations. Common risk identification tools and techniques and risk classification methods used in the construction risk management process were investigated. Also, common potential risks that affect construction projects were identified from the selected articles, categorized based on the nature of the risks, and ranked. The conclusions drawn in this chapter are based on the review and content analysis done on the selected articles.

The findings of the content analysis show that a combination of two or more risk identification tools and techniques were widely used in the selected articles. An appropriate combination of tools and techniques helps to achieve better results in identifying potential risks. For identifying risks, literature reviews, questionnaire surveys, and expert interviews were the most frequently used tools and techniques, while diagramming and analysis-based risk identification tools and techniques were rarely used. The review of existing classification methods revealed that there is no standard or consensus on the categorization of risks in the construction industry. Risk classification based on the nature and source of risks was the most common method in the selected articles. A two-level RBS was used in a large proportion of the selected articles, and the top five common category names used for classifying risks based on their nature were economic, political, construction, financial, and management. In this chapter, the risks identified from the selected articles were categorized into eleven categories: management, technical, construction, resource-related, site conditions, contractual and legal, economic and financial, social, political, environmental, and health and safety. Categorizing risks in such a manner helps to avoid redundancy and ambiguity and contributes to the effectiveness and quality of the risk identification process because the categories are detailed and comprehensive. In order to rank the risks belonging in each category, the percentage of articles in which a particular risk is mentioned was used, and the top ten risks in each category were presented in this chapter. The top five most frequently mentioned risks in the selected articles based on the overall rank of the risks were unpredicted change of inflation rate; design errors and poor engineering; changes in government laws, regulations, and policies affecting the project; adverse weather conditions (continuous rainfall, snow, temperature, wind); and unpredicted adverse subsurface conditions. The comparison between risk categories reflects that the economic and financial risk category was the most frequently identified, while health and safety and social risk categories were the least frequently identified.

The main contributions of this chapter can be grouped into four areas. First, the chapter presents a critical review of the state of the art in risk identification, which has not been examined in as great detail as compared to risk modeling and analysis. The chapter also provides a systematic and in depth content analysis of previous studies and establishes research areas in need of further examination. Second, the chapter identifies the most common risk identification tools and techniques and risk classification methods used in the selected articles published in construction engineering and management journals. Third, the chapter identifies, categorizes, and ranks the most common risks affecting construction projects. Fourth, a comprehensive risk classification method applicable for different types of construction projects and project stakeholders has been proposed. The proposed classification method helps to categorize diverse risks identified from the selected articles. The findings of this chapter are of value to both researchers and industry practitioners seeking a useful reference on common potential risks affecting construction projects for future risk identification, analysis, and modeling purposes. In the next chapter, the methodology for developing hybrid FSD model to analyze the severity of risk and opportunity events on work package cost and determine work package and project contingency is presented.

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Chapter 4 Fuzzy System Dynamics Modelling Methodology[4]

4.1 Introduction

In this chapter, the overall methodology and detailed steps for developing the hybrid FSD model to analyze the severity of risk and opportunity events on work package costs and to determine work package and project contingencies are presented. The methodology is illustrated in Figure 4.1 and the details are described in the following sections.

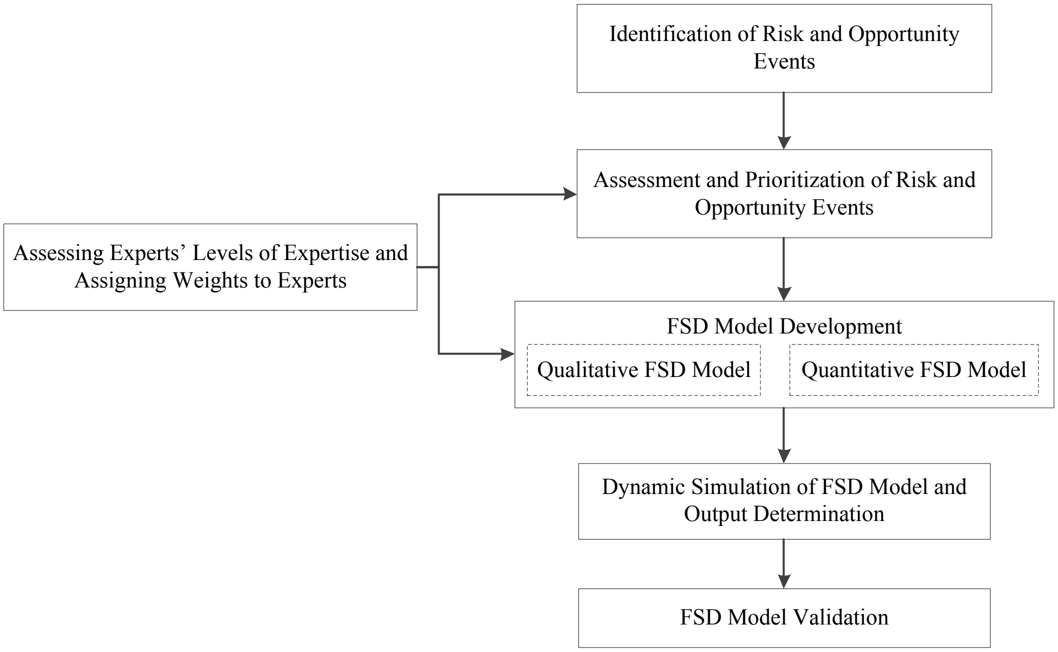

Figure 4.1. Steps for developing FSD model for risk analysis and contingency determination

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4.2 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 as discussed in Chapter 3. The risk and opportunity events identified from the selected articles 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.

4.3 Assessing Experts' Levels of Expertise and Assigning Importance weights to Experts

Groups of experts with different levels of knowledge, experience, and expertise are often involved in decision-making at different stages of risk assessment and management. Decision-making groups in risk management can be classified as either homogeneous or heterogeneous. This classification is based on the importance degree of the experts in a group. If the opinions of all experts are considered equally important, the group is considered homogeneous; otherwise, it is referred to as a heterogeneous group (Herrera-Viedma et al. 2014). The most common approach for addressing the heterogeneity of a group in risk management is to assign importance weights to every expert based on their expertise level (Herrera-Viedma et al. 2014).

The aggregation methods employed in previously developed FSD methods do not take into account experts' levels of expertise in risk management. In most cases, importance weights are assigned to experts directly by a moderator or manager (Siraj et al. 2018). In this chapter, 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 importance weights of 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 (qualification attributes) that are quantitative or qualitative (Table 4.1). A predetermined rating scale (1−5) was established for assessing each of the qualitative qualification attributes, as shown in Appendix B. After assessing the experts' levels of expertise based on the qualification attributes, 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). The FAHP method allows experts to carry out pairwise comparisons using fuzzy linguistic scales, unlike the classical AHP, which uses crisp numbers. Consequently, the relative weights of the qualification attributes and criteria are determined using the FAHP method based on the pairwise assessments of the experts (Monzer et al. 2019).

Table 4.1. Criteria and sub-criteria for assessing experts' expertise level (Monzer et al. 2019)

Criteria	Sub-Criteria	Scale of measure
1. Experience	1.1 Total years of experience	Real number
	1.2 Diversity of experience	Integer
	1.3 Relevant experience	Real number
	1.4 Applied experience	Real number
	1.5 Varied experience	Integer
2. Knowledge	2.1 Academic knowledge	Real number
	2.2 Education level	Predetermined rating
	2.3 On the job training	Integer
3. Professional performance	3.1 Current occupation in the company	Predetermined rating
	3.2 Years in current occupation	Real number
	3.3 Expertise self-evaluation	Predetermined rating
4. Risk management practice	4.1 Average hours of work in risk per week	Real number
	4.2 Risk management training	Integer
	4.3 Risk management conferences experience	Integer
	4.4 Risk identification and planning	Predetermined rating
	4.5 Risk monitoring and control	Predetermined rating
	4.6 Crisis management	Predetermined rating
5. Project specifics	5.1 Project size limit	Real number
	5.2 Commitment to time deadlines	Real number
	5.3 Commitment to cost budget	Real number
	5.4 Safety adherence	Integer
	5.5 Geographic diversity experience	Integer
6. Reputation	6.1 Social acclamation	Predetermined rating
	6.2 Willingness to participate in survey	Predetermined rating
	6.3 Professional reputation	Predetermined rating
	6.4 Enthusiasm and willingness	Predetermined rating
	6.5 Level of risk conservativeness	Predetermined rating
7. Personal attributes and skills	7.1 Level of communication skills	Predetermined rating
	7.2 Level of teamwork skills	Predetermined rating
	7.3 Level of leadership skills	Predetermined rating
	7.4 Level of analytical skills	Predetermined rating
	7.5 Level of ethics	Predetermined rating

4.4 Assessment and Prioritization of Risk and Opportunity Events

Risk and opportunity events are commonly prioritized and ranked based on a probability–impact (P–I) score determined using probability–impact matrix (CII 2012) and based on mean criticality index by assessing the criticality of risk events (Wang et al. 2004). These approaches are simple and transparent; however, the probability and impact in P–I matrix and the criticality of risks are assessed using linguistic terms represented by numerical values or a Likert scale, neither of which captures the subjective uncertainties involved in assessing the probability and impact of risks. Moreover, risk assessment and prioritization are carried out at the project level, and opportunities are often not incorporated in the assessment. This chapter presents a fuzzy-based risk assessment procedure, which assesses the probability and impact of both risk and opportunity events and considers the experts' expertise level, to assess and prioritize risk and opportunity events. An interview survey was designed based on the refined risk and opportunity events. The survey was divided into two major sections: the first section included general information to assess project and work package characteristics (see Appendix C), and the second section deals with the assessment of potential risk and opportunity events affecting work packages (see Appendix D). 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: very low, low, medium, high, and very high (in addition to N/A-Not applicable), represented by triangular or trapezoidal fuzzy numbers. Each risk and opportunity event was assessed twice: once assuming it may lead to a risk (using probability and impact scales for risk), and once assuming it may lead to an opportunity (using probability and impact scales for opportunity). 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. (4.1) and Eq. (4.2) to obtain the collective assessment of the experts.

$$\tilde{P}_{R_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{P}_{R_{ib}}^{(k)} \; ; \; \tilde{I}_{R_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{I}_{R_{ib}}^{(k)} ; \; \tilde{P}_{O_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{P}_{O_{ib}}^{(k)} \; ; \; \tilde{I}_{O_{ib}} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k \otimes \tilde{I}_{O_{ib}}^{(k)} \qquad (4.1)$$

$$C_{ib} = \sum_{\mathrm{k=1}}^{\mathrm{v}} W_k C_{ib}^{(k)} \qquad (4.2)$$

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

$\otimes$ is fuzzy multiplication, and the summation in Eq. (4.1) is carried out using fuzzy addition.

Once the aggregated probabilities ($\tilde{P}_{R_{ib}}$, $\tilde{P}_{O_{ib}}$) and aggregated impacts ($\tilde{I}_{R_{ib}}$, $\tilde{I}_{O_{ib}}$) of risk and opportunity events and the aggregated percentage of work package cost affected (C_{ib}) are obtained, the net severity percentage of the ith risk and opportunity event on the bth work package ($\widetilde{NS}_{ib}$) is determined as follows:

$$\widetilde{NS}_{ib} = C_{ib} \otimes \left[\tilde{S}_{R_{ib}} \ominus \tilde{S}_{O_{ib}}\right] = C_{ib} \otimes [(\tilde{P}_{R_{ib}} \otimes \tilde{I}_{R_{ib}}) \ominus (\tilde{P}_{O_{ib}} \otimes \tilde{I}_{O_{ib}})] \qquad (4.3)$$

where:

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

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

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

The overall net severity percentage of the ith risk and opportunity event on the project ($\widetilde{NS}_i$) is determined by taking into account the relative weight of the work package (K_b) in terms of its share of the total project cost, as follows:

$$\widetilde{NS}_i = \sum_{\mathrm{b}=1}^{\mathrm{g}} K_b \otimes \widetilde{NS}_{ib} \qquad (4.4)$$

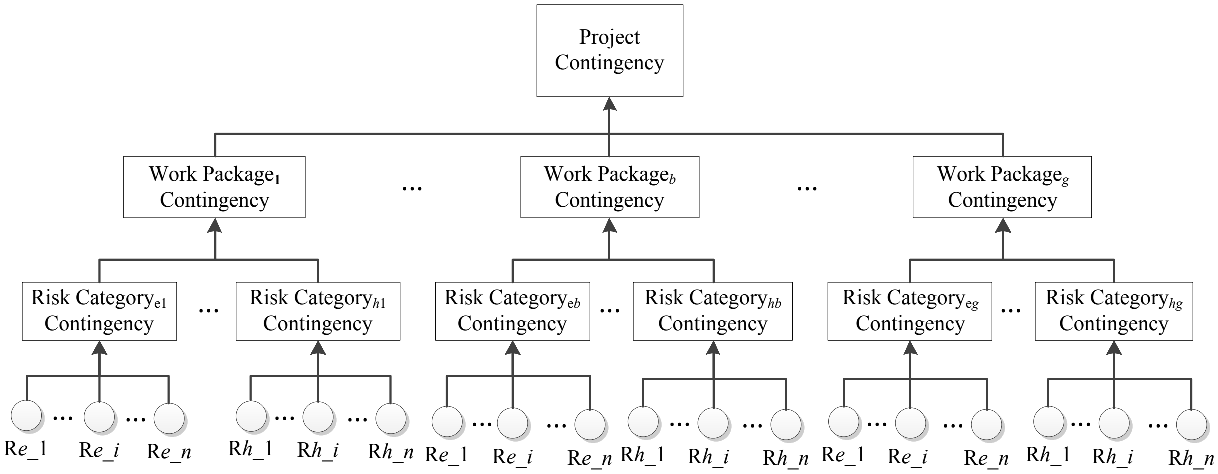
The net severity percentage of risk and opportunity events on a work package ($\widetilde{NS}_{ib}$) and the overall net severity percentage of risk and opportunity events on a project ($\widetilde{NS}_i$) were defuzzified using the center of area (COA) method as it best represents the shape of the fuzzy number. Then, the risk and opportunity events were ranked and prioritized at a work package and project level based on their defuzzified net severity percentage (NS_{ib}^{Def}) and overall net severity percentage (NS_i^{Def}), respectively. Finally, the most severe risk and opportunity events which need to be considered in the FSD model were determined.

4.5 FSD Model Development

In this chapter, the FSD model for risk analysis and contingency determination was developed in two stages: (1) development of the qualitative model to establish the causal interactions and feedback structures among risk and opportunity events and to define the flows and stocks and (2) development of the quantitative model to analyse the severity of prioritized risk and opportunity events on work package cost and consequently determine work package and project contingency. The steps involved in these two stages are discussed in the following subsections.

4.5.1 Constructing the Qualitative FSD Model

The first step in constructing the qualitative FSD model is determining the risk and opportunity events that need to be considered in the FSD model, which was achieved by ranking and prioritizing the risk and opportunity events as discussed in the previous section. Other key model parameters and variables, such us *forecasted total work package cost*, *forecasted monthly progress percentage*, and *forecasted monthly progress in dollars*, that need to be considered when formulating the model were identified. Then, the model boundary, which reflects the modeling scope, and the level of aggregation, which deals with grouping activities into subsystems (components), were established in order to achieve realistic abstraction and representation. In this chapter, risk analysis and contingency determination was carried out at the work package level. Risk and opportunity events were grouped into 11 categories, and the causal relationships among the risk and opportunity events were modeled to determine the cost contingency of each work package (subsystem). Then, the work package FSD models were aggregated to create the whole project system and determine project contingency. Figure 4.2 depicts the level of aggregation in the FSD model.



Where: Work package$_b$ (b=1,2,..,g) is the bth work package in a project

Risk Category$_{eb}$ (e=1,2,..,h; b=1,2,..g) is the eth risk category in the bth work package

Re_i (e=1,2,..,h; i=1,2,..n) is the ith risk and opportunity event in the eth risk category

Figure 4.2. Level of aggregation in the FSD model

The fundamental purpose of SD and FSD is to capture how the parts in a system interact with one another and how a change in one variable affects the other variable over time (Boateng et al. 2012; Nasirzadeh et al. 2008). Causal loop diagrams (CLDs) are employed in SD and FSD models to map interdependencies and causal structures among model variables. The literature reveals that there is a lack of structured and systematic methods for constructing CLDs to capture the causal relationships among risk and opportunity events. CLDs in SD and FSD models for risk analysis and contingency determination in construction are commonly constructed based on modellers' assumptions and experts' verification (Wang and Yuan 2017; Boateng et al. 2012) or, alternatively, the conceptual foundations of the models are borrowed from other fields and modified to make them applicable for construction projects (Nasirzadeh et al. 2008; Nasirzadeh et al. 2014).

A structured and systematic method based on fuzzy DEMATEL (decision making trial and evaluation laboratory) is proposed in this chapter 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 (Nazeri and Naderikia 2017; Jalal and Shoar 2017). The DEMATEL method has several benefits: it gathers group knowledge for capturing causal interactions among elements; it helps with the visualization of complex causal interactions through matrices and diagraphs (directed graphs); it determines the degree of causal interactions among elements; and it separates elements into cause and effect groups (Bavafa et al. 2018; Dehdasht et al. 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), Can and Toktas (2018), and Samani and Shahbodaghlou (2012) 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 (i.e., to avoid repetition in the assessment) for which the causal relationships will be investigated. Then, a fuzzy DEMATEL survey form comprising a pairwise comparison matrix is created in Excel worksheet (see Appendix E). 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 (i.e., very low, low, medium, high, and very high, in addition to N/A-not applicable) that are represented by triangular fuzzy numbers, as shown in Table 4.2. The experts also define the types of causal relationships (i.e., the polarity of the causal link) between risk and opportunity events as positive, negative, or N/A-not applicable. A positive link implies that the risk and opportunity events change in the same direction while a negative link signifies the contrary.

Table 4.2. Linguistic terms and fuzzy numbers for assessing the degree of causal influence

Linguistic terms	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 experts' pairwise assessments of the risk and opportunity events using linguistic terms are replaced with the corresponding triangular fuzzy numbers (Table 4.2). The assessment by each expert results nxn initial fuzzy matrix ($\tilde{X}^{(k)}$) for each work package, which is expressed as

$$\tilde{X}^{(k)} = \left[\tilde{x}_{ij}^{(k)}\right]_{nxn} = \begin{bmatrix} 0 & \tilde{x}_{12}^{(k)} & \cdots & \tilde{x}_{1n}^{(k)} \\ \tilde{x}_{21}^{(k)} & 0 & \cdots & \tilde{x}_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1}^{(k)} & \tilde{x}_{n2}^{(k)} & \cdots & 0 \end{bmatrix} \tag{4.5}$$

where $\tilde{x}_{ij}^{(k)}$ $(i, j = 1, 2, \ldots, n; k = 1, 2, \ldots, v)$, 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 $\tilde{X}^{(1)}, \tilde{X}^{(2)}, \ldots, \tilde{X}^{(v)}$ of v experts are aggregated by taking into account the importance weight of each expert using Eq. (4.6), and as a result, the fuzzy direct-relation matrix ($\tilde{X}^{C}$), represented by Eq. (4.7), is generated.

$$\tilde{x}_{ij}^{C} = \sum_{k=1}^{v} W_k \otimes \tilde{x}_{ij}^{(k)} = \sum_{k=1}^{v} W_k \otimes \left(l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)}\right) \qquad (4.6)$$

$$\tilde{X}^{C} = \left[\tilde{x}_{ij}^{C}\right]_{nxn} = \begin{bmatrix} 0 & \tilde{x}_{12}^{C} & \cdots & \tilde{x}_{1n}^{C} \\ \tilde{x}_{21}^{C} & 0 & \cdots & \tilde{x}_{2n}^{C} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1}^{C} & \tilde{x}_{n2}^{C} & \cdots & 0 \end{bmatrix} \qquad (4.7)$$

where $\tilde{x}_{ij}^{C}$ $(i, j = 1, 2, \ldots, n)$, defined by a triplet $(\bar{l}_{ij}, \bar{m}_{ij}, \bar{u}_{ij})$, denotes the aggregated degree of causal influence of the ith risk and opportunity event on the jth risk and opportunity event; and W_k $(k = 1, 2, \ldots, v$ and $\sum_{k=1}^{v} W_k = 1)$ 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 by dividing the elements of the fuzzy direct-relation matrix $(\tilde{X}^{C})$ by the number λ as expressed in Eqs. (4.8)–(4.9). The resulting matrix is the normalized fuzzy direct-relation matrix $(\tilde{Z})$, defined in Eq. (4.10).

$$\tilde{Z} = \frac{\tilde{X}^{C}}{\lambda} = \frac{\tilde{x}_{ij}^{C}}{\lambda} = \left(\frac{\bar{l}_{ij}}{\lambda}, \frac{\bar{m}_{ij}}{\lambda}, \frac{\bar{u}_{ij}}{\lambda}\right) \qquad (4.8)$$

$$\lambda = \max_{1 \le i \le n} \sum_{j=1}^{n} \bar{u}_{ij} \qquad (4.9)$$

$$\tilde{Z} = \left[\tilde{z}_{ij}\right]_{nxn} = \begin{bmatrix} 0 & \tilde{z}_{12} & \cdots & \tilde{z}_{1n} \\ \tilde{z}_{21} & 0 & \cdots & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \cdots & 0 \end{bmatrix} \qquad (4.10)$$

where $\tilde{z}_{ij}$ $(i, j = 1, 2, \ldots, n)$, defined by a triplet $\left(l'_{ij}, m'_{ij}, u'_{ij}\right)$, denotes the normalized degree of causal influence of the ith risk and opportunity event on the jth 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. (4.11), where I is the identity matrix.

$$T = \lim_{m\to\infty}(Z + Z^2 + \cdots + Z^m) = \sum_{m=1}^{\infty} Z^m = Z(I - Z)^{-1} \qquad (4.11)$$

In order to adopt 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 as follows:

$$Z_l = \left[l'_{ij}\right]_{nxn} = \begin{bmatrix} 0 & l'_{12} & \cdots & l'_{1n} \\ l'_{21} & 0 & \cdots & l'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l'_{n1} & l'_{n2} & \cdots & 0 \end{bmatrix} \qquad (4.12)$$

$$Z_m = \left[m'_{ij}\right]_{nxn} = \begin{bmatrix} 0 & m'_{12} & \cdots & m'_{1n} \\ m'_{21} & 0 & \cdots & m'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m'_{n1} & m'_{n2} & \cdots & 0 \end{bmatrix} \qquad (4.13)$$

$$Z_u = \left[u'_{ij}\right]_{nxn} = \begin{bmatrix} 0 & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & 0 & \cdots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{n1} & u'_{n2} & \cdots & 0 \end{bmatrix} \qquad (4.14)$$

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, (4.11) as follows:

$$T_l = \left[l''_{ij}\right]_{nxn} = Z_l(I - Z_l)^{-1} \qquad (4.15)$$

$$T_m = \left[m''_{ij}\right]_{nxn} = Z_m(I - Z_m)^{-1} \quad (4.16)$$

$$T_u = \left[u''_{ij}\right]_{nxn} = Z_u(I - Z_u)^{-1} \qquad (4.17)$$

Finally, the fuzzy total-relation matrix ($\tilde{T}$) defined by Eq. (4.18) 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 ($\tilde{T}$).

$$\tilde{T} = \left[\tilde{t}_{ij}\right]_{nxn} = \begin{bmatrix} 0 & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & 0 & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & 0 \end{bmatrix} \qquad (4.18)$$

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 ith risk and opportunity event on the jth risk and opportunity event and I is the identity matrix.

Step 6: Compute the sum of rows ($\tilde{R}$) and columns ($\tilde{C}$) from the fuzzy total-relation matrix using Eq. (4.19) and (4.20), respectively.

$$\tilde{R} = [\tilde{r}_i]_{nx1} = \left[\sum_{j=1}^{n} \tilde{t}_{ij}\right]_{nx1} \qquad (4.19)$$

$$\tilde{C} = \left[\tilde{c}_j\right]_{nx1} = \left[\sum_{j=1}^{n} \tilde{t}_{ij}\right]_{1xn} \qquad (4.20)$$

where $\tilde{r}_i$ denotes the total causal influence of the ith risk and opportunity event on all other risk and opportunity events considered for a given work package and $\tilde{c}_j$ shows the effect of all other risk and opportunity events on the jth risk and opportunity event.

Step 7: Construct the influence relation map (IRM).

The IRM of the risk and opportunity events for each work package are constructed by mapping the defuzzified values of $(\tilde{R} + \tilde{C})$ and $(\tilde{R} - \tilde{C})$. The horizontal axis $(\tilde{R} + \tilde{C})^{def}$ is referred to as "prominence" and shows the importance degree of the risk and opportunity event (in terms of its causal relationship). Risk and opportunity events with high $(\tilde{R}+\tilde{C})^{def}$ values have more causal relations with the other risk and opportunity events. The vertical axis $(\tilde{R}-\tilde{C})^{def}$ is referred to as "relation" and divides the risk and opportunity events into cause and effect groups. When the $(\tilde{R}-\tilde{C})^{def}$ value is positive, the risk and opportunity event belongs to the cause group, and the event belongs to the effect group if the value is negative.

Step 8: Construct the CLDs from the IRMs.

First, the fuzzy total-relation matrix $(\tilde{T})$ is defuzzified using the COA method to determine the corresponding defuzzified total-relation matrix (T^{Def}). The defuzzified total-relation matrix (T^{Def}) has a two fold benefit: (1) it helps to systematically determine the causal relationships among the risk and opportunity events to be considered in developing the CLDs and (2) it helps to obtain the degree of causal influence values (t_{ij}^{Def}) between two risk and opportunity events that will later be used in the quantitative FSD model. 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. The threshold value is commonly determined by experts through discussion, based on a certain percentile (e.g., 75th percentile) value of all elements in the T^{Def} matrix, or based on the average of all elements in the T^{Def} matrix (Si et al. 2018). Then, the IRMs of the work packages are translated to CLDs based on the defuzzified total-relation matrix (T^{Def}).

After the CLDs are developed based on the proposed fuzzy DEMATEL method, the flows and stocks used in the FSD model are identified. The flows (rates) considered in the FSD model are *Risk Severity in Dollars*, *Opportunity Severity in Dollars*, and *Net Severity in Dollars* for each risk and opportunity category, work package, and project. The corresponding stocks (representing the accumulation of the severities) are *Risk Contingency in Dollars*, *Opportunity Contingency in Dollars*, and *Net Contingency in Dollars* of the risk and opportunity categories, work packages, and project. Finally, the qualitative FSD model of the project (comprising the work packages and their corresponding risk and opportunity event categories) are created using simulation software (AnyLogic® 8.2.3).

A wind farm construction project with three major work packages, namely civil, structural, and electrical, is used as an example to illustrate the qualitative FSD model. Figure 4.3 depicts the CLD showing the causal relationships between management risk and opportunity events and the causal effects of risk and opportunity events from other categories on management risk and opportunity events for a structural work package. The flow and stock diagrams of the management risk and opportunity event category, a structural work package, and the wind farm project are shown in Figures 4.4–4.6, respectively.

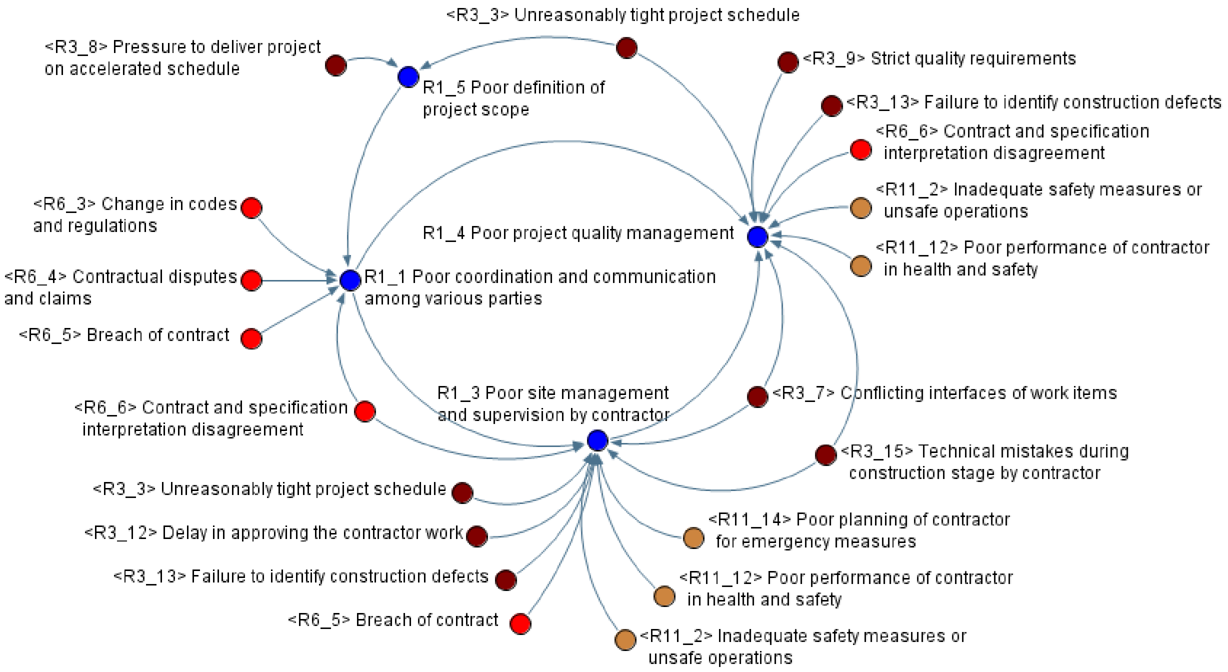


Figure 4.3. Causal loop diagram of the management risk and opportunity event category for structural work package

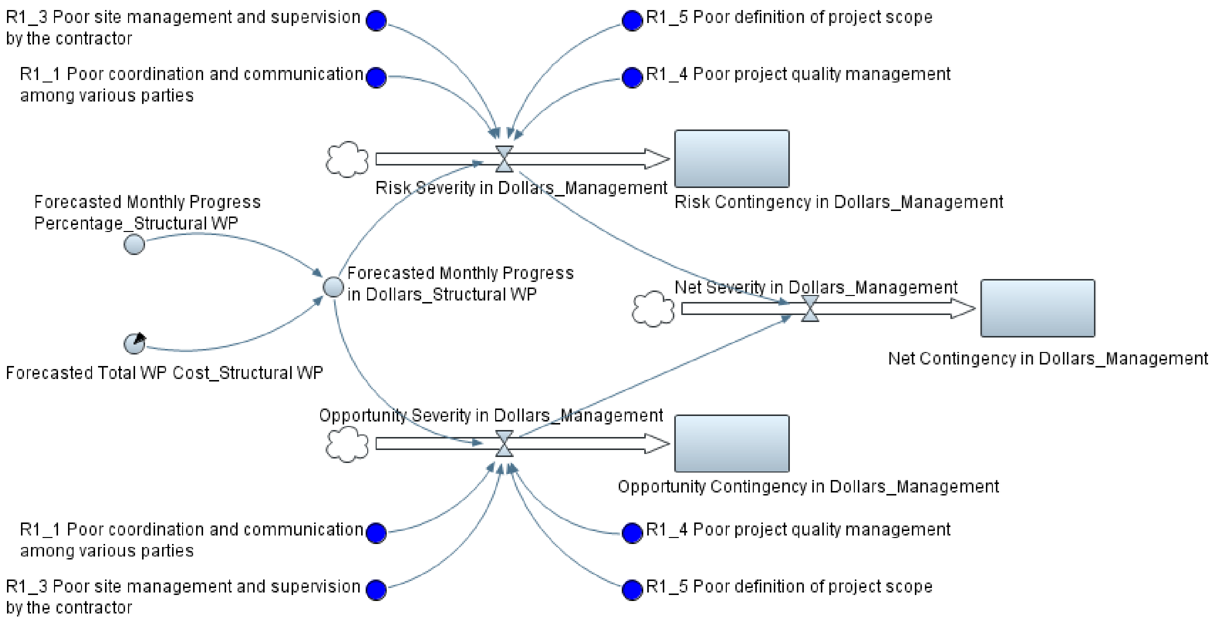


Figure 4.4. Flow and stock diagram of the management risk and opportunity event category for structural work package

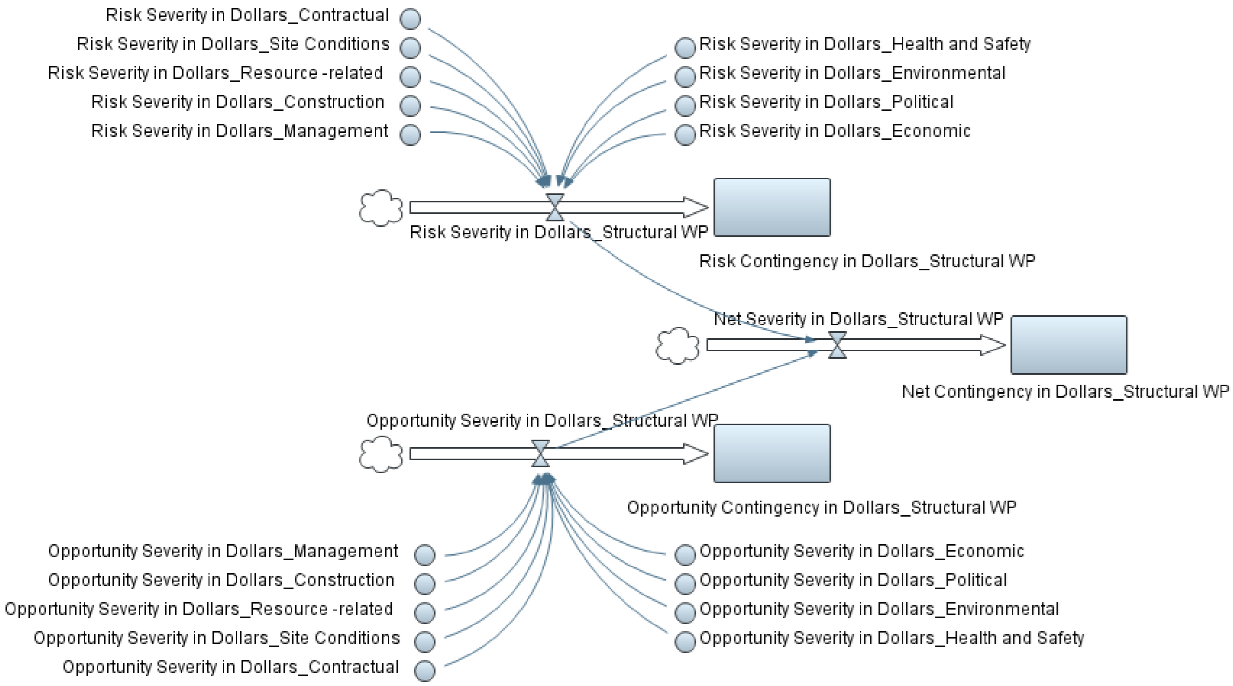


Figure 4.5. Flow and stock diagram of a structural work package

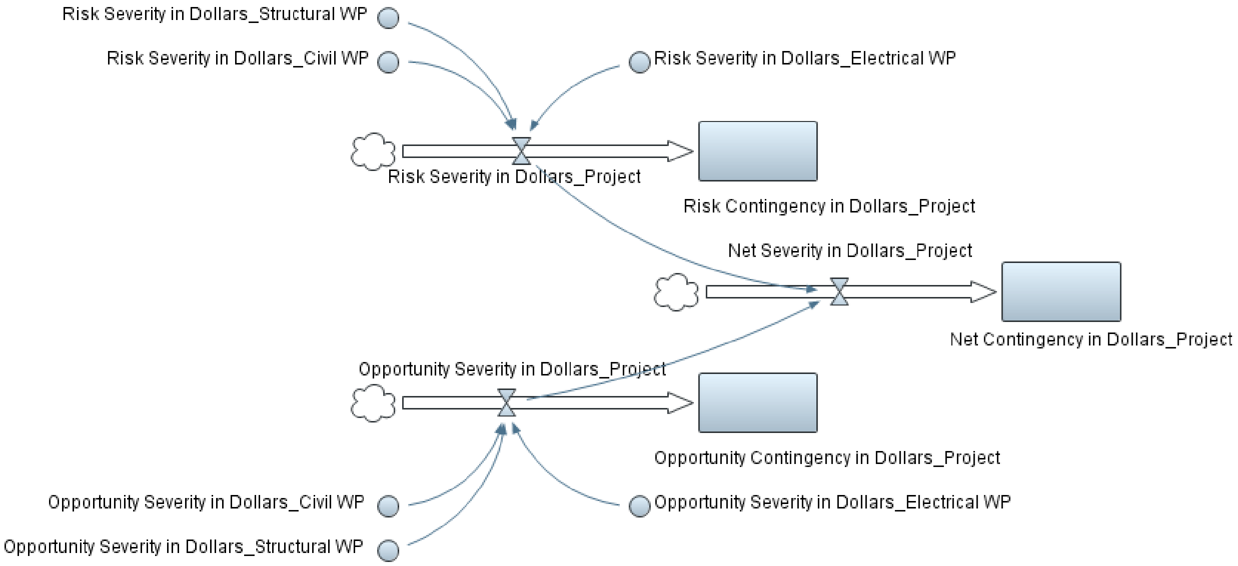


Figure 4.6. Flow and stock diagram of the wind farm project

4.5.2 Constructing the Quantitative FSD Model

The causal relationships in the CLDs as well as the flows and stocks in the qualitative model need to be formulated to develop the quantitative FSD model and simulate it. The quantitative FSD model determines work package and project cost contingency by analyzing the severity of interrelated risks and opportunity events on the work packages. Schedule, quality, and health and safety risk and opportunity events are accounted for in the FSD model and monetized based on their severity on work package costs. However, the time contingency that should be added to the project duration is not accounted for. The mathematical procedure used in the FSD model to determine the work package and project contingency are described as follows.

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

First, the parameters and variables involved in the FSD model are identified as objective and subjective (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 (probabilistic uncertainties). In the FSD model, objective variables (e.g., *forecasted monthly progress percentage* (A_b), *forecasted total work package cost* (D_b), and *forecasted monthly progress in dollars* (F_b)) of the bth work package are quantified using crisp numbers. Subjective (fuzzy) variables are defined by membership functions to capture the subjective uncertainties resulting from linguistic approximation. Since the probability and impact of the risk and opportunity events are assessed using linguistic scales represented by triangular and trapezoidal fuzzy numbers, the risk and opportunity events are considered as subjective (fuzzy) variables in the FSD model and they are represented by fuzzy arrays. Using arrays allow to store multi-dimensional data to a given system variable. Arrays can have any number of dimensions, and each dimension has a finite number of indices (subscripts). In other words, the use of an array with two dimensions is similar to the representation of a given system variable by a matrix. 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}) as expressed in Eq. (4.21). The advantage of using an array is that it can represent large number of fuzzy variables with several attributes (dimensions) while keeping the FSD model compact and efficient. If each element of the attributes were represented as a variable instead of using arrays, the model would be complicated and would become more difficult to understand as the number of variables increased, consequently increasing the simulation run time.

$$\tilde{R}_{ib} = \begin{array}{c|cccc|} & l_{ib} & m_{1ib} & m_{2ib} & u_{ib} \\ \tilde{P}_{R_{ib}} & 0.18 & 0.35 & 0.40 & 0.64 \\ \tilde{I}_{R_{ib}} & 0.06 & 0.25 & 0.44 & 0.69 \\ \tilde{S}_{R_{ib}} & 0.01 & 0.09 & 0.18 & 0.44 \\ \tilde{P}_{O_{ib}} & 0.06 & 0.21 & 0.21 & 0.26 \\ \tilde{I}_{O_{ib}} & 0.00 & 0.07 & 0.13 & 0.19 \\ \tilde{S}_{O_{ib}} & 0.00 & 0.01 & 0.03 & 0.04 \\ C_{ib} & 0.20 & 0.20 & 0.20 & 0.20 \\ t_{ij}^{Def} & 0.08 & 0.08 & 0.08 & 0.08 \end{array} \qquad (4.21)$$

Step 2: Define the relationships between risk and opportunity events and calculate the values of the risk and opportunity event attributes (i.e., risk probability, opportunity probability, risk severity and opportunity severity).

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. If the causal link between the predecessor and posterior risk and opportunity events is positive, an increase/decrease in the probability of occurrence of the predecessor risk and opportunity event results in an increase/decrease of the probability of occurrence of the posterior risk and opportunity event. The opposite is true if the causal link is negative between the predecessor and 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. (4.22).

$$\tilde{P}^*_{R_{jb}} = \frac{\tilde{P}_{R_{jb}} \oplus \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def} \otimes \tilde{P}_{R_{ib}}}{1.0 + \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def}}; \quad \tilde{P}^*_{O_{jb}} = \frac{\tilde{P}_{O_{jb}} \oplus \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def} \otimes \tilde{P}_{O_{ib}}}{1.0 + \sum_{\mathrm{i}=1}^{\mathrm{n}} t_{(ij)b}^{Def}} \quad (4.22)$$

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 events 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 events 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}, $t_{(ij)b}^{Def}$) 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 level.

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 ($\tilde{S}_{R_{ib}}^{*}$) 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 (monthly) using Eqs. (4.23)–(4.31), as provided in Table 4.3. The accumulations of each of the flow variables result 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. (4.32)–(4.40) in Table 4.3. The time plots of the contingency values will result in contingency accumulation curves as the forecasted monthly progress percentage (A_b) is used in determining the risk and opportunity severities at each time step. The corresponding contingency depletion curves for the work packages and the project can be constructed from the contingency accumulation curves, as described in the next chapter (Section 5.5).

Table 4.3. 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 ($\widetilde{RSD}_{eb}^{RC}$)	$\widetilde{RSD}_{eb}^{RC} = \sum_{i=1}^{n} C_{ib}\, F_b \otimes \tilde{S}_{R_{ib}}^{*}$ (4.23)	Risk contingency in dollars ($\widetilde{RCD}_{eb}^{RC}$)	$\widetilde{RCD}_{eb}^{RC} = \int_{t_0}^{t} \widetilde{RSD}_{eb}^{RC}\,(t)dt$ (4.32)
	Opportunity severity in dollars ($\widetilde{OSD}_{eb}^{RC}$)	$\widetilde{OSD}_{eb}^{RC} = \sum_{i=1}^{n} C_{ib}\, F_b \otimes \tilde{S}_{O_{ib}}^{*}$ (4.24)	Opportunity contingency in dollars ($\widetilde{OCD}_{eb}^{RC}$)	$\widetilde{OCD}_{eb}^{RC} = \int_{t_0}^{t} \widetilde{OSD}_{eb}^{RC}\,(t)dt$ (4.33)
	Net severity in dollars ($\widetilde{NSD}_{eb}^{RC}$)	$\widetilde{NSD}_{eb}^{RC} = \widetilde{RSD}_{eb}^{RC} \ominus \widetilde{OSD}_{eb}^{RC}$ (4.25)	Net contingency in dollars ($\widetilde{NCD}_{eb}^{RC}$)	$\widetilde{NCD}_{eb}^{RC} = \int_{t_0}^{t} \widetilde{NSD}_{eb}^{RC}\,(t)dt$ (4.34)
Work package ($1 \leq b \leq g$)	Risk severity in dollars ($\widetilde{RSD}_{b}^{WP}$)	$\widetilde{RSD}_{b}^{WP} = \sum_{e=1}^{h} \widetilde{RSD}_{eb}^{RC}$ (4.26)	Risk contingency in dollars ($\widetilde{RCD}_{b}^{WP}$)	$\widetilde{RCD}_{b}^{WP} = \int_{t_0}^{t} \widetilde{RSD}_{b}^{WP}\,(t)dt$ (4.35)
	Opportunity severity in dollars ($\widetilde{OSD}_{b}^{WP}$)	$\widetilde{OSD}_{b}^{WP} = \sum_{e=1}^{h} \widetilde{OSD}_{eb}^{RC}$ (4.27)	Opportunity contingency in dollars ($\widetilde{RCD}_{b}^{WP}$)	$\widetilde{OCD}_{b}^{WP} = \int_{t_0}^{t} \widetilde{OSD}_{b}^{WP}\,(t)dt$ (4.36)
	Net severity in dollars ($\widetilde{NSD}_{b}^{WP}$)	$\widetilde{NSD}_{b}^{WP} = \widetilde{RSD}_{b}^{WP} \ominus \widetilde{OSD}_{b}^{WP}$ (4.28)	Net contingency in dollars ($\widetilde{NCD}_{b}^{WP}$)	$\widetilde{NCD}_{b}^{WP} = \int_{t_0}^{t} \widetilde{NSD}_{b}^{WP}\,(t)dt$(4.37)
Project	Risk severity in dollars ($\widetilde{RSD}^{PR}$)	$\widetilde{RSD}^{PR} = \sum_{b=1}^{g} \widetilde{RSD}_{b}^{WP}$ (4.29)	Risk contingency in dollars ($\widetilde{RCD}^{PR}$)	$\widetilde{RCD}^{PR} = \int_{t_0}^{t} \widetilde{RSD}^{PR}\,(t)dt$ (4.38)
	Opportunity severity in dollars ($\widetilde{OSD}^{PR}$)	$\widetilde{OSD}^{PR} = \sum_{b=1}^{g} \widetilde{OSD}_{b}^{WP}$ (4.30)	Opportunity contingency in dollars ($\widetilde{OCD}^{PR}$)	$\widetilde{OCD}^{PR} = \int_{t_0}^{t} \widetilde{OSD}^{PR}\,(t)dt$ (4.39)
	Net severity in dollars of ($\widetilde{NSD}^{PR}$)	$\widetilde{NSD}^{PR} = \widetilde{RSD}^{PR} \ominus \widetilde{OSD}^{PR}$ (4.31)	Net contingency in dollars ($\widetilde{NCD}^{PR}$)	$\widetilde{NCD}^{PR} = \int_{t_0}^{t} \widetilde{NSD}^{PR}\,(t)dt$ (4.40)

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.

4.6 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 is involved in a given mathematical expression. The type of fuzzy arithmetic and output determination methods used in the FSD model are discussed in the following section.

4.7 Fuzzy Arithmetic and Output Determination Methods

The type of fuzzy arithmetic method used and the choice of fuzzy operators, such as *t*-norm, have a considerable effect on the output of the FSD model. Basically, there are two methods of carrying out fuzzy arithmetic operations in the FSD model: the alpha-cut (α-cut) method and the extension principle, based on *t*-norms. The α-cut method applies interval arithmetic to each α-cut level of any two fuzzy numbers, at any level α ε (0,1] (Eq. 4.41), and takes the union of the results to determine an output fuzzy number based on the representation theorem (Eq. 4.42) (Pedrycz and Gomide, 2007).

$$(A * B)_\alpha = A_\alpha * B_\alpha \qquad (4.41)$$

$$A * B = \bigcup_{\alpha \in [0,1]} (A * B)_\alpha \qquad (4.42)$$

where A and B are two fuzzy numbers, $*$ is any of the four basic arithmetic operations and when $*$ is a division operation, it is that that $0 \notin B_\alpha, \forall\, \alpha \epsilon\, (0,1]$.

The α-cut method is the most commonly used arithmetic method in FSD models. However, the α-cut method is based on interval arithmetic, which can lead to the phenomenon of accumulating fuzziness (due to growth of the support) and the overestimation of uncertainty in the model (Chang et al., 2006). On the other hand, the extension principle performs a point-wise calculation between the elements of the input fuzzy numbers and calculates the membership degree of the output points of the final fuzzy number by taking the supremum of the *t*-norms of the membership degrees of the input points as shown in Eq. (4.43) (Pedrycz and Gomide 2007).

$$(A * B)(z) = \operatorname*{Sup}_{z=x*y} [A(x)\ t\ B(y)] \qquad \forall \in \boldsymbol{R} \qquad (4.43)$$

where t stands for a *t*-norm, which is a binary operation on the unit interval [0,1] that is commutative, associative, and monotonic and $t(0, x) = 0$ and $t(1, x) = 1$ for every $x \in [0,1]$. The most widely used basic *t*-norms are: minimum *t*-norm (t_{min}), product *t*-norm (t_{prod}), Lukasiewicz (bounded difference) *t*-norm (t_{Luk}), and drastic *t*-norm (t_d). The minimum *t*-norm and drastic *t*-norm are the strongest and weakest *t*-norms, respectively as indicated in Eq. (4.44).

$$t_d(A * B) \leq t(A * B)(z) \leq t_{min}(A * B) \qquad (4.44)$$

The minimum *t*-norm gives the same result as the α-cut method. Moreover, the support of the fuzzy numbers obtained by using the minimum *t*-norm and the product *t*-norm are the same. Hence, the accumulations of fuzziness due to the minimum *t*-norm and the product *t*-norm are similar to the α-cut method (Gerami Seresht and Fayek 2018). The drastic *t*-norm, defined by Eq. (4.45), reduce the growth of fuzziness and the overestimation of uncertainty during calculations (Chang et al. 2006; Lin et al. 2011; Gerami Seresht and Fayek 2018). A more detailed discussion on fuzzy arithmetic can be found in Hanss (2005) and Pedrycz and Gomide (2007).

$$t_d(x,y) = \begin{cases} x, & if\ y = 1 \\ y, & if\ x = 1 \\ 0, & otherwise \end{cases} \qquad (4.45)$$

The literature shows that there is a lack of research on the implementation of fuzzy arithmetic by the extension principle method in FSD models for risk analysis and contingency determination. Recently, Gerami Seresht and Fayek (2018) explored the implementation of fuzzy arithmetic operations by both the α-cut and extension principle methods in an FSD model to determine the multi-factor productivity of equipment intensive activities. However, the fuzzy arithmetic approach they used is applicable only to triangular fuzzy numbers. In this research, 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.

In order to carry out fuzzy arithmetic based on the extension principle, continuous membership functions of fuzzy numbers need to be discretized into a finite number of points to obtain the corresponding fuzzy sets. Discretization can be achieved using a vertical or horizontal method, which subdivide the universe of discourse (x-axis) and the membership degree (y-axis), respectively into intervals of definite length (Hanss 2005). The vertical discretization method is straightforward and simple to implement. However, this method does not guarantee the inclusion of modal and boundary values of fuzzy numbers in the discretized sets for arbitrarily chosen intervals. In addition, it is difficult to maintain reasonable and consistent discretization intervals for fuzzy numbers with different dimensions (Hanss 2005). The horizontal method effectively addresses the problems of the vertical method as discretization in the horizontal method is done on the range of membership degrees, which is always equal to the closed interval [0, 1] (Hanss

2005). Thus, 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 can be represented as: (1) a single crisp value using different defuzzification methods, such as the center of area (COA), smallest of maxima (SOM), middle of maxima (MOM), and largest of maxima (LOM) or (2) an interval value using a selected α-cut level representing a specific possibility degree associated with a specific confidence level $(1 - \alpha)$ (Mauris et al. 2001; Elbarkouky et al. 2016). Both methods were implemented in this research and the results were compared.

A fuzzy arithmetic library was developed using the Java programing language (complied as a JAR file) 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 and confidence levels. At each time step, equations involving fuzzy variable are computed in the fuzzy arithmetic library based on the arithmetic method selected, and the corresponding output fuzzy numbers or defuzzified values are obtained (Figure 4.7). The steps in incorporating fuzzy arithmetic to SD model in AnyLogic® are as follows. First, the JAR file is imported to the AnyLogic® model at the top-level in the model tree (e.g., wind farm project). Second, the required classes of the JAR file, such as fuzzy arithmetic method and defuzzification method, are imported to the sub-models (e.g., civil, structural, and electrical work package). Third, methods in the classes of the JAR file (e.g., multiplication of two fuzzy numbers based on α-cut method or the drastic *t*-norm) are referenced in the model variables for solving equations involving fuzzy variables at each time step. Fourth, input values of variables (fuzzy parameters) in model equations are declared. Fifth, the referenced methods in the JAR file and input values of the variables are sent to the JAR library, and the equations are computed at each time step. Sixth, the output values are obtained from the JAR library as fuzzy numbers and stored in a selected data set at each time step or used as an input to model equations in the next time step. Finally, the time plots of the variables, flows, and stocks can be created using the fuzzy parameters or the defuzzified crisp values based on the selected defuzzification method.

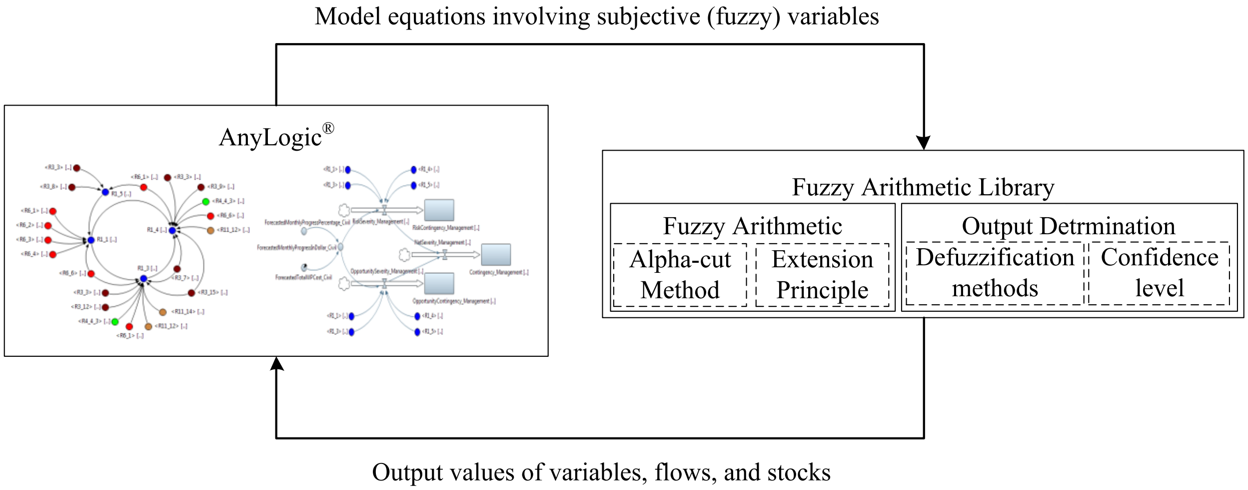


Figure 4.7. FSD model architecture

4.8 Chapter Summary

This chapter presented a methodology for developing hybrid FSD model to analyze the severity of dynamic and interacting risk and opportunity events on work package costs and determine work package and project contingencies. A comprehensive literature review was conducted to identify risk and opportunity events to be considered in the FSD model. Linguistic scales, represented by triangular or trapezoidal fuzzy numbers, were adopted to allow experts to use natural language to assess the probability and impact of risk and opportunity events and to evaluate the degree of causal interactions among risk and opportunity events. The expertise level of the experts in risk management was assessed in terms of certain qualification attributes and importance weights of the experts were considered in combining experts' evaluations. A systematic and structured method based on fuzzy DEMATEL was employed to construct the CLDs in the qualitative model development stage. Fuzzy arithmetic based on α-cut method and drastic *t*-norm was utilized to solve the mathematical equations in FSD model. Different defuzzification methods and confidence levels were applied to transform contingency fuzzy numbers into a crisp and interval values, respectively.

The main contributions of this chapter can be grouped into three areas. First, the chapter provides a systematic risk assessment and prioritization procedure, which uses linguistic scales represented by fuzzy numbers to assess probability and impact of risk and opportunity events. The proposed risk assessment and prioritization procedure incorporates opportunity in the assessment and allows risk assessment at the work package level. Moreover, it accounts for differing levels of expertise in risk management based on a comprehensive set of expert qualification attributes. Second, the chapter provides a hybrid FSD modeling approach that considers the dynamic causal interactions and dependencies between risk and opportunity events and quantify their severity on work package and project cost contingency. Third, it contributes to the advancement of the state of the art in FSD modeling for risk analysis and contingency determination by (i) providing a structured and systematic method that uses linguistic terms for constructing CLDs; (ii) providing a method for handling subjective uncertainty in FSD; and (iii) implementing fuzzy arithmetic methods (α-cut method and drastic *t*-norm) in FSD to carry out algebraic operations in mathematical equations involving fuzzy variables. The next chapter presents the application of the proposed modelling methodology to develop FSD model for determining the work package and project contingencies of the construction of a wind farm power generation project and the FSD model validation process.

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Chapter 5 Construction Application and Model Validation: Case Study[5]

5.1 Introduction

In this chapter, the modeling approach proposed in Chapter 4 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 (USD) million 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.

The rest of this chapter is organized as follows. First, the risk identification, assessment, and prioritization procedures are described and the results are presented. Second, the steps involved in developing the qualitative FSD model for the wind farm project is explained and the CLDs and flow and stock diagrams of selected work package and the project are presented. Third, the mathematical procedure in developing the quantitative FSD model is explained and the results of the dynamic simulation of the model based on α-cut method and drastic *t*-norm are presented and discussed. Finally, the validation process of the FSD model is presented.

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[5] Parts of this chapter have been submitted for publication in the *Automation in Construction*: Siraj, N. B., and Fayek, A. Robinson (2019). "Hybrid fuzzy system dynamics model for analyzing the impacts of interrelated risk and opportunity events on project contingency." *Automat. Constr.*, 70 manuscript pages, submitted July 9, 2019.

5.2 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 were selected based on their involvement in the case study project, their total years of experience, their years of experience in risk management, and the number of similar projects they had been involved in. All the experts were members of the project team and had been involved in more than five similar projects of comparable scale. They 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, as shown in Appendix B. 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 importance weights of the experts are relative weights and when added together should be equal to 1 ($\sum_{k=1}^{v} W_k = 1$). This ensures that the opinions of the experts with higher importance weights have more influence in the collective assessment of the experts.

The applicability of the identified risk and opportunity events and their categorizations for the construction of the wind farm project under consideration were verified by the group of experts. Based on the opinions of the experts, new risk and opportunity events that were not included in the list were added, the descriptions of some of the risk and opportunity events were revised, and risk and opportunity events that were not relevant to the project under investigation were omitted. Consequently, the final number of risk and opportunity events was reduced to 140.

The experts assessed the level of complexity of the project with respect to the number of work packages involved and the over all complexity of the project on a scale of 1–5, where 1 = low, 2 = somewhat low, 3 = average, 4 = somewhat high, and 5 = High (see Appendix C). The aggregated result of the experts' assessments, which took into account the importance weight of the experts (W_k), revealed that the project had an average (2.77) level of complexity with respect to the number of work packages involved and an average (2.77) overall complexity. A similar scale was used to assess the complexity and criticality of the work packages based on the descriptions (factors) provided in Appendix C. The aggregated assessment of the work packages are presented in Table 5.1.

Table 5.1. Complexity and criticality of the work packages

Description	Complexity and criticality rating of the work packages		
	Civil work package	Structural work package	Electrical work package
1. Complexity of the work package with respect to:			
1.1 Number of activities involved	Average (2.77)	Average (3.23)	Somewhat high (4.01)
1.2 Work scope	Average (2.73)	Average (3.23)	Average (3.49)
1.3 Construction methods	Somewhat low (2.25)	Average (3.25)	Average (3.27)
1.4 Constructability	Somewhat low (2.26)	Average (3.00)	Average (3.03)
2. Criticality of the work package in terms of:			
2.1 Its share of the total project cost	Average (3.26)	Average (3.27)	Somewhat high (3.73)
2.2 Its share of the total project contingency	Somewhat high (3.75)	Somewhat high (3.52)	Somewhat high (3.52)
2.3 Its proneness to several risks	Average (3.26)	Somewhat high (4.27)	Somewhat high (3.56)

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 5.2. The linguistic terms and their respective fuzzy numbers used to assess risk probability, risk impact, opportunity probability, and opportunity impact were adopted from Elbarkouky et al. (2016). The fuzzy numbers, which represent the linguistic terms, were generated using the modified horizontal approach coupled with curve fitting (Elbarkouky et al. 2016). The experts also determined the percentage of the work packages' costs impacted by each risk and opportunity event (see Appendix D). The experts' risk probability ($\tilde{P}_{R_{ib}}^{(k)}$), risk impact ($\tilde{I}_{R_{ib}}^{(k)}$), opportunity probability ($\tilde{P}_{O_{ib}}^{(k)}$), and opportunity impact ($\tilde{I}_{O_{ib}}^{(k)}$) assessments and the percentage of the work packages' costs impacted ($C_{ib}^{(k)}$) by each risk and opportunity event were aggregated using Eq. (4.1) and Eq. (4.2), respectively, resulting in the corresponding aggregated $\tilde{P}_{R_{ib}}$, $\tilde{I}_{R_{ib}}$, $\tilde{P}_{O_{ib}}$, $\tilde{I}_{O_{ib}}$ (fuzzy numbers), and C_{ib} (crisp value). The importance weights of the experts (W_k) were taken into account when aggregating the experts' assessments in Eq. (4.1) and Eq. (4.2). The net severity percentage ($\widetilde{NS}_{ib}$) of each of the risk and opportunity events for the three work packages were calculated using Eq. (4.3) and defuzzified using the COA method to obtain the defuzzified net severity percentage ($\widetilde{NS}_{ib}^{Def}$). Then, the risk and opportunity events were ordered based on 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 along with their respective risk and opportunity event categories, NS_{ib}^{Def}, and rankings are presented in Table 5.3 as an example. Most of the identified risk and opportunity events have a negative effect (i.e., risks) on work package costs; only a few have a positive effect (i.e., opportunity). Risk and opportunity events that can be handled by management reserve, for example, R10_2 (force majeure, i.e., natural and man-made disasters that are beyond the control of the firm doing the risk analysis), are included in the FSD model, as the risk analysis is done from the project owner's perspective. The prioritized lists of risk and opportunity events for the structural and electrical work packages are provided in Appendix F and Appendix G, respectively.

Table 5.2. 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)

Table 5.3. 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 control of the firm doing the risk analysis)	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
R6_6	Contract and specification interpretation disagreement	Contractual and legal	0.69	18

Risk ID	Description of risk and opportunity event	Risk and opportunity event category	Net severity percentage ($\widetilde{NS}_{i1}^{Def}$)	Rank
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 labour 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

5.3 Qualitative FSD Model Development

The fuzzy DEMATEL survey described in Chapter 4 and shown in Appendix E was completed by three of the experts (i.e., E_1, E_2, and E_4 with importance weight of 0.33, 0.36, and 0.31, respectively) who were involved in the risk assessment and prioritization stage. Each expert determined the causal influence of the ith risk and opportunity event on the jth risk and opportunity event using the fuzzy linguistic scales depicted in Table 4.2. The experts also defined the types of causal relationships between the risk and opportunity events as positive, negative, or not applicable (N/A). 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 Chapter 4 were applied for each work package to construct the causal loop diagrams (CLDs) in the qualitative model development stage. For brevity, only the results of the civil work package and the whole project are presented and discussed in this chapter.

The fuzzy direct-relation matrix ($\tilde{X}^C$), which combines the ratings of the experts, was developed for each work package by aggregating the initial fuzzy matrices ($\tilde{X}_k$) using Eq. (4.6) by taking into account the importance weights of the experts (W_k). The normalized fuzzy direct-relation matrix ($\tilde{Z}$) was obtained for each work package by dividing the elements of the fuzzy direct-relation matrix ($\tilde{X}^C$) by the number λ, as described in Eq. (4.8) and Eq. (4.9). The fuzzy total-relation matrix ($\tilde{T}$) was calculated for each work package based on the normalized fuzzy direct-relation matrix ($\tilde{Z}$) using Eqs. (4.12)–(4.18). Table 5.4 depicts part of the fuzzy total-relation matrix ($\tilde{T}$) of the civil work package. The row ($\tilde{R}$) and column ($\tilde{C}$) summations of the fuzzy total-relation matrix ($\tilde{T}$) was computed for each work package using Eq. (4.19) and Eq. (4.20), respectively. Then, the ($\tilde{R} + \tilde{C}$) and ($\tilde{R} - \tilde{C}$) fuzzy values were calculated and defuzzified to obtain the prominence,

$(\tilde{R}+\tilde{C})^{def}$, and relation, $(\tilde{R}-\tilde{C})^{def}$, vectors, as shown in Table 5.5. Finally, the influence relation map (IRM) was constructed for each work package by mapping the $(\tilde{R}+\tilde{C})^{def}$ and $(\tilde{R}-\tilde{C})^{def}$ values of each risk and opportunity event. The IRM of risk and opportunity events for the civil work package is shown in Figure 5.1.

Table 5.4. Fuzzy total-relation matrix ($\tilde{T}$) of risk and opportunity events for the civil work package

Risk ID	R1_1	R1_3	R1_4	R1_5	…	R11_1	R11_12	R11_14
R1_1	(0.00, 0.02, 0.15)	(0.02, 0.05, 0.19)	(0.02, 0.05, 0.19)	(0.00, 0.02, 0.15)	…	(0.02, 0.05, 0.19)	(0.02, 0.05, 0.18)	(0.02, 0.04, 0.19)
R1_3	(0.01, 0.04, 0.17)	(0.00, 0.02, 0.18)	(0.02, 0.05, 0.22)	(0.01, 0.03, 0.18)	…	(0.02, 0.05, 0.22)	(0.02, 0.05, 0.21)	(0.02, 0.05, 0.21)
R1_4	(0.01, 0.03, 0.19)	(0.00, 0.03, 0.18)	(0.03, 0.02, 0.17)	(0.00, 0.02, 0.16)	…	(0.02, 0.03, 0.17)	(0.02, 0.03, 0.18)	(0.02, 0.04, 0.16)
R1_5	(0.02, 0.05, 0.18)	(0.01, 0.03, 0.15)	(0.02, 0.04, 0.17)	(0.00, 0.01, 0.11)	…	(0.01, 0.03, 0.16)	(0.01, 0.03, 0.15)	(0.01, 0.03, 0.15)
…	…	…	…	…	…	…	…	…
R11_1	(0.01, 0.04, 0.16)	(0.01, 0.05, 0.15)	(0.01, 0.03, 0.19)	(0.00, 0.02, 0.15)	…	(0.00, 0.02, 0.15)	(0.00, 0.03, 0.15)	(0.00, 0.03, 0.16)
R11_12	(0.01, 0.04, 0.17)	(0.02, 0.05, 0.2)	(0.02, 0.05, 0.20)	(0.00, 0.03, 0.16)	…	(0.02, 0.05, 0.20)	(0.00, 0.02, 0.15)	(0.01, 0.04, 0.18)
R11_14	(0.01, 0.04, 0.17)	(0.02, 0.04, 0.19)	(0.01, 0.03, 0.18)	(0.00, 0.02, 0.16)	…	(0.02, 0.05, 0.19)	(0.02, 0.05, 0.18)	(0.00, 0.02, 0.14)

Table 5.5. Fuzzy and defuzzified values of $(\tilde{R} + \tilde{C})$ and $(\tilde{R} - \tilde{C})$ for the civil work package

Risk ID	$(\tilde{R} + \tilde{C})$	$(\tilde{R} - \tilde{C})$	$(\tilde{R} + \tilde{C})^{def}$	$(\tilde{R} - \tilde{C})^{def}$
R1_1	(0.71, 2.37, 11.45)	(-6.02, -0.26, 4.72)	4.22	-0.45
R1_3	(0.77, 2.56, 12.33)	(-5.78, 0.08, 5.77)	4.55	0.04
R1_4	(0.73, 2.47, 11.99)	(-6.05, -0.14, 5.21)	4.42	-0.28
R1_5	(0.50, 1.88, 9.90)	(-5.15, -0.08, 4.26)	3.54	-0.26
…	…	…	…	…
R11_1	(0.73, 2.43, 11.40)	(-5.85, -0.25, 4.82)	4.25	-0.39
R11_12	(0.75, 2.45, 11.43)	(-5.46, -0.05, 5.23)	4.27	-0.08
R11_14	(0.70, 2.34, 11.05)	(-5.37, -0.08, 4.98)	4.11	-0.14

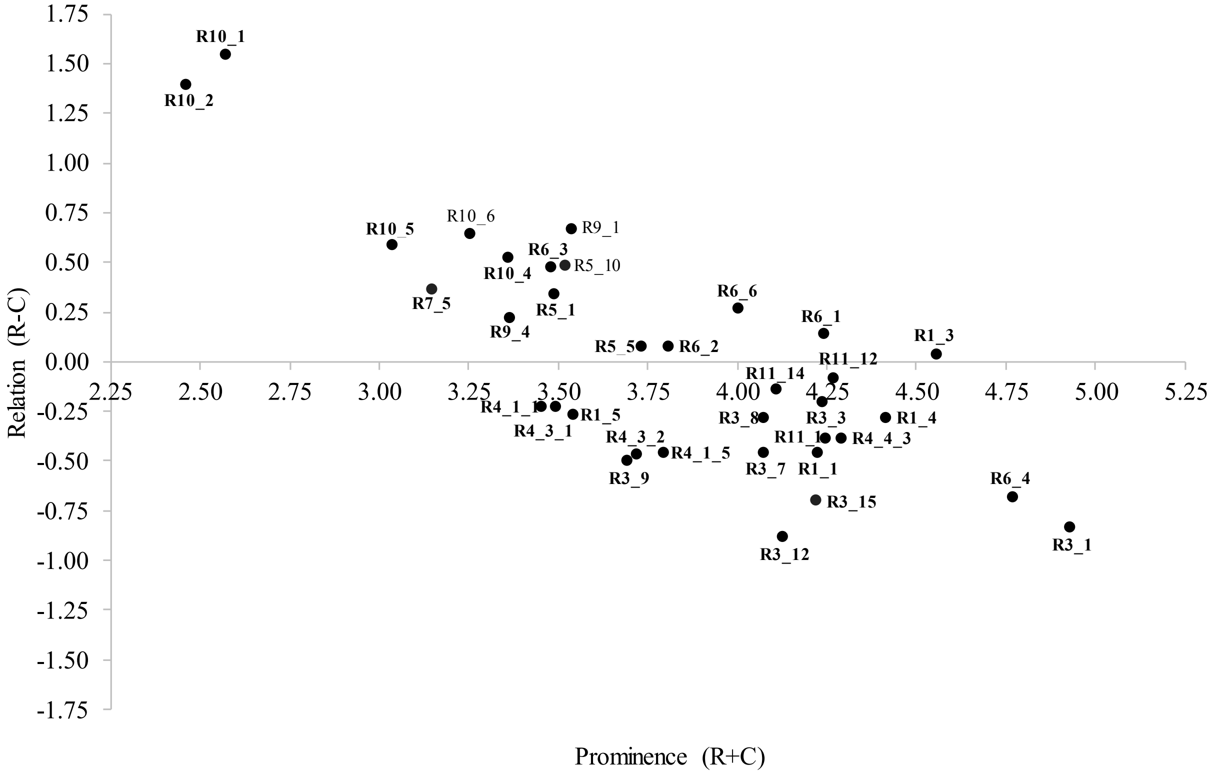


Figure 5.1. Influence relation map (IRM) of risk and opportunity events for the civil work package

As shown in Figure 5.1, risk and opportunity events having the highest values of prominence ($(\tilde{R}+\tilde{C})^{def}$), such as R3_1 (delays and interruptions causing a cost increase to the work package/project (4.93)), R6_4 (possibility of contractual disputes and claims (4.77)), and R1_3 (poor site management and supervision by the contractor (4.55)), have the highest level of causal interactions with the rest of the risk and opportunity events. In contrast, the risk and opportunity events with the lowest $(\tilde{R}+\tilde{C})^{def}$ values, such as R10_2 (force majeure, i.e., natural and man-made disasters that are beyond the control of the firm doing the risk analysis (2.46)) and R10_1 (adverse weather conditions (2.57)) have the fewest causal interactions with the rest of the risk and opportunity events. The risk and opportunity events with the lowest values of relation ($(\tilde{R}-\tilde{C})^{def}$) are the most affected by the rest of the risk and opportunity events, such as R3_12 (delay in approving contractor work by the consultant or owner of the project (-0.88)), R3_1 (delays and interruptions causing a cost increase to the work package/project (-0.83)), and R3_15 (technical mistakes during the construction stage by the contractor (-0.70)). R10_1 (adverse weather conditions (1.55)), R10_2 (force majeure, i.e., natural and man-made disasters that are beyond the control of the firm doing the risk analysis (1.39)), and R9_1 (changes in government laws, regulations, and policies affecting the project (0.67)) are the least affected risk and opportunity events.

The CLDs were constructed from the IRM based on the defuzzified total-relation matrix values (Table 5.6). 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 were depicted, reducing the complexity of the resulting CLDs. Thus, only those causal relationships having values greater than 0.070 (i.e., threshold value) in Table 5.6 were considered when developing the CLDs. The direction of the causal relationships were established from Table 5.6 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 with in the category as well as the causal influence of risk and opportunity events from other categories on the given category. When the number of risk and opportunity events in a given category or the number of causal relationships in a category were too few (e.g., as in the economic and financial category and the political category), the CLDs for two or more closely related risk and opportunity event categories were combined. The CLDs of management, construction, resource-related, environmental, and health and safety risk and opportunity event categories for the civil work package are shown as an example in Figures 5.2–5.6, respectively. Figure 5.7 depicts a CLD that combines the contractual and legal, economic and financial, and political risk and opportunity event categories. The CLDs of risk and opportunity categories for the structural and electrical work packages are provided in Appendix H and Appendix I, respectively.

Table 5.6. 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 considered in the CLDs.

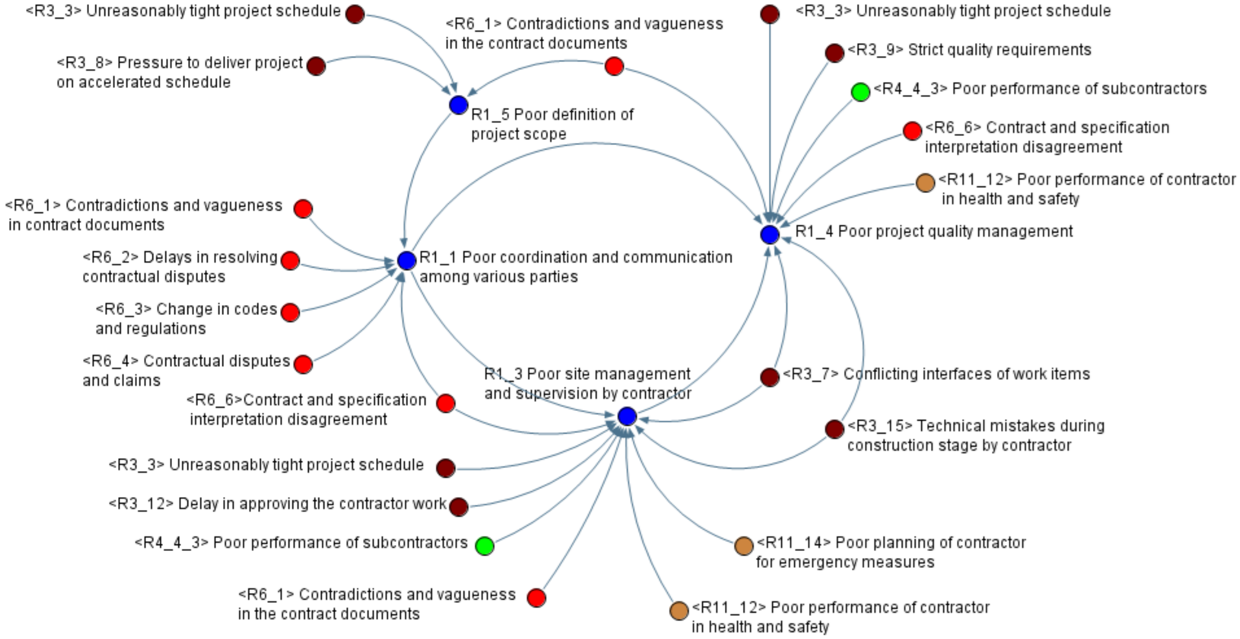


Figure 5.2. Causal loop diagram of the **management** risk and opportunity event category for the civil work package

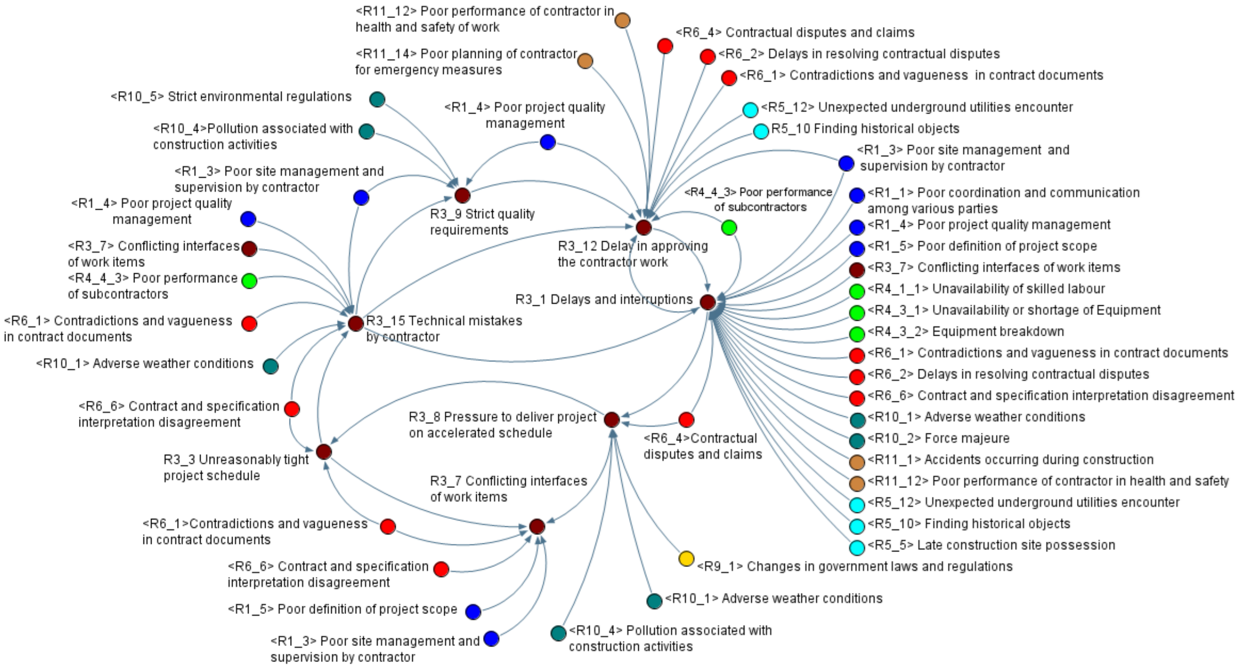


Figure 5.3. Causal loop diagram of the **construction** risk and opportunity event category for the civil work package

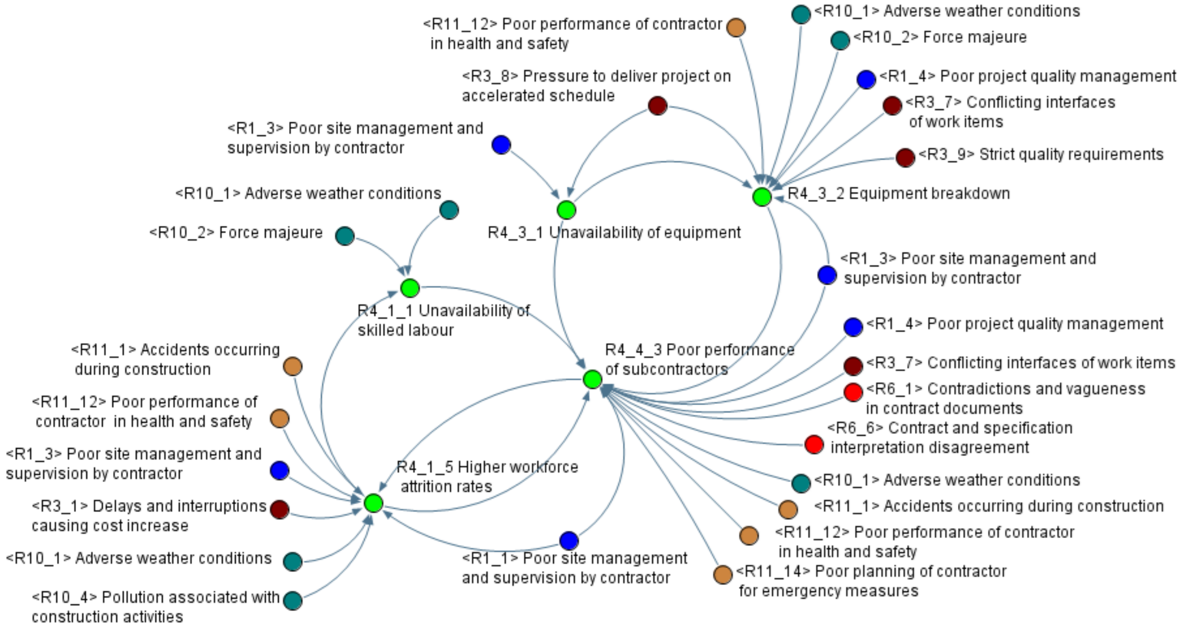


Figure 5.4. Causal loop diagram of the **resource-related** risk and opportunity event category for the civil work package

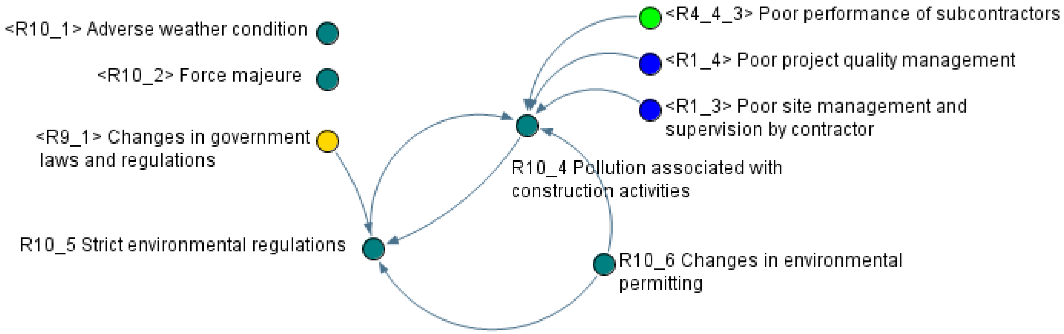


Figure 5.5. Causal loop diagram of the **environmental** risk and opportunity event category for the civil work package

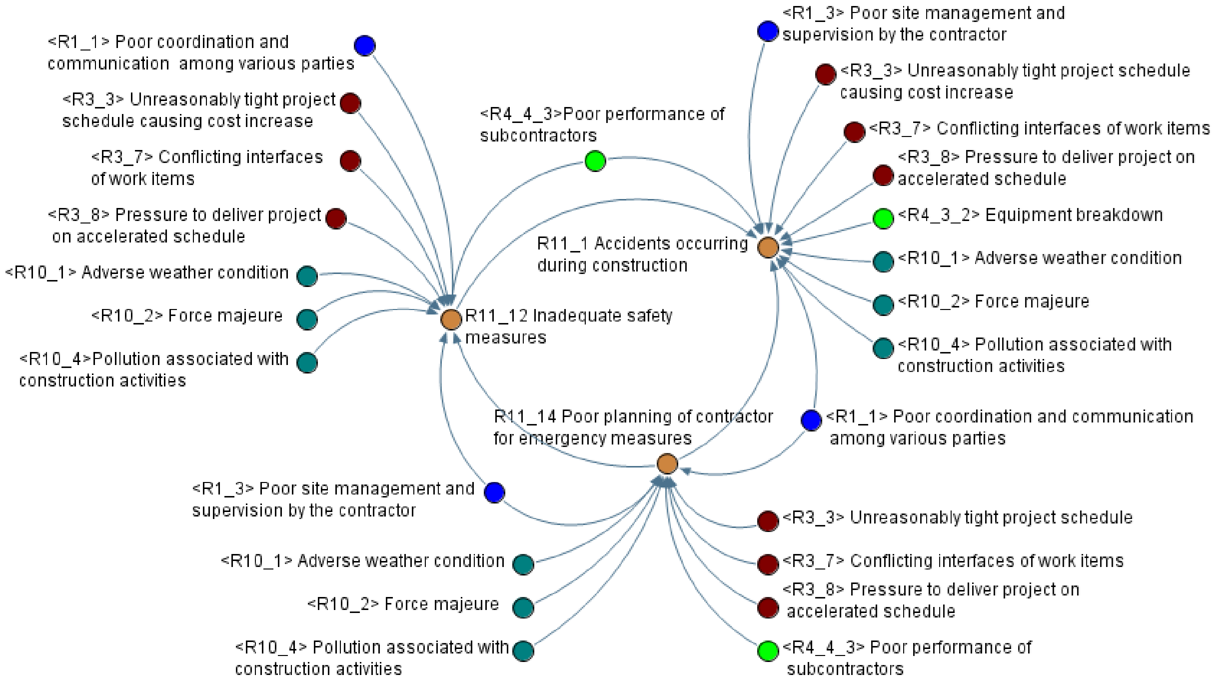


Figure 5.6. Causal loop diagram of the **health and safety** risk and opportunity event category for the civil work package

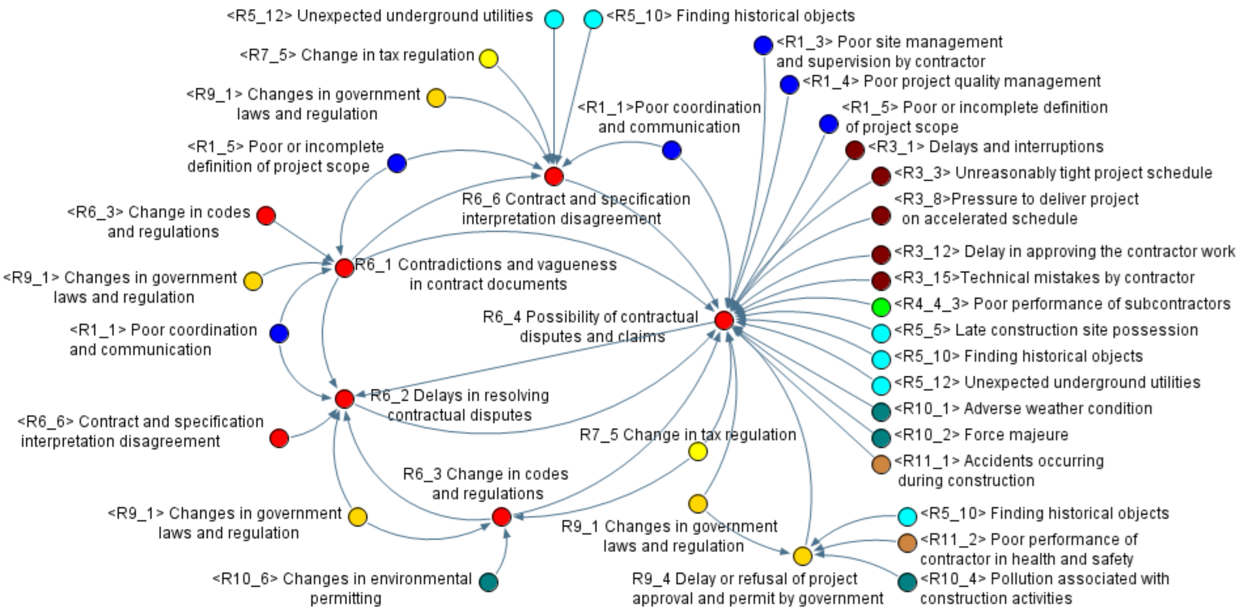


Figure 5.7. Causal loop diagram of the **contractual and legal, economic and financial**, and **political** risk and opportunity event categories for the civil work package

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. The overall qualitative FSD model of the project was created using simulation software (AnyLogic® 8.2.3). Figures 5.8–5.10 depict the flow and stock diagrams of the management risk and opportunity event category, the civil work package, and the wind farm project, respectively. As shown in Figures 5.8–5.10, each risk and opportunity event category, work package, and project has three flow variables representing the risk severity, opportunity severity, and net severity in dollars due to the risk and opportunity events in a given category, work package, and project, respectively at each time step, i.e., monthly. The corresponding three stock variables (i.e., risk contingency, opportunity contingency, and net contingency in dollars) represent the cumulative contingency values of each risk category, work package and project at a given time step (i.e. a given month).

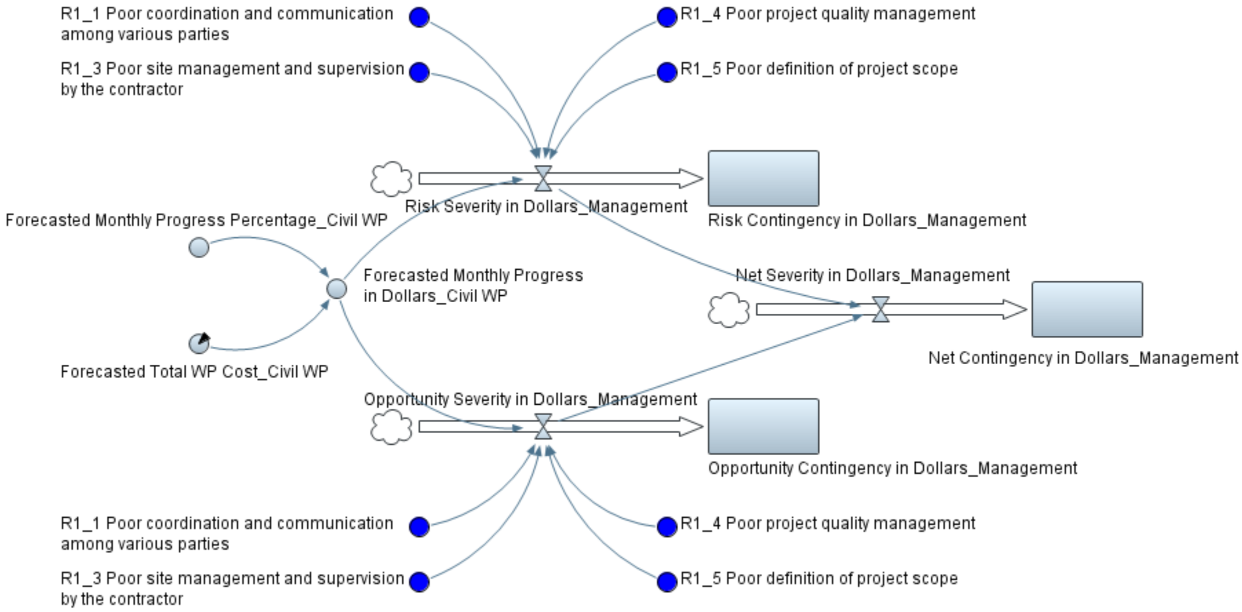


Figure 5.8. Flow and stock diagram of the management risk and opportunity event category for the civil work package

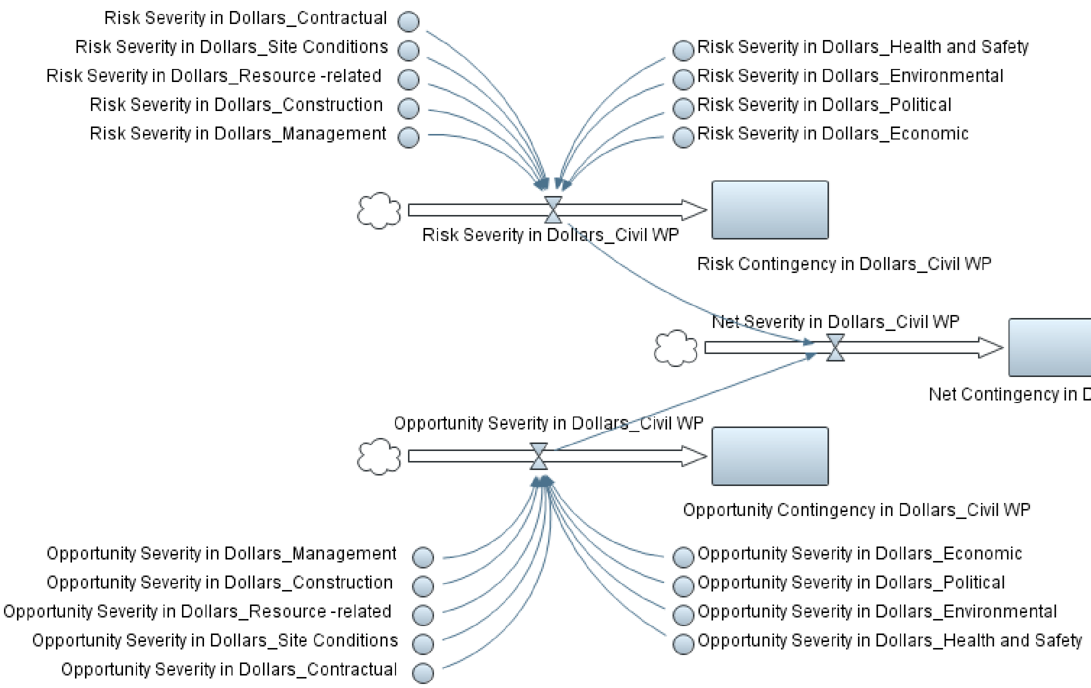


Figure 5.9. Flow and stock diagram of the civil work package

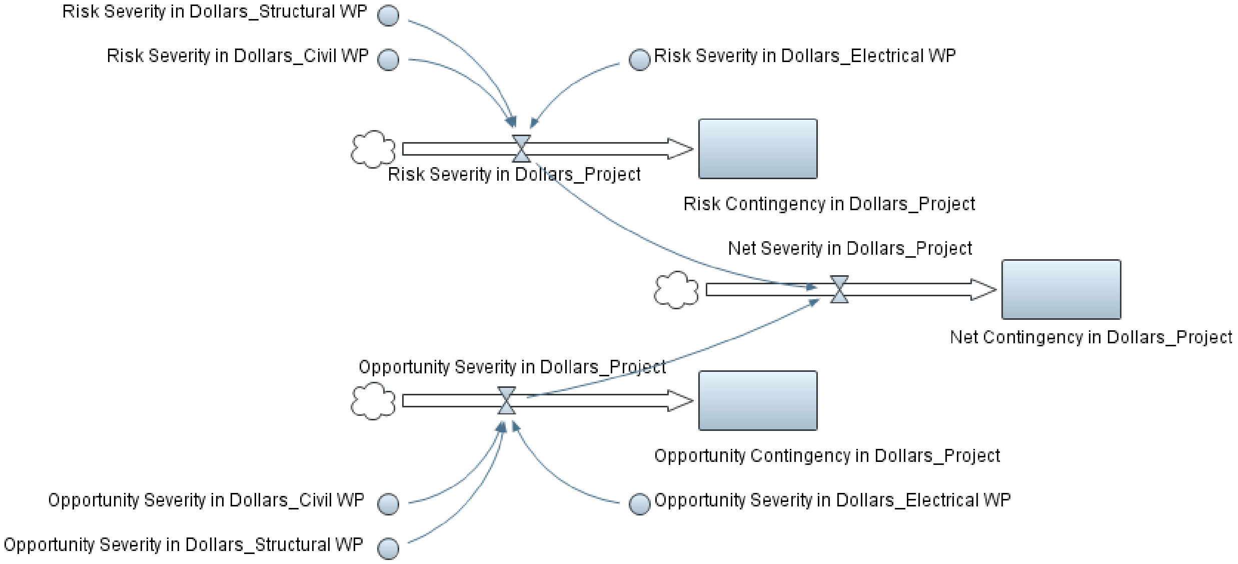


Figure 5.10. Flow and stock diagram of the wind farm project

5.4 Quantitative FSD Model Development

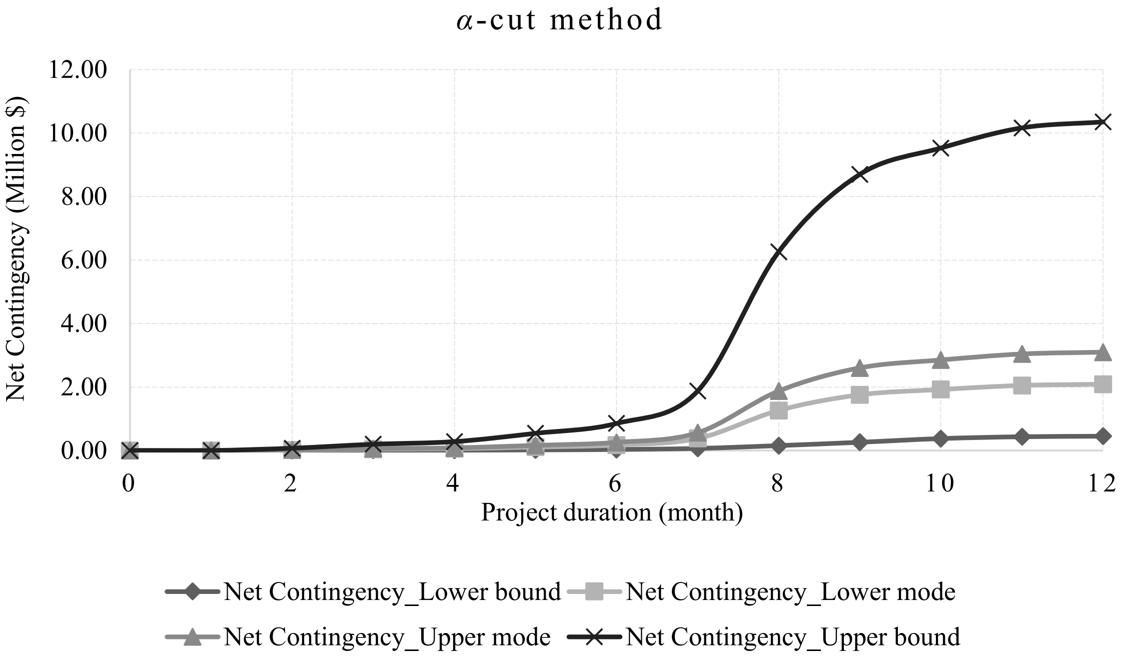
In developing the quantitative FSD model of the wind farm project, the objective and subjective (fuzzy) parameters and variables were first identified as described in Chapter 4. Each risk and opportunity event was modeled as a dynamic fuzzy array defined by the risk and opportunity event attributes ($\tilde{P}_{R_{ib}}$, $\tilde{I}_{R_{ib}}$, $\tilde{S}_{R_{ib}}$, $\tilde{P}_{O_{ib}}$, $\tilde{I}_{O_{ib}}$, $\tilde{S}_{O_{ib}}$, C_{ib}, t_{ij}^{Def}) and their corresponding fuzzy membership function parameters (l_{ib}, m_{1ib}, m_{2ib}, u_{ib}). 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 (Table 5.2). 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). The forecasted monthly progress percentage (A_b) for each work package was obtained from the project's forecasted cash flow S-curve. 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.

The weighted risk probability ($\tilde{P}^{*}_{R_{jb}}$) and weighted opportunity probability ($\tilde{P}^{*}_{O_{jb}}$), which reflect the effect of the predecessor risk and opportunity events on the posterior risk and opportunity event, were determined for the risk and opportunity events at each time step based on Eq. (4.22). Consequently, the weighted risk severity ($\tilde{S}^{*}_{R_{jb}}$) and weighted opportunity severity ($\tilde{S}^{*}_{O_{jb}}$) of the risk and opportunity events were computed at each time step. The risk severity in dollars ($\widetilde{RSD}_{eb}^{RC}$), opportunity severity in dollars ($\widetilde{OSD}_{eb}^{RC}$), and net severity in dollars ($\widetilde{NSD}_{eb}^{RC}$) of the risk and opportunity event categories were determined at each time step using Eqs. (4.23)–

(4.25). The accumulation of these severity values resulted in the corresponding risk contingency in dollars ($\widetilde{RCD}_{eb}^{RC}$), opportunity contingency in dollars ($\widetilde{OCD}_{eb}^{RC}$), and net contingency in dollars ($\widetilde{NCD}_{eb}^{RC}$) at the category level (Eqs. (4.32)–(4.34)). Then, the severity and contingency dollar values at the category level were aggregated to determine the severity in dollars ($\widetilde{RSD}_{b}^{WP}$, $\widetilde{OSD}_{b}^{WP}$, and $\widetilde{NSD}_{b}^{WP}$) and contingency in dollars ($\widetilde{RCD}_{b}^{WP}$, $\widetilde{RCD}_{b}^{WP}$, and $\widetilde{NCD}_{b}^{WP}$) at the work package level using Eqs. (4.27)–(4.29) and Eqs. (4.36)–(4.38), respectively. Finally, the severity and contingency dollar values of the work packages were aggregated to obtain the severity in dollars ($\widetilde{RSD}^{PR}$, $\widetilde{OSD}^{PR}$, and $\widetilde{NSD}^{PR}$) and contingency in dollars ($\widetilde{RCD}^{PR}$, $\widetilde{OCD}^{PR}$, and $\widetilde{NCD}^{PR}$) at the project level using Eqs. (4.29)–(4.31) and Eqs. (4.38)–(4.40), respectively.

5.5 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. For any trapezoidal fuzzy number represented by a tuple (l, m_1, m_2, u), l and u represent the lower and upper bound of the support (i.e., the set of all elements of the universe of discourse that have a non-zero membership degree in the fuzzy number), respectively. The parameters m_1 and m_2 denote the lower and upper mode of the core (i.e., the set of all elements of the universe of discourse that have a membership degree of 1 in the fuzzy number), respectively. The plots of the fuzzy numbers representing the civil work package and net project contingency based on the α-cut and drastic t-norm are shown in Figure 5.11 and Figure 5.12, respectively.



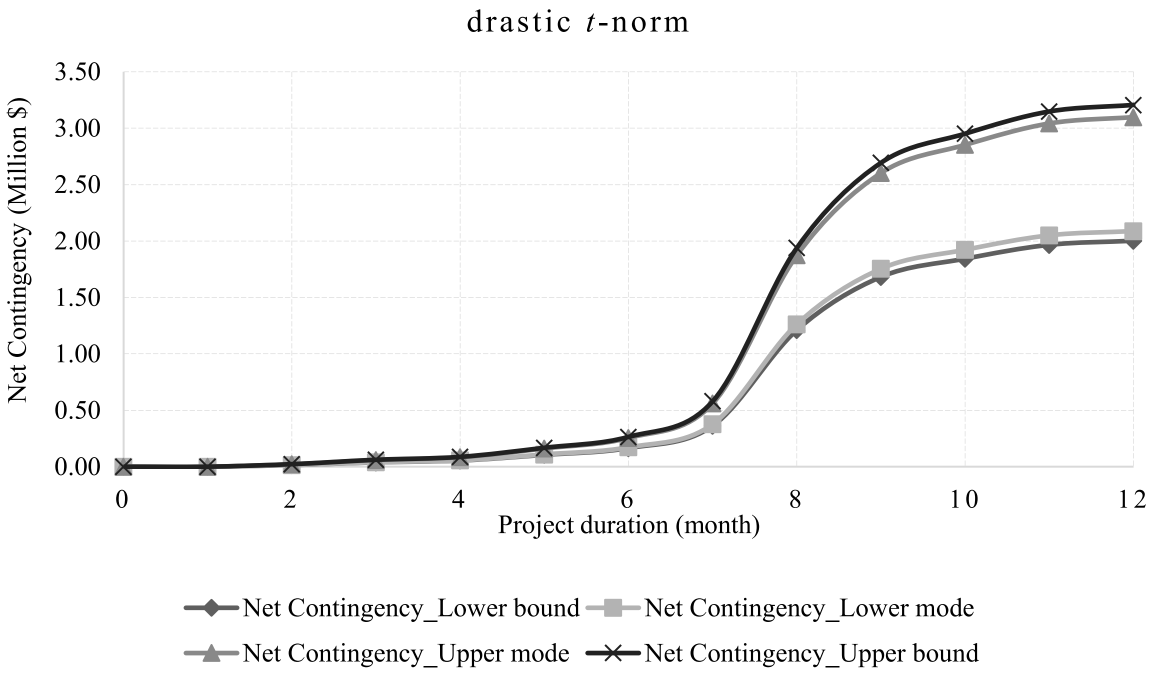


Figure 5.11. Civil work package net contingency based on the α-cut method and the drastic t-norm

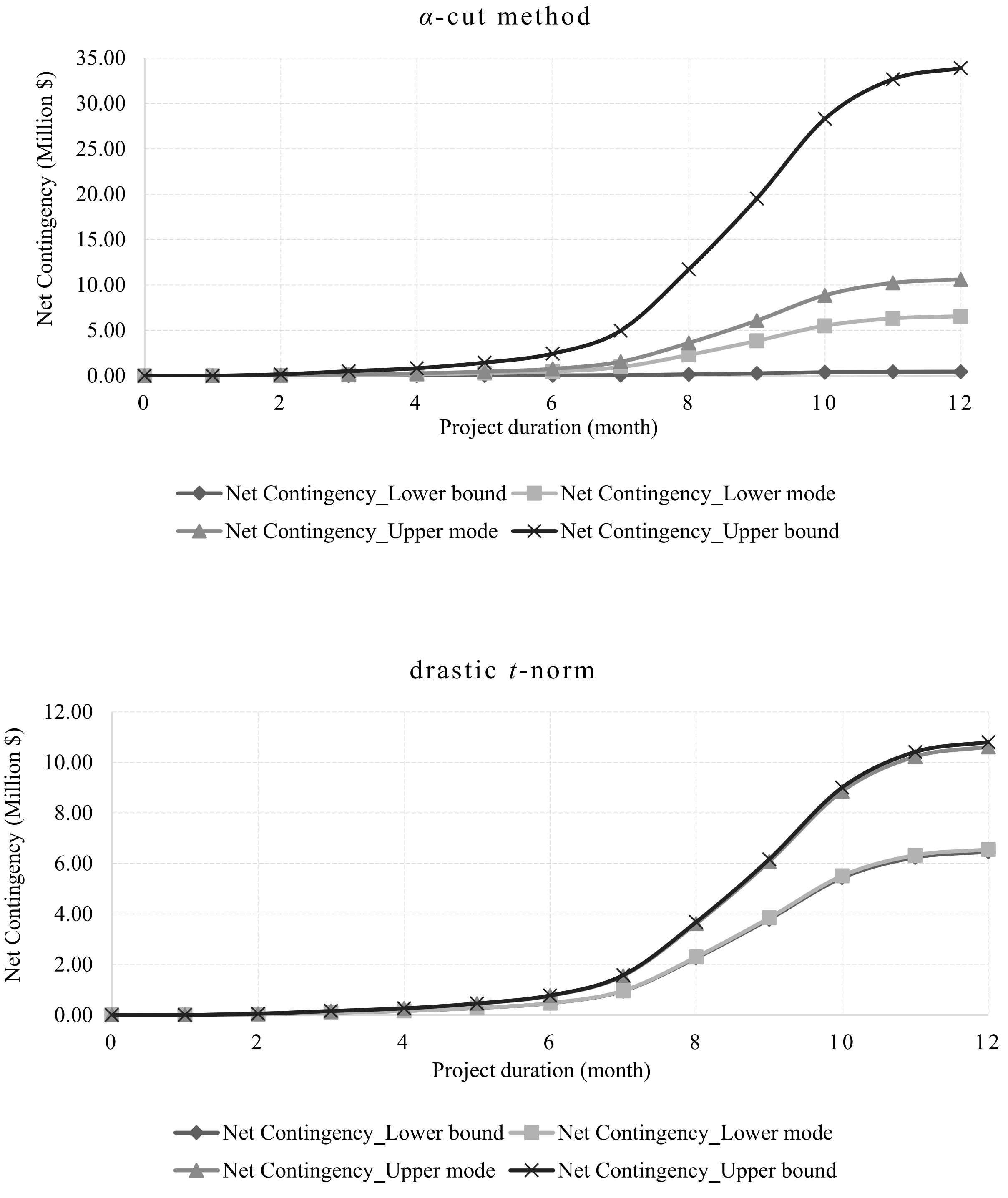


Figure 5.12. Net project contingency based on the α-cut method and the drastic t-norm

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 Figure 5.12) is [450,300.61 33,892,516.73] for the α-cut method, which means that the net project contingency value will fall between \$450,300.61 and \$33,892,516.73. For the drastic *t*-norm, the net project contingency value will be between \$6,460,369.29 and \$10,806,716.21. In order to observe the accumulation of fuzziness phenomenon in the two arithmetic methods, the length of the support (also referred to as the fuzzy spread) 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 5.7 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 summarised in Table 5.7. The length of the support at the end of the project duration for the α-cut method is close to eight times larger than the length of the support for the drastic *t*-norm, reflecting the significant growth of uncertainty that occurs when the α-cut method is employed in the FSD model. The excessive accumulation of fuzziness and overestimation of uncertainty encountered in the FSD model was significantly reduced by using drastic *t*-norm instead of the α-cut method. For instance, the length of the support at the end of the project duration was reduced by 87.00%. 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 5.7. Comparison of the length of the 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 Figure 5.13, represent the total net contingency of the wind farm project based on the α-cut method and the drastic *t*-norm, respectively. The crisp and interval values that represent the net contingency fuzzy numbers were determined using defuzzification methods and the confidence level (i.e., the possibility degree), respectively. The fuzzy numbers were defuzzified using the smallest of maxima (SOM), middle of maxima (MOM), largest of maxima (LOM), and center of area (COA) methods to obtain representative crisp values. The SOM, MOM, and LOM are the smallest, middle, and largest of the x-axis values with the largest membership degree, respectively. The COA is the x-axis value that corresponds to the center of area of the fuzzy number. 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 (Figure 5.13). 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 (Figure 5.13). The defuzzified net contingency values of the project over the entire project duration based on the COA method are depicted in Figure 5.14 for the two arithmetic methods. As shown in Figure 5.14, the defuzzified net contingency values based on the COA method for the α-cut method are higher than the drastic *t*-norm throughout the project duration. There is no standard or guideline for selecting the most appropriate defuzzification method that can be applied to all types of projects. The defuzzification method can be selected based on project context, familiarity of the risk analyst with the methods, and the preferences and risk attitude of the analyst (Elbarkouky et al. 2016). 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 run time are major drawbacks of the COA method.

The net contingency fuzzy numbers can also be expressed as confidence intervals at different levels of confidence (Figure 5.15). For a given α-cut level, the confidence level is 1 − α with a possibility degree equal to α. For instance, at an α-cut level of 0.6, there is a confidence level of 0.4 and a possibility of 0.6 that the net contingency of the project will be [4,110,162.633 19,926,114.12] and [6,514,189.814 10,691,793.91] for the α-cut method and the drastic *t*-norm, respectively (Figure 5.15). The confidence level is suitable for representing uncertainty in a way that is compatible with the confidence interval of the Monte Carlo simulation method and when both specificity and certainty of information are important to the decision-maker.

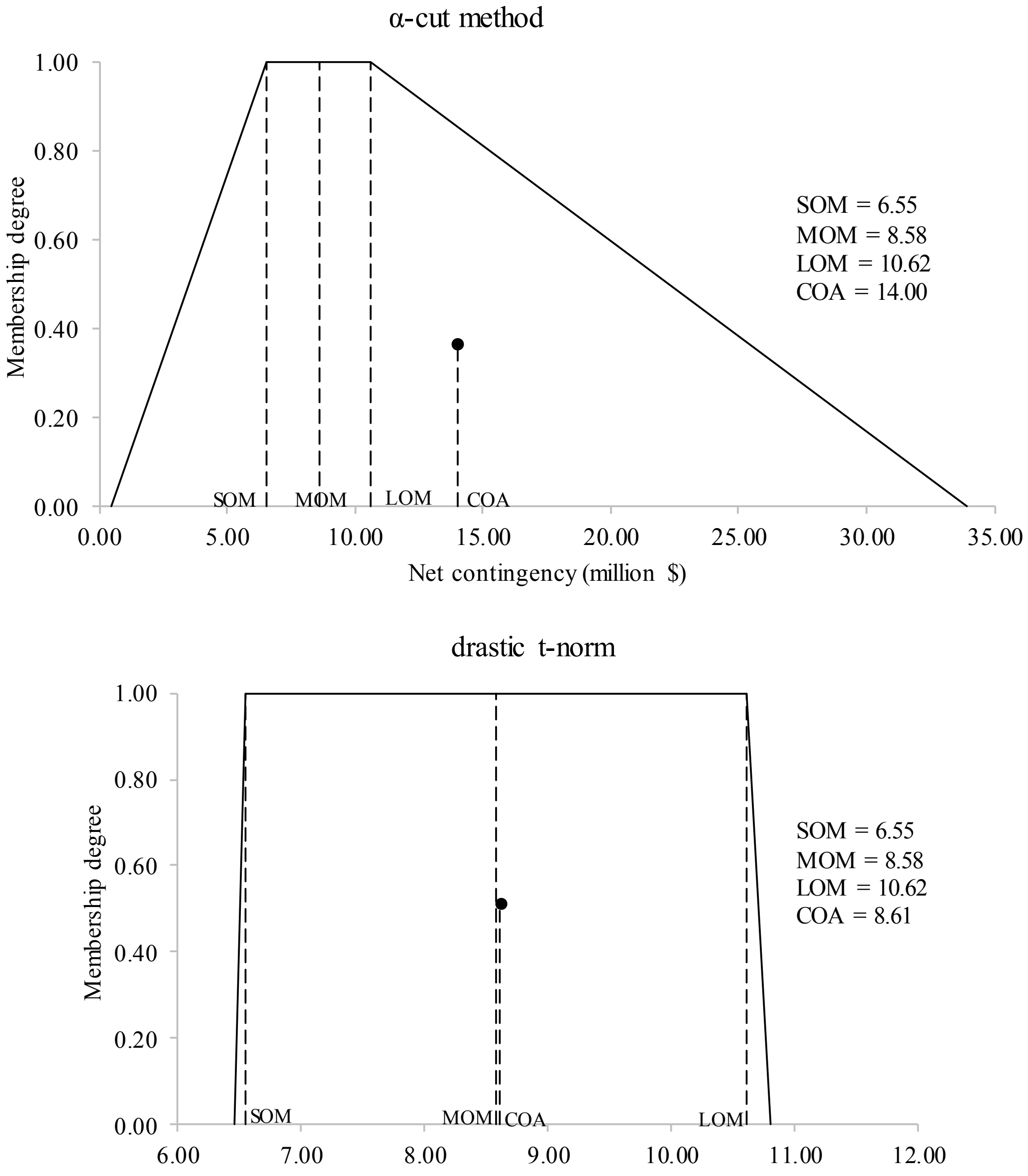


Figure 5.13. Defuzzified values of the net project contingency fuzzy numbers

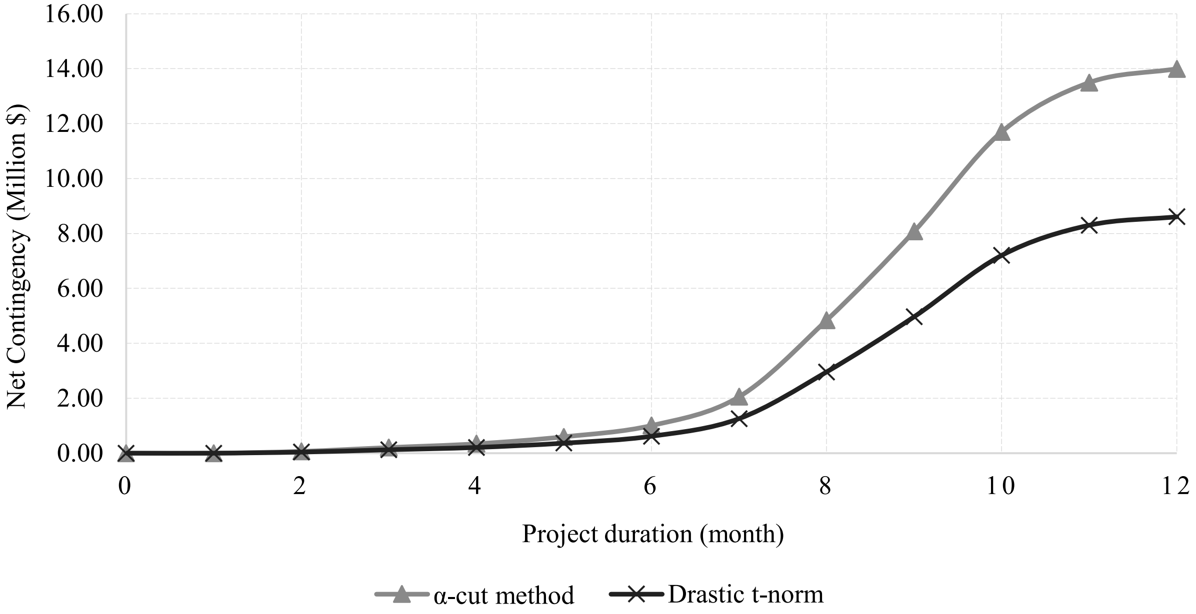
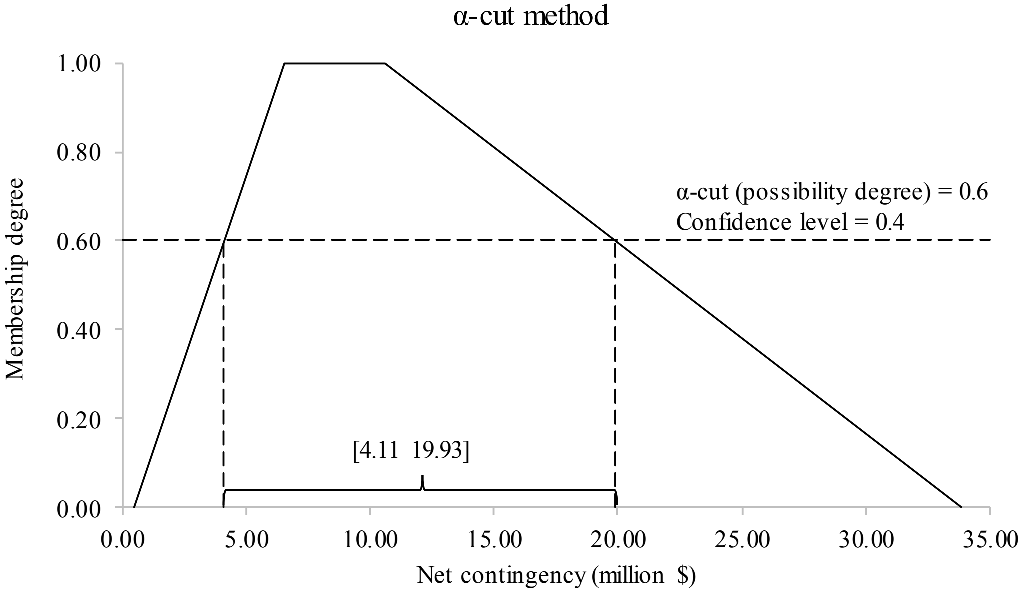


Figure 5.14. Defuzzified net contingency of the project based on the COA method for the α-cut method and the drastic *t*-norm



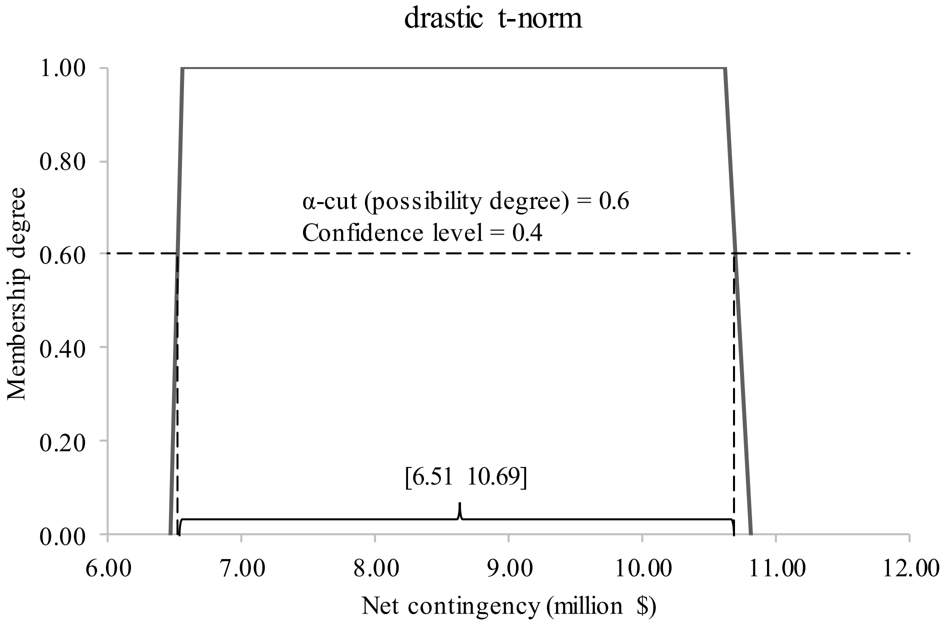


Figure 5.15. Net project contingency intervals based on the confidence level

The defuzzified contingency depletion curves for the work packages and the project can be constructed from the defuzzified contingency accumulation curves. The defuzzified values of the contingency depletion curve at each time step are calculated by subtracting the defuzzified cumulative contingency value at a given time step from the defuzzified contingency value at the end of the project duration (t=12 months). The defuzzified net contingency depletion curves of the project based on the COA method for the α-cut method and the drastic *t*-norm are shown in Figure 5.16.

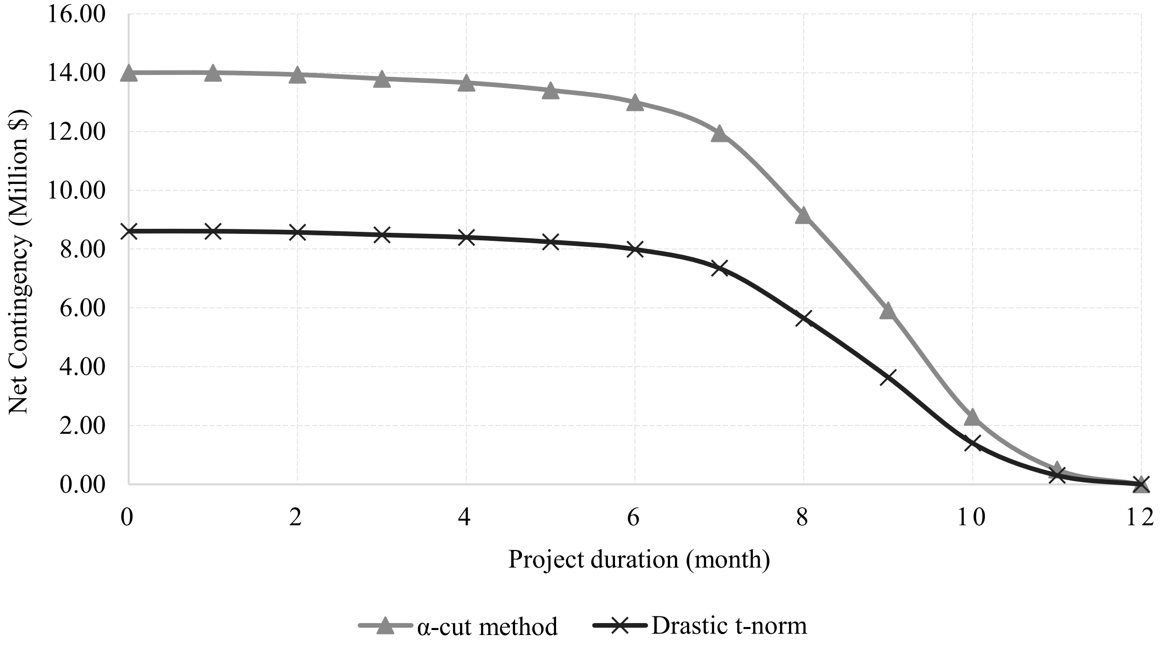


Figure 5.16. Defuzzified net contingency depletion curves of the project based on the COA method for the α-cut method and the drastic *t*-norm

5.6 FSD Model Validation

The qualitative and quantitative FSD models were validated by conducting structural and behavioral validations (Sterman 2000; Lee et al. 2005; Lee and Peña-Mora 2007). Structural validation, which comprises structural verification, parameter verification, and dimensional consistency, was carried out on the CLDs, flow and stock diagrams, and mathematical equations. Structural verification, which indicates how realistic the FSD model is in representing the variables and relationships in the system, was conducted at different stages of the FSD model development. The literature review, data collected from project documents, and experts' assessments were used to identify, assess, and prioritize the risk and opportunity events for each work package to be considered in the FSD model. The final list of the prioritized risks used in the FSD model were verified by the experts who were involved in the risk identification and assessment. The CLDs constructed using the fuzzy DEMATEL method were also reviewed by the same experts who completed the fuzzy DEMATEL survey to check if the defined causal relationships were realistic. For parameter verification, all the parameters used in the FSD model (e.g., work package cost) were obtained from project documents and verified by the project manager of the case study under consideration. The dimensional consistency test was conducted to uncover flaws in mathematical equations and dimensional errors. All the equations in the FSD model were inspected, and automatic dimensional analysis was carried out using AnyLogic® simulation software. The fuzzy arithmetic class developed using the Java programing language for implementing the α-cut method and the drastic t-norm was also tested for all arithmetic operations, and the results were compared against fuzzy arithmetic examples provided in Lin et al. (2011) and Pedrycz and Gomide (2007). In order to test the level of aggregation of the FSD model for mathematical accuracy, the project model was disaggregated into subsystem models (work packages). Then, the subsystem models were simulated individually and the resulting work packages' contingencies were aggregated and compared with the project's contingency result obtained by simulating the whole project model.

For behavior validation, the FSD model was checked to see if it reproduces the anticipated behavior in the system. To achieve this, the forecasted contingency values of the work packages and the project throughout the project duration were plotted and compared with the shape of the corresponding forecasted work package and project cost S-curves. In addition, an integration error test was conducted on the FSD model by running the model at different time steps and using different numerical integration methods to make sure the model was not sensitive to the choice of time step or integration method (Sterman 2000; Lee et al. 2005; Lee and Peña-Mora 2007).

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) model developed by the wind farm project owner. MCS was chosen for comparison because it is the most commonly used method for risk analysis and contingency determination in the construction domain. 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. 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). SMAPE is expressed as shown in Eq.(5.1).

$$SMAPE = \frac{100\%}{n} \sum_{\mathrm{t}=1}^{\mathrm{n}} \frac{|Q_t - V_t|}{(|Q_t| + |V_t|)/2} \qquad (5.1)$$

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 SMAPE ranges from 0% to 200% and a value of 0% implies a perfect agreement between the contingency results of the FSD model and MCS.

Table 5.8 presents the SMAPE results calculated based on the P50 and P95 project contingency output of MCS. The comparison between the FCD net project contingency results and MCS P50 shows that the lowest SMAPE are observed for the COA (8.67%) defuzzification method when the drastic *t*-norm is used. The comparison between the FSD net project contingency results and MCS P95 indicates that the lowest SMAPE is achieved for the COA (5.15%) defuzzification method when the α-cut method is used. The SMAPE results obtained for the SOM, MOM, and LOM defuzzification methods are 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 judgement, 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 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).

Table 5.8. Symmetric mean absolute percentage error (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

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 drastic t-norm in Fuzzy Contingency Determinator© (FCD©) software (Elbarkouky et al. 2016). FCD© was selected because it uses linguistic terms represented by triangular and trapezoidal fuzzy numbers to assess the probability and impact of risk and opportunity events, and because it uses fuzzy arithmetic procedures based on both the α-cut method and the extension principle similar to the FSD model to determine work package and project contingencies. The SMAPE defined in Eq. (5.1), 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 5.9. 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. However, the comparison between FSD and FCD© for similar arithmetic and defuzzification methods (i.e., the SMAPE results highlighted in Table 5.9) reflects that a better degree of agreement (14.64%) was achieved when the LOM defuzzification method was used, irrespective of the fuzzy arithmetic method that was employed. 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.

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 depend on different factors such as project scale, project context, and the preferences of decision makers.

Table 5.9. Symmetric mean absolute percentage error (SMAPE): FSD net project contingency results compared to FCD$^{\copyright}$ project contingency results

Fuzzy system dynamics (FSD)		Symmetric mean absolute percentage error (SMAPE) (%)							
		Fuzzy Contingency Determinator (FCD$^{\copyright}$)							
		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 list of criteria and sub-criteria (qualification attributes) for assessing experts' expertise levels, the risk assessment and prioritization procedure, and the hybrid FSD modeling approach proposed in this thesis are generalizable and can be adapted to any type of construction project. In addition, the risk and opportunity events and CLDs can be used as a starting point for developing qualitative FSD models for future projects. However, the linguistic scales and fuzzy numbers for assessing the probability and impact of risk and opportunity events, the prioritization and ranking of risk and opportunity events, and the degree of causal influences among risks and opportunity events are specific to the wind farm project considered in the case study.

5.7 Chapter Summary

In this chapter, a hybrid FSD model is developed to analyze the severity of dynamic and interacting risk and opportunity events on work package costs and to determine work package and project contingencies of the construction of a wind farm power generation project. The expertise levels of the experts' involved in the FSD model development were assessed based on certain qualification attributes and consequently importance weights of the experts' were determined and then considered in combining experts' evaluations. The experts assessed the work package and project characteristics to establish the context of the project selected as a case study. The probability and impact of the risk and opportunity events as well as the causal interaction between the risk and opportunity events were assessed by the experts using linguistic scales represented by fuzzy numbers. A structured and systematic method based on fuzzy DEMATEL was employed to determine the degree of causal influence between the risk and opportunity events and construct the CLDs. The FSD model was simulated over the project duration and the work packages and project contingencies were determined as fuzzy numbers based on both the α-cut method and the drastic t-norm. The comparison of the results obtained based on the two fuzzy arithmetic methods indicate that excessive accumulation of fuzziness and overestimation of uncertainty was encountered when α-cut method was used in the FSD model. The contingency fuzzy numbers obtained from the FSD model were transformed into crisp and interval values using different defuzzification methods and confidence levels, respectively. The FSD model was validated using structural and behavioral validation tests. Moreover, the defuzzified contingency values obtained from the FSD model at the end of the project duration were compared with the MCS P50 and P95 project contingency results and the defuzzified values of FCD$^{©}$. The FSD model provides comparable contingency results to those obtained through MCS P50 and P95 and FCD$^{©}$. The FSD modelling approach addresses the challenges of the probabilistic risk analysis approach by using expert judgement and linguistic scales that do not require historical data. The FSD modelling approach also accounts for the dynamic nature of risk and opportunity events and causal interactions that exist among them, unlike MCS and FCD$^{©}$, which consider risk and opportunity events to be causally independent and estimate contingency at a specific time (e.g., quarterly). The FSD model also helps to track the severity of dynamic and interacting risk and opportunity events over time. The next chapter presents summary of the work conducted in this research, research contributions, research limitations, and recommendations for future research.

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Chapter 6 Conclusions and Recommendations[6]

6.1 Introduction

This chapter presents summary of the work conducted in this research and outlines the academic and industrial contributions. Moreover, limitations of this research and recommendations for future research are presented.

6.2 Research Summary

Construction projects are inherently fraught with risks and uncertainties throughout their life cycle. Hence, managing risks in construction projects is crucial to successfully achieving project objectives. Risk identification is the first and critical stage in risk management process as it develops the basis for later stages and ensures risk management effectiveness. Despite the abundance of published articles emphasizing on construction risk identification, there is a lack of systematic review and content analysis of risk identification literature in construction. As such, there is a need to examine common risk identification techniques and risk classification methods used in construction risk management process as well as identify, categorize and rank common risks impacting construction projects through systematic review and content analysis of selected published articles. Traditional risk analysis and contingency determination methods are ineffective

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[6] Parts of this chapter have been published in the *Journal of Construction Engineering and Management*: Siraj, N. B., and Fayek, A. Robinson (2019). "Risk identification and common risks in construction: Literature review and content analysis." *J. Const. Eng. Manage.*, 145(9), 03119004-1–03119004-13; and submitted for publication in *Automation in Construction*: Siraj, N. B., and Fayek, A. Robinson (2019). "Hybrid fuzzy system dynamics model for analyzing the impacts of interrelated risks and opportunity events on project contingency." *Automat. Constr.*, 70 manuscript pages, submitted July 9, 2019.

for capturing the dynamic causal interactions and subjective uncertainties involved in assessing risk and opportunity events. The lack of consideration of the dynamic nature of risk and opportunity events and the causal interactions and dependency between them can lead to over estimation or underestimation of contingency. Even though system dynamic (SD) is a viable option in capturing such characteristics, it has limited ability in handling subjective uncertainties and imprecisions associated to risk assessment. Subjective uncertainties and impressions can be best dealt with using fuzzy logic. Research endeavors to integrate SD and fuzzy logic so as to address the shortcomings of SD in risk analysis and contingency determination are very few. The main objective of this research is thus to develop a hybrid fuzzy system dynamics model (FSD) to analyze the severity of interrelated and interacting risk and opportunity events on work package cost and consequently determine work package and project contingencies. The stages followed to achieve the objectives of this research are discussed in the following subsections.

6.2.1 The First Stage

In the first stage, literature review was conducted on risk identification process and risk analysis in construction. The literature review aimed at identifying research gaps of past studies and establishing the theoretical framework of this research and the rationale for selecting the FSD modeling approach for risk analysis and contingency determination. The literature review conducted on risk identification process revealed that positive risks (opportunities) are often overlooked or addressed reactively; there is no standard or consensus on how to categorize risks in the construction industry; and there is lack of systematic review and content analysis of published articles related to risk identification in construction. Deterministic, probabilistic, fuzzy-based, and hybrid risk analysis and contingency determination methods in construction were reviewed, with a special focus on SD and FSD. The results of the literature review identified a lack of dynamic risk analysis and contingency determination method capable of capturing the complex interrelationships and interactions among risk and opportunity events, the dynamic nature of risk and opportunity events, and the subjective uncertainties and imprecisions associated in assessing them. The results of the literature review also revealed that there is a lack of structured and systematic method to define causal relationships among risk and opportunity events and construct causal loop diagrams (CLDs) in the qualitative FSD model. Additionally, the results indicate a lack of effective method for representing large number of fuzzy variables in FSD models for risk analysis and contingency determination. Furthermore, the results identified a lack of research on implementation of fuzzy arithmetic by the extension principle method in the FSD models for risk analysis and contingency determination, as most of the models are limited to the use of α-cut method.

6.2.2 The Second Stage

In the second stage, common risk identification tools and techniques and risk classification methods in construction were examined as well as potential risks affecting construction projects were identified, systematically categorized, and ranked. In order to achieve these objectives, a systematic review and detailed content analysis was carried out on 130 selected articles from 14 well-regarded academic journals in construction engineering and management published in the last three decades. A three-stage process—comprising selection of journals, selection of articles, and content analysis—was employed to conduct a systematic review and detailed content analysis on the selected articles. The findings of the content analysis showed that the majority of the selected articles identified risks for construction projects—mainly infrastructure projects—in the Asia and

Europe regions, and in most cases the identified risks were either classified based on their nature or listed without any categorization. For identifying risks, combinations of different information-gathering techniques were predominantly used in the selected articles, while diagramming and analysis-based techniques were seldom used. A comprehensive and structured risk classification method was established based on the existing category names in the selected articles and the risks identified from the selected articles were grouped into eleven categories: management, technical, construction, resource-related, site conditions, contractual and legal, economic and financial, social, political, environmental, and health and safety. The risk in each category were ranked based on their frequencies (i.e., total number of references each risk had). The most frequently identified risks based on the overall ranking were unpredicted change of inflation rate; design errors and poor engineering; and changes in government laws, regulations, and policies affecting the project. The common risks identified in this stage were used to design the risk identification and assessment survey form.

6.2.3 The Third Stage

In the third stage, a data collection protocol was prepared to describe the methodology and data collection process for developing the FSD model. Four different data collection forms were designed: experts' levels of expertise in risk management assessment survey form; project and work package characteristics survey form; risk and opportunity events identification and assessment survey form; and risk and opportunity events causal relationship assessment survey form. Qualification criteria such as experience, knowledge, professional performance, risk management practice, project specifics, reputation, and personal attributes and skills were used to assess the experts' levels of expertise in risk management. Predetermined rating scales and numerical values were used to assess the qualitative and quantitative qualification attributes, respectively. The project work package and characteristics survey form was used to record information about the selected project and work packages and to establish the context of the project. The risk identification and assessment survey form was designed to identify the risk and opportunity events applicable to the selected project and to assess the probability of occurrence of risk and opportunity events and their impact on the work package cost using linguistic terms represented by fuzzy numbers. The causal relationship assessment survey form comprised a pairwise comparison matrix and allows experts to assess the degree of causal influence of one risk and opportunity event on the other and define the type of causal relationship between them. Once the data survey forms were ready, a candidate project was selected as a case study through a meeting in the presence of senior management staff from the participating company. A group of experts, who were directly involved in the selected project, was formed and the surveys were administered in the form of structured interview survey.

6.2.4 The Fourth Stage

In the fourth stage, a hybrid FSD modeling methodology was developed to analyze the severity of dynamic and interacting risk and opportunity events on work package cost and consequently determine work package and project contingencies. The proposed modelling methodology was applied to develop a FSD model for determining the work package and project contingencies of the construction of a wind farm power generation project. The hybrid FSD model was developed in the following six steps: identification of risk and opportunity events; assessing experts' levels of expertise and assigning importance weights to experts; assessment and prioritization of risk and opportunity events; FSD model development; dynamic simulation of the FSD model and output determination; and FSD model validation.

A comprehensive literature review was conducted to identify common risk and opportunity events in construction and to establish a risk classification method as mentioned in the second stage. Then, the applicability of the identified risk and opportunity events and the risk categorization for the selected case study project was verified by the group of experts. The expertise level of the experts in risk management was assessed based on certain qualification attributes and the importance weights of the experts were determined using a fuzzy analytical hierarchical process (FAHP) weight assigning model.

A fuzzy-based risk assessment and prioritization procedure, which assesses the probability and impact of risk and opportunity events at work package level, takes into account the percentage of the work package affected, and considers the experts' expertise level, was adopted. Also, linguistic scales, represented by triangular or trapezoidal fuzzy numbers, were adopted to allow experts to use natural language to assess the probability and impact of risk and opportunity events. The experts' assessment of each risk and opportunity events for a given work package were aggregated to obtain the collective assessment of the experts by taking into account the importance weights of the experts. Then, the net severity percentage and overall net severity percentage of risk and opportunity events on a work package and project was determined, respectively. Subsequently, the risk and opportunity events to be considered in the FSD model were prioritized and selected.

The FSD model for risk analysis and contingency determination was developed in two stages: development of the qualitative and quantitative model. The first step in constructing the qualitative FSD model is to determine the risk and opportunity events that need to be considered in the model. Following, other key model parameter and variables were identified and the model boundary and level of aggregation was established. Then, a structured and systematic method, based on fuzzy DEMATEL (decision making trial and evaluation laboratory), was employed to define the causal relationships among risk and opportunity events and to construct the corresponding CLDs. 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. Finally, the qualitative FSD model of the project was created using AnyLogic® 8.2.3 simulation software.

In developing the quantitative FSD model, first, the objective and subjective (fuzzy) model parameter and variables were identified. The objective variables were quantified using crisp numbers and the risk and opportunity events were represented using fuzzy array. Then, the causal relationship between risk and opportunity events were defined using fuzzy weighted average to reflect the effect of predecessor risk and opportunity events on the posterior risk and opportunity event. Then, mathematical equations were developed to calculate the values of flow and stock variables at risk and opportunity event category, work package, and project level. A fuzzy arithmetic library was developed using Java programing language and imported to the quantitative FSD model in AnyLogic® to perform arithmetic operations based on α-cut method and drastic *t*-norm on mathematical equations involving both objective and subjective (fuzzy) variables.

The FSD model for the case study project was simulated over the project duration and the work packages and project contingencies were determined as fuzzy numbers. Different defuzzification methods—including smallest of maxima (SOM), middle of maxima (MOM), largest of maxima (LOM), and center of area (COA)—and confidence levels were applied to transform contingency fuzzy numbers into a crisp and interval values, respectively. The comparison of project contingency fuzzy numbers obtained based on the two fuzzy arithmetic methods indicate that excessive accumulation of fuzziness and overestimation of uncertainty was encountered when α-cut method was used in the FSD model. Lastly, structural and behavioral validation tests were performed to validate the FSD model. Moreover, the defuzzified contingency values obtained from FSD model at the end of the project duration were compared with Monte Carlo simulation (MCS) P50 and P95 project results and defuzzified values of Fuzzy Contingency Determinator© (FCD©). The FSD model provided comparable contingency result to MCS P50 and P95 and FCD© estimates.

The list of criteria and sub-criteria (qualification attributes) for assessing experts' expertise levels, the risk assessment and prioritization procedure, and the hybrid FSD modeling approach proposed in this thesis are generalizable and can be applied to other construction projects. To do so, the expertise levels of the experts to be involved in the risk assessment and model development should be evaluated based on the proposed set of criteria and sub-criteria (qualification attributes). In addition, the risk and opportunity events and CLDs can be used as a starting point for developing qualitative FSD models for future projects. However, the fuzzy membership functions of the linguistic terms for assessing the probability and impact of risk and opportunity events should be calibrated for new projects. The prioritization and ranking of the risk and opportunity events and the degree of causal influences among risks and opportunity events (i.e., the CLDs) should be modified to suit new projects.

6.3 Research Contributions

The academic and industrial contributions of this research relevant to academic researchers and construction industry practitioners, respectively are presented in the following subsections.

6.3.1 Academic Contributions

The main academic contributions of this research are summarised as follows:

1. *Providing a systematic and in-depth content analysis of published articles related to risk identification in construction; and a useful reference on common potential risks affecting construction projects for future risk identification, analysis, and modeling purposes*. This research addresses the lack of a systematic review and content analysis of published articles related to risk identification in construction and establishes research areas in need of further examination. The most common risk identification tools and techniques and risk classification methods used in construction projects were identified. Also, common potential risks affecting construction projects were identified, systematically categorized, and ranked. Moreover, a comprehensive risk classification method applicable to different types of construction projects and project stakeholders has been proposed. The proposed risk classification method helps to avoid redundancy and ambiguity and contributes to the effectiveness and quality of the risk identification process because the categories are detailed and comprehensive.

2. *Providing a systematic fuzzy-based risk assessment and prioritization procedure, which uses linguistic scales represented by fuzzy numbers to assess probability and impact of risks; incorporates opportunity in the assessment; allows risk assessment at the work package level; and accounts for differing levels of expertise in risk management based on*

a comprehensive set of expert qualification attributes. The proposed risk assessment and prioritization procedure allows experts to use natural language to assess the probability and impact of risk and opportunity events and captures the subjective uncertainty involved in assessing them. It also incorporates opportunity in the assessment which is rarely considered in previous construction risk assessment models. Assessing and prioritizing risk and opportunity events at the work package level have an advantage as the risk and opportunity events affecting a specific work package, their level of severity, and percentage of the work package affected could considerably vary for work packages in a project. Most previous risk assessment and prioritization procedures either do not take into account the experts' levels of expertise in risk management or importance weights are assigned to experts directly by a moderator or a manager. However, in this research the expertise level of the experts in risk management was assessed based on certain qualification attributes and consequently importance weights of the experts were determined and considered in aggregating experts assessments.

3. *Providing an approach, using hybrid FSD modeling, that can consider the dynamic causal interactions and dependencies between risks (opportunities) and quantify their severity on work package cost and consequently determine work package and project contingency by using expert judgement, linguistic scales, and fuzzy numbers*. Traditional risk analysis and contingency determination methods are ineffective in capturing the dynamic nature of risk and opportunity events and the complex causal interactions that exist between them. In most cases, risk and opportunity events are often modeled and analyzed as if they are independent, which can lead to over estimation or under estimation of contingency. This research addresses the limitations of traditional risk analysis and contingency

determination methods by providing a hybrid FSD modeling approach to analyze the severity of interrelated and interacting risk and opportunity events on work package cost and determine work package and project contingencies over the life cycle of the project.

4. *Contributing to the advancement of the state of the art in FSD modeling for risk analysis and contingency determination by (a) providing a structured and systematic method that uses linguistic terms for constructing causal loop diagrams (CLDs); (b) providing a method for handling subjective uncertainty in FSD; and (c) implementing fuzzy arithmetic methods (both α-cut and extension principle based on drastic t-norm) in FSD to carry out algebraic operations in mathematical equations involving fuzzy variables*. The CLDs in existing SD and FSD models are commonly developed based on the modelers' assumptions or the conceptual foundations of the models are borrowed from other fields. This research addresses the lack of structured and systematic method that uses linguistic terms for assessing the causal relationships among risk and opportunity events and for constructing CLDs. Common approaches in SD modelling use either numerical values or probabilistic distributions to define system variables and the approaches are incapable in accounting for subjective uncertainties associated with system variables. Integrating fuzzy logic with SD allows to capture the subjective uncertainty and imprecisions of variables and parameters involved in risk analysis and contingency determination. The methodology proposed in this research enables to represent large number of subjective (fuzzy) variables with multi-dimensional data in FSD model by using fuzzy arrays. The fuzzy arithmetic methods used in existing FSD models are limited to α-cut method because of its simplicity. However, the α-cut method leads to accumulation of fuzziness (due to growth of support) and the overestimation of uncertainty in the FSD model. This research addresses the lack of

research on implementation of fuzzy arithmetic by the extension principle method in FSD models for risk analysis and contingency determination by implementing both α-cut method and extension principle based on drastic t-norm. Moreover, it implements different defuzzification methods and confidence level to represent contingency fuzzy numbers with crisp and interval values, respectively.

6.3.2 Industrial Contributions

The main industrial contributions of this research are summarised as follows:

1. *Providing a useful reference on common potential risks affecting construction projects for future risk identification, analysis, and modeling* purposes through systematic review and content analysis of published articles. This research provides industry practitioners with a list of the most common potential risks affecting construction projects as well as a comprehensive risk classification method applicable to different types of construction projects and project stakeholders. The list of identified risks and the proposed classification method contributes to the effectiveness and quality of the risk identification process.
2. *Providing a risk modeling and analysis approach that allows construction industry practitioners to assess risks and opportunities by using subjective evaluation and experience*. The proposed modeling and analysis approach allows experts to use natural language to assess the probability and impact of risk and opportunity events as well as the causal relationships between them. The proposed approach does not require historical data; rather it uses expert judgement, linguistic scales, and fuzzy numbers to overcome the data reliance challenges of probabilistic methods. Also, the proposed approach takes into account the importance weights of experts in aggregating experts' evaluations and

addresses limitations of consensus reaching process and Delphi methods, which require several rounds of revisions to reach to an acceptable level of agreement.

3. *Providing a hybrid FSD modeling approach to understand the dynamic causal interactions and dependencies among risks; quantify and track their severity on work package cost; and determine work package and project contingency*. Unlike the traditional risk analysis and contingency determination methods, the proposed FSD modeling approach allows industry practitioners to determine realistic work package and project contingencies by considering the dynamic nature of risk and opportunity events and the causal interactions that exist between them. It also allows industry practitioners to explore different scenarios and track the severity of interacting risk and opportunity events over time.

6.4 Research Limitations and Recommendations for Future Research

The limitations of this research and recommendations for future research are discussed in the following subsections.

6.4.1 Content Analysis on Risk Identification Process and Common Risks in Construction

The systematic review and content analysis carried out on risk identification process and common risks in construction is more general and not context specific. Using the research methodology adopted for the content analysis, future research should focus on the identification of common risks, risk identification tools and techniques, and risk classification methods for different contexts based on project type, project location, project stakeholders, and project delivery type; for example, the identification of common risks for public-private partnership infrastructure projects in a given country or region from the contractors' perspective.

Some of the common risks identified from the selected articles are not stated as risks (but rather, are expressed as consequences), and some are not stated in a systematic and clear way to reduce subjectivity in evaluating them. Thus, future research will focus on systematically structuring and detailing the way risks are stated and refining the descriptions of the identified risks for different project contexts.

The common risks identified from the selected articles are ranked solely based on their frequencies, i.e., the total number of references each risk had. The frequencies only reflect how common the risks are in the construction industry or how frequently the risks are identified in the selected articles and do not show the probability of occurrence, impact, or severity of the identified risks on project objectives. Further studies are required to conduct extensive surveys and assess the probability, impact, and severity of the identified risks and rank them based on their severity level for different types of projects and contexts.

The findings of the content analysis show that there are a vast number of risk management tools and techniques and risk classification methods in the literature. Therefore, it has become increasingly challenging to select an appropriate tool and technique and classification method for risk identification on construction projects. Future research is required to develop a framework to assist with the selection of an appropriate risk identification tool and technique and risk classification method. In order to develop such a framework, important criteria that need to be considered for the selection of risk identification tools and techniques and risk classification methods (e.g., complexity of the project, risk maturity of the organization, simplicity of use, completeness of the tools and techniques, etc.) should be identified, and a multi-criteria decision-making model should be developed.

6.4.2 Assessing Experts' Levels of Expertise and Assigning Importance weights to Experts

In the risk assessment and prioritization step of this research, importance weights of the experts were considered to be the same for risk assessment of a given project, regardless of the work package being assessed. However, in reality, some experts are more knowledgeable than others or have backgrounds more relevant to a specific work package. Consequently, the importance weights assigned to experts should vary based on the work package being assessed. Thus, future research should explore the development of weight assigning method that considers the expertise level of experts specific to the work package under evaluation. The FAHP weight-assigning model used in this research considers the elements in the hierarchy (criteria and sub-criteria (i.e., qualification attributes)) for assessing the experts' expertise level to be independent of one another. Future research will explore the development of a weight assigning method based on the fuzzy analytic network process (ANP), which accounts for the interdependence among criteria as well as the sub-criteria belonging to a given criterion.

6.4.3 Development of Membership Functions for Linguistic Terms

In this research, the membership functions of the linguistic terms for assessing probability and impact of risk and opportunity events were generated based on a modified horizontal approach coupled with curve fitting, which is an expert-driven and direct method. The modified horizontal method is relatively simple to implement and allows the formulation of several questions into one question. However, it heavily relies on experts' judgements and can be subject to errors due to the subjectivity of experts and inconsistencies in answering questions. Expert-driven indirect methods such as pairwise comparison using the analytic hierarchy process (AHP), which allows for the checking of the consistency of the expert evaluations, and automatic data-driven approaches based on clustering methods (e.g., fuzzy c-means clustering (FCM)) will be explored to specify membership functions of the linguistic terms.

6.4.4 Prioritization of Risk and Opportunity Events

In this research, the risk and opportunity events considered in the FSD model were prioritized based on the net severity percentage without taking into account the causal interactions between them. Thus, an improved prioritization procedure that considers both the net severity percentage and the causal interaction between the risk and opportunity events is recommended for further investigation. The risk and opportunity events would be prioritized using the new prioritization procedure as follows: first the defuzzified net severity percentage of each risk and opportunity event would be calculated as described in Chapter 4. Second, a fuzzy DEMATEL approach would be employed to determine the prominence, $(\tilde{R} + \tilde{C})^{def}$, and relation, $(\tilde{R} - \tilde{C})^{def}$, vectors, which reflect the level of causal interactions among the risk and opportunity events, as discussed in Chapter 4. Third, the importance weight of each risk and opportunity event would be determined by adding the squared values of the prominence and relation, and taking the square root (Can and Toktas 2018). Fourth, the relative importance weight of each risk and opportunity event would be determined by dividing the importance weight of a given risk and opportunity event by the sum of the importance weights of all risks and opportunities under consideration (Can and Toktas 2018). Fifth, the weighted net severity percentage of each risk and opportunity event would be determined by multiplying the net severity percentage with the relative importance weight. Finally, the risk and opportunity events would be ranked and prioritized based on the weighted net severity percentage.

6.4.5 Improvement of the Fuzzy DMEATEL Method

In this research, a fuzzy DEMATEL method was employed to establish the causal relationship between risk and opportunity events and to construct the CLDs. The fuzzy DEMATEL method involves lengthy mathematical procedures (matrix computations and fuzzy arithmetic calculations), which limit the use of this method by industry practitioners. Thus, a software tool should be developed in the future to automate the fuzzy DEMATEL procedures and facilitate tits implementation.

In this research, the threshold value to filter negligible causal relations was determined based on a 75th percentile value of all elements in the defuzzified total-relation matrix (T^{Def}). Future research should explore the use of other methods and algorithms, such as maximum mean de-entropy (Li and Tzeng 2009), for determining the threshold value.

6.4.6 Implementation of Fuzzy Arithmetic Methods

In this research, the α-cut method and the extension principle based on drastic t-norm were implemented to carry out fuzzy arithmetic operations involving both triangular and trapezoidal fuzzy numbers in the FSD model. The fuzzy arithmetic method implemented in the FSD model should be extended to incorporate the other basic t-norms in engineering applications such as product t-norm (t_{prod}) and Lukasiewicz (bounded difference) t-norm (t_{Luk}) as well as common parametrised t-norms such as Yager t-norm, Hamacher t-norm, and Schweizer-Sklar t-norm. The parameterized t-norms are defined by explicit formula involving a parameter p and provide flexibility to adjust the amount of uncertainty included in the resulting fuzzy numbers by varying the parameters. The arithmetic method should also be extended, so that it can be applied on

Gaussian fuzzy numbers, which is a common fuzzy number used in engineering applications other than triangular and trapezoidal fuzzy numbers.

6.4.7 Further Expansion of the FSD Model

The FSD model developed in this research is only capable of determining the severity of interacting risk and opportunity events on work package and project cost. Risk and opportunity events may have an impact on two or more project objectives at the same time (i.e., concurrent impact). Moreover, the cumulative impact of interrelated and interacting risks on two or more project objectives is different than the sum of the individual impacts of independent risks on a specific project objective (Boateng 2012). Thus, this research should be extended in the future to develop a 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 number of experts involved in defining the causal relationships between the risk and opportunity events and constructing the CLDs was few. Moreover, the FSD modelling methodology was applied only to one windfarm project. In future research, more experts should be involved and more projects should be considered in developing a generalizable FSD model for determining work package and project contingencies for the construction of wind farm projects. The CLDs were reviewed and verified by the same experts who completed the fuzzy DEMATEL survey. In the future, “cold eye” reviews should be done on the CLDS by experts who were not involved in the qualitative model development stage. For validation purpose, the project contingencies estimated by FSD was compared with MCS and FCD© contingency estimates, both of which determine project contingency by considering risk and opportunity events to be independent and static. Thus, further validation should be done by comparing the FSD contingency results with the final actual cost variance of completed work packages and project to check if the FSD model offers better predictive capability than MCS and FCD©. Further validation will also help in selecting the appropriate fuzzy arithmetic and defuzzification method for future projects.

The FSD model developed in this research only deals with subjective uncertainties. Hence, this research should be extended to provide the ability to account for both probabilistic (i.e., randomness) and subjective uncertainties in the FSD. Future research should also explore the application of machine learning techniques, such as data-driven fuzzy rule-based systems (FRBSs), artificial neural networks (ANNs), fuzzy neural networks, and neuro-fuzzy systems to define the relationships between system variables in FSD automatically from data.

Traditional risk management techniques do not support the risk response stage. Rather, they focus primarily on the risk identification and analysis stages and tend to recommend response strategies based on the severity level of risk and opportunity events without further investigating the impact of response strategies on work package and project contingency. Furthermore, most techniques do not take into account the impact of secondary risks, which may arise as a direct result of implementing a response strategy. Therefore, future research is required to develop an FSD model that is capable of incorporating response strategies for critical risks along with their associated secondary risks to determine their severity on work package and project contingency and evaluate the effectiveness of response strategies prior to their implementation.

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Appendices

Appendix A. Selected Articles for the Content Analysis

No.	Journal Name	Author(s)	Year	Title of the article
1	ESA	Ameyaw, E.E. and Chan, A.P.C.	2015	Evaluation and Ranking of Risk Factors in Public–Private Partnership Water Supply Projects in Developing Countries Using Fuzzy Synthetic Evaluation Approach
2	ESA	Ebrahimnejad, S., Mousavi, S.M., and Seyrafianpour, H.	2010	Risk Identification and Assessment for Build–Operate–Transfer Projects: A Fuzzy Multi Attribute Decision Making Model
3	ESA	Fan, Z., Li, Y, and Zhang, Y.	2015	Generating Project Risk Response Strategies Based on CBR: A Case Study
4	ESA	Mousavi, S.M., Tavakkoli-Moghaddam, R., Azaron, A., Mojtahedi, S.M.H., and Hashemi, H.	2011	Risk Assessment for Highway Projects Using Jackknife Technique
5	AC	Cheng, M. and Lu, Y.	2015	Developing a Risk Assessment Method for Complex Pipe Jacking Construction Projects
6	AC	Chien, K., Wu, Z., and Huang, S.	2014	Identifying and Assessing Critical Risk Factors for BIM Projects: Empirical Study
7	AC	Dikmen, I., Birgonul, M.T., Anac, C., Tah, J.H.M., and Aouad, G.	2008	Learning from risks: A Tool for Post-Project Risk Assessment
8	AC	Ding, L.Y., Yu, H.L., Li, H., Zhou, C., Wu, X.G., Yu, M.H.	2012	Safety Risk Identification System for Metro Construction on the Basis of Construction Drawings
9	AC	Tserng, H.P., Yin, S.Y.L., Dzeng, R.J., Wou, B., Tsai, M.D., and Chen, W.Y.	2009	A Study of Ontology-Based Risk Management Framework of Construction Projects through Project Life Cycle
10	AC	Xu, Y., Yeung, J.F.Y., Chan, A.P.C, Chan, D.W.M., Wang, S.Q., and Ke, Y.	2010	Developing a Risk Assessment Model for PPP Projects in China — A Fuzzy Synthetic Evaluation Approach
11	AC	Yildiz, A.E., Dikmen, I., Birgonul, M.T., Ercoskun, K., and Alten, S.	2014	A Knowledge-based Risk mapping Tool for Cost Estimation of International Construction Projects
12	IJPM	Akintoye, A.S. and Macleod, M.J.	1997	Risk Analysis and Management in Construction
13	IJPM	Baloi, D. and Price, A.D.F.	2003	Modelling Global Risk Factors Affecting Construction Cost Performance
14	IJPM	Bing, L., Akintoye, A., Edwards, P.J., and Hardcastle, C.	2005	The Allocation of Risk in PPP/PFI Construction Projects in the UK
15	IJPM	Dikmen, I., Birgonul, M.T., and Han, S.	2007	Using Fuzzy Risk Assessment to Rate Cost Overrun Risk in International Construction Projects
16	IJPM	El-Sayegh, S.M.	2008	Risk Assessment and Allocation in the UAE Construction Industry
17	IJPM	Ghosh, S. and Jintanapakanont, J.	2004	Identifying and Assessing the Critical Risk Factors in an Underground Rail Project in Thailand: A Factor Analysis Approach
18	IJPM	Hwang, B., Zhao, X., and Gay, M.J.S.	2013	Public Private Partnership Projects in Singapore: Factors, Critical Risks and Preferred Risk Allocation from the Perspective of Contractors
19	IJPM	Jin, X. and Zhang, G.	2011	Modelling Optimal Risk Allocation in PPP Projects Using Artificial Neural Networks
20	IJPM	Kartam, N.A. and Kartam, S.A.	2001	Risk and Its Management in the Kuwaiti Construction Industry: A Contractors' Perspective
21	IJPM	Ke, Y., Wang, S.Q., Chan, A.P.C., and Lam, P.T.I.	2010	Preferred Risk Allocation in China's Public–Private Partnership (PPP) Projects

No.	Journal Name	Author(s)	Year	Title of the article
22	IJPM	Kuo, Y. and Lu, S.	2013	Using Fuzzy Multiple Criteria Decision Making Approach to Enhance Risk Assessment for Metropolitan Construction Projects
23	IJPM	Lam, K.C., Wang, D., Lee, P.T.K., and Tsang, Y.T.	2007	Modelling Risk Allocation Decision in Construction Contracts
24	IJPM	Liu, J., Jin, F., Xie, Q., and Skitmore, M.	2017	Improving Risk Assessment in Financial Feasibility of International Engineering Projects: A Risk Driver Perspective
25	IJPM	Lu, S. and Yan, H.	2013	A Comparative Study of the Measurements of Perceived Risk among Contractors in China
26	IJPM	Nieto-Morote, A. and Ruz-Vila, F.	2011	A Fuzzy Approach to Construction Project Risk Assessment
27	IJPM	Qazi, A., Quigley, J., Dickson, A., and Kirytopoulos, K.	2016	Project Complexity and Risk Management (ProCRiM): Towards Modelling Project Complexity Driven Risk Paths in Construction Projects
28	IJPM	Yu, T., Shen, G.Q., Shi, Q., Lai, X., Li, C.Z., and Xu, K.	2017	Managing Social Risks at the Housing Demolition Stage of Urban Redevelopment Projects: A Stakeholder-Oriented Study Using Social Network Analysis.
29	IJPM	Zayed, T., Amer, M., and Pan, J.	2008	Assessing Risk and Uncertainty Inherent in Chinese Highway Projects Using AHP
30	IJPM	Zeng, J., Min, A., and Smith, N.J	2007	Application of a Fuzzy Based Decision Making Methodology to Construction Project Risk Assessment
31	IJPM	Zhang, Y.	2016	Selecting Risk Response Strategies Considering Project Risk Interdependence
32	IJPM	Zhi, H.	1995	Risk Management for Overseas Construction Projects
33	IJPM	Zou, P.X.W., Zhang, G., and Wang, J.	2007	Understanding the Key Risks in Construction Projects in China
34	B&E	Jannadi, O.A.	2008	Risks Associated with Trenching Works in Saudi Arabia
35	B&E	Oztas, A. and Okmen, O.	2004	Risk Analysis in Fixed-Price Design–Build Construction Projects
36	B&E	Oztas, A. and Okmen, O.	2005	Judgmental Risk Analysis Process Development in Construction Projects
37	B&E	Tam, V.W.Y., Shen, L.Y., Tam, C.M., and Pang, W.W.S.	2007	Investigating the Intentional Quality Risks in Public Foundation Projects: A Hong Kong Study
38	B&E	Zhang, L., Wu, X., Ding, L., and Skibniewski, M.J.	2013	A Novel Model for Risk Assessment of Adjacent Buildings in Tunneling Environments
39	JCEM	Al-Bahar, J.F. and Crandall, K.C.	1990	Systematic Risk Management Approach for Construction Projects
40	JCEM	Babar, S., Thaheem, M.J., and Ayub, B.	2017	Estimated Cost at Completion: Integrating Risk into Earned Value Management
41	JCEM	Chan, E.H.W. and Au, M.C.Y.	2009	Factors Influencing Building Contractors' Pricing for Time-Related Risks in Tenders
42	JCEM	Chang, C. and Ko, J.	2017	New Approach to Estimating the Standard Deviations of Lognormal Cost Variables in the Monte Carlo Analysis of Construction Risks
43	JCEM	Choudhry, R.M., Aslam, M.A., Hinze, J.W. and Arian, F.M.	2012	Cost and Schedule Risk Analysis of Bridge Construction in Pakistan: Establishing Risk Guidelines
44	JCEM	Creedy, G.D., Skitmore, M. and Wong, J.K.W.	2010	Evaluation of Risk Factors Leading to Cost Overrun in Delivery of Highway Construction Projects
45	JCEM	Diab, M.F., Varma, A., and Kamalesh, P.	2017	Modeling the Construction Risk Ratings to Estimate the Contingency in Highway Projects

No.	Journal Name	Author(s)	Year	Title of the article
46	JCEM	Dikmen, I., Birgonul, M.T., Tah, J.H.M., and Ozer, A.H.	2004	Web-Based Risk Assessment Tool Using Integrated Duration–Cost Influence Network Model
47	JCEM	Elbarkouky, M.G., Fayek, A.R., Siraj, N.B., and Sadeghi, N.	2016	Fuzzy Arithmetic Risk Analysis Approach to Determine Construction Project Contingency
48	JCEM	Eybpoosh, M., Dikmen, I. and Birgonul, M.T.	2011	Identification of Risk Paths in International Construction Projects Using Structural Equation Modeling
49	JCEM	Fang, D., Mingen, L., Fong, P.S., and Liyin, S.	2004	Risks in Chinese Construction Market—Contractors' Perspective
50	JCEM	Goh, C.S., Abdul-Rahman, H., and Abdul Samad, Z.	2013	Applying Risk Management Workshop for a Public Construction Project: Case Study
51	JCEM	Iyer, K.C., and Sagheer, M.	2010	Hierarchical Structuring of PPP Risks Using Interpretative Structural Modeling
52	JCEM	Li, J. and Zou, P.X.W.	2011	Fuzzy AHP-Based Risk Assessment Methodology for PPP Projects
53	JCEM	Li, Y., Wang, X., and Wang, Y.	2017	Using Bargaining Game Theory for Risk Allocation of Public-Private Partnership Projects: Insights from Different Alternating Offer Sequences of Participants
54	JCEM	Molenaar, K.R.	2005	Programmatic Cost Risk Analysis for Highway Megaprojects
55	JCEM	Schatteman, D., Herroelen, W., Van de Vonder, S., and Boone, A.	2008	Methodology for Integrated Risk Management and Proactive Scheduling of Construction Projects
56	JCEM	Shrestha, A., Chan, T.K., Aibinu, A.A., Chen, C., and Martek, I.	2017	Risks in PPP Water Projects in China: Perspective of Local Governments
57	JCEM	Subramanyan, H., Sawant, P.H., and Bhatt, V.	2012	Construction Project Risk Assessment: Development of Model Based on Investigation of Opinion of Construction Project Experts from India
58	JCEM	Tang, W., Qiang, M., Duffieled, C.F., Young, D.M., and Lu, Y.	2007	Risk Management in the Chinese Construction Industry
59	JCEM	Tavakolan, M. and Etemadinia, H.	2017	Fuzzy Weighted Interpretive Structural Modeling: Improved Method for Identification of Risk Interactions in Construction Projects
60	JCEM	Xia, N., Zhong, R., Chunlin, W., Wang, X. and Wang, S.	2017	Assessment of Stakeholder-Related Risks in Construction Projects: Integrated Analyses of Risk Attributes and Stakeholder Influences
61	JCEM	Zhang, G. and Zou, P.X.W.	2007	Fuzzy Analytical Hierarchy Process Risk Assessment Approach for Joint Venture Construction Projects in China
62	JCCE	Fidan, G., Dikmen, I., Tanyer, A.M., and Birgonul, M.T.	2011	Ontology for Relating Risk and Vulnerability to Cost Overrun in International Projects
63	JCCE	Jin, X.	2010	Neurofuzzy Decision Support System for Efficient Risk Allocation in Public-Private Partnership Infrastructure Projects
64	JCCE	Karakas, K., Dikmen, I., and, Birgonul, M.	2013	Multiagent System to Simulate Risk-Allocation and Cost-Sharing Processes in Construction Projects
65	JCCE	Liu, D., Xuan, P., Li, S., and, Huang, P.	2015	Schedule Risk Analysis for TBM Tunneling Based on Adaptive CYCLONE Simulation in a Geologic Uncertainty–Aware Context
66	JCCE	Tah, J.H.M., and Carr, V.	2001	Knowledge-Based Approach to Construction Project Risk Management
67	JCCE	Zhou, Y., Su, W., Ding, L., Luo, H., and Love, P.E.D.	2017	Predicting Safety Risks in Deep Foundation Pits in Subway Infrastructure Projects: Support Vector Machine Approach

No.	Journal Name	Author(s)	Year	Title of the article
68	JME	Aladag, H. and Isik, Z.	2017	Role of Financial Risks in BOT Megatransportation Projects in Developing Countries
69	JME	Chan, A.P.C., Yeung, J.F.Y., Yu, C.C.P., Wang, S.Q., and Ke, Y.	2011	Empirical Study of Risk Assessment and Allocation of Public-Private Partnership Projects in China
70	JME	El-Sayegh, S.M. and Mansour, M.H.	2015	Risk Assessment Allocation in Highway Construction Projects in the UAE
71	JME	Jung, W. and Han, S.H.	2017	Which Risk Management is Most Crucial for Controlling Project Cost?
72	JME	Lee, N. and Schaufelberger, J.E.	2014	Risk Management Strategies for Privatized Infrastructure Projects: Study of the Build–Operate–Transfer Approach in East Asia and the Pacific
73	JME	Nielsen, K.R.	2006	Risk Management: Lessons from Six Continents
74	JME	Odediran, S.J. and Windapo, A.O.	2017	Mitigating Risks in African Construction Markets through the Interactive Behavior of Resources and Capabilities in Multinational Construction Companies and Entry Decisions
75	JME	Tran, D.Q., and Molenaar, K.R.	2014	Impact of Risk on Design-Build Selection for Highway Design and Construction Projects
76	JME	Wang, J. and Yuan, H.	2016	System Dynamics Approach for Investigating the Risk Effects on Schedule Delay in Infrastructure Projects
77	JME	Wang, M. and Chou, H.	2003	Risk Allocation and Risk Handling of Highway Projects in Taiwan
78	JIS	Ameyaw, E.E., Chan, A.P.C., Owusu-Manu, D., Edwards, D.J., and Dartey, F.,	2017	A Fuzzy-Based Evaluation of Financial Risks in Build–Own–Operate–Transfer Water Supply Projects
79	JIS	Chan, A.P.C., Lam, P.T.I., Yang, W., Ameyaw, E.E., Wang, S., and Ke, Y.	2015	Cross-Sectional Analysis of Critical Risk Factors for PPP Water Projects in China
80	JIS	Hastak, M. and Baim, E.J.	2001	Risk Factors Affecting Management and Maintenance Cost of Urban Infrastructure
81	JIS	Heravi, G., and Hajihosseini, Z.	2012	Risk Allocation in Public–Private Partnership Infrastructure Projects in Developing Countries: Case Study of the Tehran–Chalus Toll Road
82	JIS	Ke, Y., Wang, S., and Chan, A.P.C.	2010	Risk Allocation in Public-Private Partnership Infrastructure Projects: Comparative Study
83	CME	Acar, E. and Göç, Y.	2011	Prediction of Risk Perception by Owners' Psychological Traits in Small Building Contractors
84	CME	Al-Sabah, R., Menassa, C.C., and Hanna, A.	2014	Evaluating Impact of Construction Risks in the Arabian Gulf Region from Perspective of Multinational Architecture, Engineering and Construction Firms
85	CME	Andi	2006	The Importance and Allocation of Risks in Indonesian Construction Projects
86	CME	Jha, K.N. and Devaya, M.N.	2008	Modelling the Risks Faced by Indian Construction Companies Assessing International Projects
87	CME	Nasirzadeh, F., Afshar, A., Khanzadi, M., and Howick, S.	2008	Integrating System Dynamics and Fuzzy Logic Modelling for Construction Risk Management
88	CME	Ökmen, Ö. and Öztaş, A.	2010	Construction cost analysis under uncertainty with correlated cost risk analysis model
89	CME	Olawale, Y.A., and Sun, M.	2010	Cost and Time Control of Construction Projects: Inhibiting Factors and Mitigating Measures in Practice
90	CME	Tah, J.H.M., and Carr, V.	2000	A Proposal for Construction Project Risk Assessment Using Fuzzy Logic

No.	Journal Name	Author(s)	Year	Title of the article
91	CME	Thomas, A.V., Kalidindi, S.N., and Ananthanarayanan, K.	2003	Risk Perception Analysis of BOT Road Project Participants in India
92	CME	Wang, S.Q., Dulaim, M.F., and Aguria, M.Y.	2004	Risk Management Framework for Construction Projects in Developing Countries
93	CME	Xenidis, Y. and Angelides, D.	2005	The Financial Risks in Build-Operate-Transfer Projects
94	CME	Zou, P.X.W. and Li, J.	2010	Risk Identification and Assessment in Subway Projects: Case Study of Nanjing Subway Line 2
95	JCiEM	Abdul-Rahman, H., Wang, C., and Lee, Y.L.	2013	Design and Pilot Run of Fuzzy Synthetic Model (FSM) for Risk Evaluation in Civil Engineering
96	JCiEM	Ahmadi, M., Behzadian, K., Ardeshir, A., and Kapelan, Z.	2017	Comprehensive Risk Management Using Fuzzy FMEA and MCDA Techniques in Highway Construction Projects
97	JCiEM	Al-Azemi, K.F., Bhamra, R., and Salman, A.F.M.	2014	Risk Management Framework for Build, Operate and Transfer (BOT) Projects in Kuwait
98	JCiEM	Hwang, B., Zhao, X., and Yu, G.S.	2016	Risk Identification and Allocation in Underground Rail Construction Joint Ventures: Contractors’ Perspective
99	JCiEM	Ke, Y., Wang, S.Q., and Chan, A.P.C.	2012	Risk Management Practice in China’s Public-Private Partnership Projects
100	JCiEM	Valipour, A., Yahaya, N., Noor, N.M., Antucheviciene, and Tamosaitiene, J.	2017	Hybrid SWARA-COPRAS Method for Risk Assessment in Deep Foundation Excavation Project: an Iranian Case Study
101	JCiEM	Valipour, A., Yahaya, N., Noor, N.M., Kildienė, S., Sarvari, H., and Mardani, A.	2015	A Fuzzy Analytic Network Process Method for Risk Prioritization in Freeway PPP Projects: An Iranian Case Study.
102	JCiEM	Yazdani-Chamzini, A.	2014	Proposing a New Methodology Based on Fuzzy Logic for Tunnelling Risk Assessment
103	JCiEM	Zavadskas, E.K., Turskis, Z., and Tamosaitiene, J.	2010	Risk Assessment of Construction Projects
104	JCiEM	Zhang L., Wu, X., Ding, L., Skibniewski, M.J, and Lu, Y.	2016	BIM-Based Risk Identification System in Tunnel Construction
105	ECAM	Ahmed, S.M., Ahmad, R., and Saram, D.D.	1999	Risk Management Trends in the Hong Kong Construction Industry: A Comparison of Contractors and Owners Perceptions
106	ECAM	Albogamy, A. and Dawood, N.	2015	Development of a Client-Based Risk Management Methodology for the Early Design Stage of Construction Processes
107	ECAM	Edwards, P.J. and Bowen, P.A.	1998	Risk and Risk Management in Construction: A Review and Future Directions for Research
108	ECAM	Hwang, B., Zhao, X., and Chin, E.W.	2011	International Construction Joint Ventures Between Singapore and Developing Countries: Risk Assessment and Allocation Preferences
109	ECAM	Ke, Y., Wang, S., Chan, A.P., and Cheung, E.	2011	Analysis of Political Risks and Opportunities in Public Private Partnerships (PPP) in China and Selected Asian Countries: Survey Results
110	ECAM	Mahamid, I.	2011	Risk Matrix for Factors Affecting Time Delay in Road Construction Projects: Owners’ Perspective
111	ECAM	Rostami, A. and Oduoza, C.F.	2017	Key Risks in Construction Projects in Italy: Contractors’ Perspective
112	ECAM	Santoso, S.S., Ogunlana, S.O., and Minato, T.	2003	Assessment of Risks in High Rise Building Construction in Jakarta
113	ECAM	Ye, S. and Tiong, R.K.	2000	Government Support and Risk-return Trade-off in China’s BOT Power Projects

No.	Journal Name	Author(s)	Year	Title of the article
114	CJCE	Abdul-Rahman, H., Loo, S.C., and Wang, C.	2012	Risk Identification and Mitigation for Architectural, Engineering, and Construction Firms Operating in the Gulf Region
115	CJCE	Alireza, V., Mohammadreza, Y., Zin, R.M., Yahaya, N., and Noor, N.M.	2014	An Enhanced Multi-Objective Optimization Approach for Risk Allocation in Public–Private Partnership Projects: A Case Study of Malaysia.
116	CJCE	Bu-Qammaz, A.S., Dikmen, I., and Birgonul, M.T.	2009	Risk Assessment of International Construction Projects Using the Analytic Network Process
117	CJCE	Dikmen, I. and Birgonul, M.T.	2006	An Analytic Hierarchy Process Based Model for Risk and Opportunity Assessment of International Construction Projects
118	CJCE	Li, H.X., Al-Hussien, M., Lei, Z., and Ajwej, Z.	2013	Risk Identification and Assessment of Modular Construction Utilizing Fuzzy Analytic Hierarchy Process (AHP) and Simulation
119	CJCE	McIntosh, K. and McCabe, B.	2003	Risk and Benefits Associated with International Construction–Consulting Joint Ventures in the English-Speaking Caribbean
120	CJCE	Nasirzadeh, F., Afhar, A. and Khanzadi, M.	2008	Dynamic Risk Analysis in Construction Projects
121	CJCE	Salem D., Elwakil, E., Hegab, M.	2017	Risk Level Problems Affecting Microtunneling Projects Installation
122	IJCM	Jin, X. and Zuo, J.	2011	Critical Uncertainty Factors for Efficient Risk Allocation in Privately Financed Public Infrastructure Projects in Australia
123	IJCM	Mohammed, O., Abd-Karim, S.B., Roslan, N.H., Danuri, M.S., and Zakaria, N.	2015	Risk Management: Looming the Modus Operandi among Construction Contractors in Malaysia
124	IJCM	Perera, B.A.K., Rameezdeen, R., Chileshe, N., and Hosseini, M.R.	2014	Enhancing the Effectiveness of Risk Management Practices in Sri Lankan Road Construction Projects: A Delphi Approach
125	IJCM	Perez, D., Gray, J., and Skitmore, M.	2017	Perceptions of Risk Allocation Methods and Equitable Risk Distribution: A Study of Medium to Large Southeast Queensland Commercial Construction Projects
126	IJCM	Samaras, G.D., Gkanas, N.I., and Vista, K.C.	2014	Assessing Risk in Dam Projects Using AHP and ELECTRE I
127	IJCM	Zou, P.X.W., and Zhang, G.	2009	Managing Risks in Construction Projects: Life Cycle and Stakeholder Perspectives
128	JRUES	Mehany, M.S.H. and Guggemos, A.A.	2016	Risk-Managed Lifecycle Costing for Asphalt Road Construction and Maintenance Projects under Performance-Based Contracts
129	JRUES	Tolo, S., Patelli, E., and Beer, M.	2017	Risk Assessment of Spent Nuclear Fuel Facilities Considering Climate Change
130	JRUES	Wang, Z., Qiao, L., Li, S., and Bi, L.	2016	Risk Assessment for Stability and Containment Property of an Underground Oil Storage Facility in Construction Phase Using Fuzzy Comprehensive Evaluation Method

Appendix B. Expertise Level of the Experts in Risk Management

Appendix B.1. Self-evaluation Form (Completed by Experts)

Please enter numerical data values for the quantitative qualification attributes and assign a data value for each qualitative qualification attributes based on the corresponding predetermined rating scales provided.

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
1. Experience	1.1 Total years of experience	Number of years you have been working in this discipline	Real number		N/A
	1.2 Diversity of experience	Number of different companies you have worked for	Integer		N/A
	1.3 Relevant experience	Number of years you have been working in risk management	Real number		N/A
	1.4 Applied experience	Number of projects in which you performed risk management tasks	Real number		N/A
	1.5 Varied experience	Number of different functional areas or project types worked with in your entire career	Integer		N/A
2. Knowledge	2.1 Academic knowledge	Number of years of study in your discipline	Real number		N/A
	2.2 Education level	Highest degree achieved to date	1-5 predetermined rating		1. High School Degree; 2. College Degree; 3. Technical Degree; 4. Bachelor Degree; 5. Masters Degree
	2.3 On the job training	Number of courses taken in current discipline	Integer		N/A
3. Professional performance	3.1 Current occupation in the company	Your occupation in company currently working for	1-5 predetermined rating		1. Project Engineer; 2. Senior Engineer; 3. Project Manager; 4. Manager; 5. Senior Manager
	3.2 Years in current occupation	Number of years in your current occupation at company	Real number		N/A

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
	3.3 Expertise self-evaluation	Level of risk management expertise that participant expert acknowledges about himself/herself	1-5 predetermined rating		1. VERY LOW risk management expertise 2. LOW risk management expertise 3. AVERAGE risk management expertise 4. HIGH risk management expertise 5. VERY HIGH risk management expertise
4. Risk Management Practice	4.1 Average hours of work in risk per week	Number of hours per week working in risk management related tasks in current company	Real number		N/A
	4.2 Level of risk management training	Number of certifications you have obtained from risk management training sessions or workshops	Integer		N/A
	4.3 Risk management conferences experience	Number of risk management conferences you have attended	Integer		N/A
	4.4 Risk identification and planning	Experience level with proper risk identification and development of an overall risk management plan with risk response planning	1-5 predetermined rating		1. NO Proper risk identification, VERY POOR Development of an overall risk management plan with risk response planning; 2. NO Proper risk identification, POOR Development of an overall risk management plan with risk response planning; 3. SOME Risk identification, FAIR Development of an overall risk management plan with risk response planning; 4. SOME Risk identification, GOOD Development of an overall risk management plan with risk response planning; 5. DETAILED Risk identification, VERY GOOD Development of an overall risk management plan with risk response planning

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
4. Risk Management Practice	4.5 Risk monitoring and control	Experience level with keeping track of identified risks, monitoring residual risks and identifying new risks, ensuring the execution of risk plans, evaluating their effectiveness in reducing risk	1-5 predetermined rating		1. NOT Keeping track of identified risks, VERY POOR Monitoring of residual risks and identifying new risks, VERY POOR in Ensuring the execution of risk plans, NO Evaluation on their effectiveness in reducing risk; 2. NOT Keeping track of identified risks, POOR Monitoring of residual risks and identifying new risks, POOR in Ensuring the execution of risk plans, NO Evaluation on their effectiveness in reducing risk; 3. Keeping SOME track of identified risks, FAIR Monitoring of residual risks and identifying new risks, FAIR in Ensuring the execution of risk plans, SOME Evaluation on their effectiveness in reducing risk; 4. Keeping DETAIL track of identified risks, GOOD Monitoring of residual risks and identifying new risks, GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk; 5. Keeping DETAIL track of identified risks, VERY GOOD Monitoring of residual risks and identifying new risks, VERY GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
	4.6 Crisis management	Experience level in understanding the time phase of crisis (to be reactive or proactive), and having effective systems to prevent/control/manage crisis	1-5 predetermined rating		1. REACTIVE,VERY POOR systems to prevent crisis 2. REACTIVE,POOR systems to prevent crisis 3. REACTIVE, FAIR systems to prevent crisis 4. PROACTIVE,GOOD systems to prevent crisis 5. PROACTIVE, VERY GOOD systems to prevent crisis
5. Project Specifics	5.1 Project size limit	Monetary value of the largest risk management project you have worked on in current company	Real number		N/A
	5.2 Commitment to time deadlines	Percentage of projects finished on time by all projects you have been involved in	Real number		N/A
	5.3 Commitment to cost budget	Percentage of projects finished on budget by all projects you have been involved in	Real number		N/A
	5.4 Safety adherence	Number of projects you have worked in with zero incident rates	Integer		N/A
	5.5 Geographic diversity experience	Number of different project locations that you have worked on	Integer		N/A
6. Reputation	6.2 Willingness to participate in survey	Experts' attitude and willingness towards participating in research survey	1-5 predetermined rating		1. COMPLETELY Unwilling 2. SOMEWHAT NOT Willing 3. SOMEWHAT Willing 4. Willing 5. COMPLETELY Willing
	6.4 Enthusiasm and Willingness	Level of enthusiasm and willingness in performing risk management tasks in current company	1-5 predetermined rating		1. VERY POOR Enthusiasm and COMPLETELY Unwilling 2. POOR Enthusiasm and SOMEWHAT NOT Willing 3. AVERAGE Enthusiasm and SOMEWHAT Willing 4. GOOD Enthusiasm and WILLING

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
					5. VERY GOOD Enthusiasm and COMPLETELY Willing

Appendix B.2. Supervisor Evaluation Form (Completed by Supervisor)

Each qualitative qualification attribute is measured using the corresponding predetermined rating scales described below. Based on your own judgement **about the Expert's** expertise level, please assign a data value for each of the qualitative qualification attributes listed.

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
4. Risk Management Practice	4.4 Risk identification and planning	Experience level with proper risk identification and development of an overall risk management plan with risk response planning	1-5 predetermined rating		1. NO Proper risk identification, VERY POOR Development of an overall risk management plan with risk response planning; 2. NO Proper risk identification, POOR Development of an overall risk management plan with risk response planning; 3. SOME Risk identification, FAIR Development of an overall risk management plan with risk response planning; 4. SOME Risk identification, GOOD Development of an overall risk management plan with risk response planning; 5. DETAILED Risk identification, VERY GOOD Development of an overall risk management plan with risk response planning
4. Risk Management Practice	4.5 Risk monitoring and control	Experience level with keeping track of identified risks, monitoring residual risks and identifying new risks, ensuring the execution of risk plans, evaluating their effectiveness in reducing risk	1-5 predetermined rating		1. NOT Keeping track of identified risks, VERY POOR Monitoring of residual risks and identifying new risks, VERY POOR in Ensuring the execution of risk plans, NO Evaluation on their effectiveness in reducing risk; 2. NOT Keeping track of identified risks, POOR Monitoring of residual risks and identifying new risks, POOR in Ensuring the

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
					execution of risk plans, NO Evaluation on their effectiveness in reducing risk; 3. Keeping SOME track of identified risks, FAIR Monitoring of residual risks and identifying new risks, FAIR in Ensuring the execution of risk plans, SOME Evaluation on their effectiveness in reducing risk; 4. Keeping DETAIL track of identified risks, GOOD Monitoring of residual risks and identifying new risks, GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk; 5. Keeping DETAIL track of identified risks, VERY GOOD Monitoring of residual risks and identifying new risks, VERY GOOD in Ensuring the execution of risk plans, DETAILED Evaluation on their effectiveness in reducing risk
4. Risk Management Practice	4.6 Crisis management	Experience level in understanding the time phase of crisis (to be reactive or proactive), and having effective systems to prevent/control/manage crisis	1-5 predetermined rating		1. REACTIVE, VERY POOR systems to prevent crisis 2. REACTIVE, POOR systems to prevent crisis 3. REACTIVE, FAIR systems to prevent crisis 4. PROACTIVE, GOOD systems to prevent crisis 5. PROACTIVE, VERY GOOD systems to prevent crisis

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
6. Reputation	6.1 Social acclimation	Level of the experts' social acclimation by others	1-5 predetermined rating		1. VERY LOW social acclimation 2. LOW social acclimation 3. AVERAGE social acclimation 4. HIGH social acclimation 5. VERY HIGH social acclimation
	6.2 Willingness to participate in survey	Experts' attitude and willingness towards participating in research survey	1-5 predetermined rating		1. COMPLETELY Unwilling 2. SOMEWHAT NOT Willing 3. SOMEWHAT Willing 4. Willing 5. COMPLETELY Willing
	6.3 Professional reputation	Level of credibility of expert based on consistency and reasonableness (use of engineering judgement) of previous decisions	1-5 predetermined rating		1. VERY INCONSISTENT professional decisions and VERY UNRESONABLE professional decisions 2. INCONSISTENT professional decisions and UNRESONABLE professional decisions 3. SOMEWHAT CONSISTENT professional decisions and SOMEWHAT RESONABLE professional decisions 4. CONSISTENT professional decisions and RESONABLE professional decisions 5. VERY CONSISTENT professional decisions and VERY RESONABLE professional decisions
6. Reputation	6.4 Enthusiasm and willingness	Level of Enthusiasm and willingness in performing risk management tasks in current company	1-5 predetermined rating		1. VERY POOR Enthusiasm and COMPLETELY Unwilling 2. POOR Enthusiasm and SOMEWHAT NOT Willing 3. AVERAGE Enthusiasm and SOMEWHAT Willing 4. GOOD Enthusiasm and WILLING 5. VERY GOOD Enthusiasm and COMPLETELY Willing

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
	6.5 Level of risk conservativeness	Indicates the expert's level of conservativeness in risk management decisions	1-5 predetermined rating		1. VERY AGGRESSIVE risk-taking 2. AGGRESSIVE risk-taking 3. MODERATE risk-taking 4. CONSERVATIVE risk-taking 5. VERY CONSERVATIVE risk-taking
7. Personal Attributes and Skills	7.1 Level of communication skills	Indicates the expert's level of communication skills with other team members and peers including maintaining interpersonal skills with team, clearly expressing their point of view, and ability to communicate with others who are at different levels (technical/language/knowledge)	1-5 predetermined rating		1. VERY POOR interpersonal skills, NO eloquence, and VERY POOR vertical communication 2. POOR interpersonal skills, NO eloquence and POOR vertical communication 3. AVERAGE interpersonal skills, SOME eloquence, and AVERAGE vertical communication 4. GOOD interpersonal skills, CLEAR eloquence, and GOOD vertical communication 5. VERY GOOD interpersonal skills, CLEAR eloquence, and VERY GOOD vertical communication
7. Personal Attributes and Skills	7.2 Level of teamwork skills	Indicates the expert's level of teamwork skills within the current company such as participating as an active and contributing member to achieve the team's goals	1-5 predetermined rating		1. VERY INACTIVE team member and NO contribution to team's goals 2. INACTIVE team member and NO contribution to team's goals 3. AVERAGE ACTIVE team member and SOME contribution to team's goals 4. ACTIVE team member and FAIR contribution to team's goals 5. VERY ACTIVE team member and FAIR contribution to team's goals

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
	7.3 Level of leadership skills	Indicates the expert's level of leadership skills within the current company, such as finding resources and training team members; offering tools to support team members; communicating project objectives and progress; and willingness to coach or mentor others.			1. VERY POOR training, NO support tools to team members, VERY POOR communication of objectives and progress, COMPLETELY Unwilling to mentor 2. POOR training, NO support tools to team members, POOR communication of objectives and progress, SOMEWHAT NOT Willing to mentor 3. AVERAGE training, SOME support tools to team members, AVERAGE communication of objectives and progress, SOMEWHAT Willing to mentor 4. GOOD trainings, FAIR support tools to team members, GOOD communication of objectives and progress, Willing to mentor 5. VERY GOOD training, FAIR support tools to team members, VERY GOOD communication of objectives and progress, COMPLETELY Willing to mentor
7. Personal Attributes and Skills	7.4 Level of analytical skills	Expert's level of anticipating and identifying problems in daily tasks while accounting for any missing data	1-5 predetermined rating		1. VERY POOR anticipation and VERY POOR identification of problems 2. POOR anticipation and POOR identification of problems 3. AVERAGE anticipation and AVERAGE identification of problems 4. GOOD anticipation and GOOD identification of problems 5. VERY GOOD anticipation and VERY GOOD identification of problem

Criteria	Sub-criteria	Description	Scale of measure	Data Value	Predetermined Rating (1 - 5) Description
	7.5 Level of ethics	Expert's level of conforming to any legal or regulatory framework enforced by company, and expert’s level of morality	1-5 predetermined rating		1. VERY POOR compliance to legal and regulatory framework, and VERY POOR level of morality 2. POOR compliance to legal and regulatory framework ,and POOR level of morality; 3. AVERAGE compliance to legal and regulatory framework, and AVERAGE level of morality 4. GOOD compliance to legal and regulatory framework, and GOOD level of morality 5. VERY GOOD compliance to legal and regulatory framework, and VERY GOOD level of morality

Appendix C. Project and Work Package Characteristics Assessment

Please provide a description of the selected project by providing appropriate answers to the questions below.

1.1. Please indicate the name of the project: ____

1.2. Please indicate the project location: ____

1.3. What role does your organization play in the project?

☐ Owner
☐ Sub/Speciality contractor
☐ Project management service
☐ Financier
☐ Main contractor
☐ Consultant
☐ Supplier
☐ Other (please specify): _______________

1.4. Please specify the total contract value of the project: ________________________

1.5. Please specify the percentage of the allocated project contingency relative to the total project cost: ____________________________________

1.6. Please specify the contract duration of the project: _________________________

1.7. Please specify the project start date (for construction work): _________________________

1.8. Please specify the approximate percent complete to date in the ***Construction Work*** for this project: ____________________________

1.9. Please indicate below the project delivery system employed for the project.

☐ Traditional Design-Bid-Build
☐ Construction Management at Risk
☐ Build, Own, Operate and Transfer (BOOT)
☐ Public Private Partnership (P3)
☐ Design-Build (EPC)
☐ Parallel Primes
☐ Integrated Project Delivery (IDP)
☐ Other (please specify): ________________

1.10. Please indicate below the contract type used in the project.

☐ Unit Rate
☐ Cost Plus
☐ Guaranteed Maximum Price
☐ Lump Sum
☐ Time and Material
☐ Other (please specify): ____________

1.11. Please specify the number of similar projects completed by your organization: ___________

1.12. Please specify the number of work packages involved in the project: ________________

1.13. How would you rate the level of complexity of the project with respect to the number of work packages involved?

Low	Somewhat Low	Average	Somewhat High	High
1	2	3	4	5

1.14. How would you rate the overall complexity of the project?

Low	Somewhat Low	Average	Somewhat High	High
1	2	3	4	5

SECTION 2: WORK PACKAGE CHARACTERISTICS

Please provide a description of each work package by providing appropriate answers to the questions below.

2.1. Please indicate the name of the work package: ____________________________________

2.2. Please provide full description of the work package:

____

____

____

____

____

____

2.3. Please indicate below the contract type used in the work package:

☐ Unit Rate

☐ Cost Plus

☐ Guaranteed Maximum Price

☐ Lump Sum

☐ Time and Material

☐ Other (please specify): ____________

2.4. Please indicate the estimate type used for the work package:

☐ Indicative

☐ Historical

☐ Estimate

☐ Other (please specify): ____________

*2.5.*Please specify the total work package cost: ___________________________

2.6. Please specify the percentage of the total cost of the selected work package relative to the total project cost: _________________________________

2.7. Please specify the values of the cost components for the selected work package:

Cost component	Amount (Canadian Dollars)
Labour total cost	
Materials total cost	
Equipment total cost	
Subcontract total cost	
Indirect total cost	

2.8. Please specify the estimated duration of the work package: ___________________________

2.9. Please specify the start date of the work package (for construction work): _______________

2.10. Please specify the approximate percent complete to date in the ***Construction Work*** for this work package: ___________________________

2.11. Please specify the cumulative budgeted cost of the work package at different completion stage (percentage):

Percentage completion of the work package (%)	Cumulative budgeted cost of the work package (Canadian Dollars)
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	

2.12. Please rate the level of complexity of the selected work package based on the following descriptions using the predetermined rating scale (1-5)

		Level of Complexity				
No.	Description	Low	Somewhat Low	Average	Somewhat High	High
2.12.1	The level of complexity of the selected work package in terms of number of activities involved	1	2	3	4	5
2.12.2	The level of complexity of the selected work package with respect to the work scope	1	2	3	4	5
2.12.3	the level of the selected work package complexity with respect to the construction methods	1	2	3	4	5
2.12.4	The level of difficulty of the selected work package with regard to the constructability	1	2	3	4	5

2.13. Please rate the criticality of the work package based on the following descriptions using the predetermined rating scale (1-5):

		Level of Criticality				
No.	Description	Low	Somewhat Low	Average	Somewhat High	High
2.13.1	The criticality of the selected work package in terms of its share to the total project cost	1	2	3	4	5
2.13.2	The criticality of the selected work package in terms of its share to the total project contingency	1	2	3	4	5
2.13.3	The criticality of the selected work package in terms of its proneness to several risks	1	2	3	4	5

Appendix D. Risk and Opportunity Events Identification and Assessment

Work Package Name: ___________________________________

Percentage completion of the work package: _________________

Please assess the probability of occurrence of the following risks/opportunities and their respective impact on the selected work package on a scale of 1-5 (in addition to N/A- Not applicable), where 1 = Very low (VL), 2 = Low (L), 3 = Medium (M), 4 = High (H), and 5= Very high (VH). Please also determine the percentage of the work package cost that may be affected by each risk/opportunity. Blank rows are left intentionally to add additional risks.

1. Management risk and opportunity events

No.	Management Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
1.1	Poor coordination and communication among various parties involved in the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.2	Poor relationship among various parties involved in the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.3	Inadequate project organization structure	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.4	Poor project quality management including inadequate quality planning, quality assurance, and quality control	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.5	Poor or incomplete definition of project scope	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.6	Inadequate or poor project planning and budgeting	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.7	Interdependencies with other projects (consistency and complementarities with other projects)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.8	Poor site management and supervision by the contractor	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

No.	Management Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
1.9	Lack of experience and project management skills of the project team	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.10	Unavailability of sufficient professionals and managers	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.11	Loss of productivity due to inadequate site facilities planning or inability to manage labour	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.12	Poor capability of owner in project management	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.13	Low management competency of subcontractors	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.14	Lack of proper training program to new and existing staff in the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.15	Poor project monitoring and auditing	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.16	Low level motivation and efficiency of existing manpower	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.17	Frequent replacement of project managers and key personnel	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.18	Poor project cost management and control	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.19	Inefficiency of owner’s supervisors	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.20	Unexpected change in owner’s staff/organization	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.21	Inadequate experience of consultant with regard to type of work package/project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.22	Low project team cohesion (poor interpersonal relations between project team members)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.23	High staff turnover in the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.24	Poor time management due to change of manager or management strategies of the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.25	Consultant lacks adequate number of staff (inspector) during construction phase of the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.26	Inadequate project complexity analysis	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
1.27	Lack of proper management of subcontractors by the general contractor/owner	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

2. *Technical risk and opportunity events*

No.	Technical Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
2.1	Inappropriate design and poor engineering	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.2	Delay in issuing construction drawing due to late approval	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.3	Delay in design (design process takes longer than anticipated)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.4	Unpredicted technical problems in construction	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.5	Unclear and inadequate details in design drawings and specifications	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.6	Unanticipated engineering and design changes	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.7	Unproven engineering techniques (the techniques adopted are immature and cannot fulfill the standards and requirements as expected)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.8	Inadequate study and insufficient data before design (errors in feasibility studies)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.9	Incomplete design	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.10	Complexity of design	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.11	Problems in technology transfer and implementation	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.12	Rapidly changing technologies	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.13	Low constructability	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.14	Inefficiency in decision making on key design issues	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.15	Using inadequate software for design	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.16	Gaps between implementation and specifications; incompatibility between construction drawings and methods	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.17	Lack of proper design review and checking by consultant	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.18	Lack of skilled designers in the project region	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
2.19	Non-familiarity of the project team with a certain technology	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

3. Construction risk and opportunity events

No.	Construction Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
3.1	Delays and interruptions causing cost increase to the work package/project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.2	Poor workmanship and construction errors leading to rework	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.3	Unreasonably tight project schedule causing cost increase to the work package/project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.4	Contractor's incompetence in executing the work package/project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.5	Complexity of proposed construction methods/techniques	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.6	Change in construction methods/techniques	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.7	Conflicting interfaces of work items	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.8	Pressure to deliver project on accelerated schedule (pressure to crash project duration)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.9	Strict quality requirements	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.10	Contractor's lack of experience in similar projects	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.11	Adoption of improper, poor, or unproven construction methods/techniques	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.12	Delay in approving the contractor work by consultant or owner of the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.13	Failure to identify construction defects	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.14	Owner's improper intervention in construction phase	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.15	Technical mistakes during construction stage by contractor	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
3.16	Vagueness of construction methods/techniques	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

4. *Resource-related risk and opportunity events*

No.	Resources-Related Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
4.1	**Labour related**																									
4.1.1	Unavailability of sufficient amount of skilled labour in project region	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.1.2	Low labour productivity of local workforce	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.1.3	Untrained and inexperienced labour force	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.1.4	Strikes and labor disputes	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.1.5	Higher workforce attrition rates	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.1.6	Workforce absenteeism	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2	**Material related**																									
4.2.1	Unavailability or shortage of expected material	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.2	Delay in materials delivery	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.3	Defective or non-conforming materials that do not meet the standard	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.4	Material wastage and damage due to poor construction methods, working habit, or improper storage	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.5	Import restrictions on materials needed in construction	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.6	Changes in material types and specifications during construction	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.7	Delay in material approval	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.8	Limited capability and service quality of material suppliers and logistic service	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.2.9	Incorrect definition of type and quantity of needed materials by designer(s)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

No.	Resources-Related Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
4.3	**Equipment related**																									
4.3.1	Unavailability or shortage of expected Equipment	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.2	Equipment breakdown	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.3	Low productivity and efficiency of equipment	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.4	Delay in equipment delivery to the project site	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.5	Quality problem of construction equipment	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.6	Improper selection of construction equipment by contractor or subcontractor	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.7	Unavailability of spare parts and high maintenance cost of equipment	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.8	Equipment import restriction	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.3.9	Type and number of needed equipment are not compatible with work package/project scale	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.4	**Subcontractor related**																									
4.4.1	Unavailability of qualified subcontractors	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.4.2	Subcontractors' failure; default of subcontractors	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.4.3	Poor performance of subcontractors	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.4.4	Subcontractor lack of required technical skill	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.4.5	Subcontractor lack of adequate number of staff and equipment	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
4.4.6	Delay in appointing subcontractor	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

5. *Site conditions risk and opportunity events*

No.	Site Conditions Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
5.1	Unpredicted adverse engineering geology (subsurface conditions)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.2	Differing and unforeseen site conditions	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.3	Difficulties of access and work on site due to specific geographical constraint of region	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.4	Lack of readily available utilities on site (e.g., water, electricity, etc.) and supporting infrastructure unavailability	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.5	Late construction site possession	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.6	Inadequate site investigations (soil tests and site survey)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.7	Improper selection of project location	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.8	Security problems at project site	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.9	Delay in right of way process	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.10	Finding historical objects during excavation process	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.11	Ineffective control and management of traffic	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.12	Unexpected underground utilities encounter	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.13	Limited construction area (on-site congestion)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.14	Land acquisition and compensation problem (the cost and time for land acquisition exceeds the original plans)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.15	Obstruction to surrounding business or others	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.16	Poor preliminary assessment and evaluation of ground movement and settlements	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.17	Distance from primary sources, materials, and manufacturers	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
5.18	Ground water seepage which can damage underground construction work	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

6. *Contractual and legal risk and opportunity events*

No.	Contractual and Legal Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
6.1	Contradictions and vagueness in the contract documents	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.2	Delays in resolving contractual disputes and litigations	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.3	Change in codes and regulations	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.4	Possibility of contractual disputes and claims	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.5	Breach of contract by owner, contractor, or subcontractors	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.6	Contract and specification interpretation disagreement	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.7	Change in project scope	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.8	Unclear roles and responsibilities of project stakeholders	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.9	Intense competition at tender stage	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.10	Frequent change orders	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.11	Rigidity of contract provision	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.12	Lack of integrity in the tendering process (unfairness in tendering)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.13	Contract strategy changes from plan	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.14	Inadequate claim administration	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.15	Excessive contract variation	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.16	Immaturity and/or unreliability of legal system	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.17	Extent of work differs from contract	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.18	Errors or omissions in BOQ	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.19	Intensity of contract (the ratio of contract value and contract period)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.20	Inappropriate form or type of contract	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
6.21	Lack of legal judgement reinforcement	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

7. *Economic and financial risk and opportunity events*

No.	Economic ad Financial Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
7.1	Unpredicted change of inflation rate	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.2	Fluctuation in currency exchange and/or difficulty of convertibility	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.3	Escalation of material prices	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.4	Unpredicted change of interest rate	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.5	Change in tax regulation	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.6	Project funding problems	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.7	Delay in payments	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.8	Poor financial market or unavailability of financial instrument resulting difficulty of financing	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.9	Economic recession or instability of economic condition	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.10	Financial failure of the owner or contractor	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.11	Change in government funding policy	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.12	Lack of insurance (insufficient insurance)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.13	Market demand change	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.14	Wage inflation (increase in labors and employee salaries)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.15	Inaccurate assessment or forecast of market demand	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.16	Enactment of a new bylaw leading to cost changes	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.17	Energy price changes	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.18	Tight fiscal and monetary policies	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.19	Change in bankers policy for loans	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
7.20	Conflict between project financiers	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

8. *Economic and financial risk and opportunity events*

No.	Social Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
8.1	Differences in social, cultural and religious background	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.2	Unfavorable social environment	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.3	Public opposition to the project (public objections)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.4	Societal conflict and/or public unrest	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.5	Insecurity and crime (theft, vandalism and fraudulent practices)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.6	Land acquisition and compensation problems; the cost and time for land acquisition exceeds the original plans	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.7	Poor public relations with local contacts	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.8	Social grievances; local communities pose objections	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.9	Substance abuse	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.10	Unexpected aboriginal claims or protests leading to cost increase	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.11	Disturbances to public activities	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
8.12	Loss of public trust/goodwill	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

9. *Political risk and opportunity events*

No.	Political Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
9.1	Changes in government laws, regulations, and policies affecting the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.2	Outbreak of hostilities (wars, revolution, civil disorder/riots, and terrorism)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.3	Political instability of the government (unfavorable political environment)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.4	Delay or refusal of project approval and permit by government departments	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.5	Corrupt local government officials demand bribes or unjust rewards	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.6	High level of bureaucracy of the authority	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.7	Poor relations with related government departments	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.8	Government's improper intervention during construction	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.9	Poor international relations; instability of international relation	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.10	Government restrictions on foreign companies (e.g. mandatory technology transfer, differential taxation of foreign firms, etc.)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.11	Multinational sanctions (embargos)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.12	Change of government (government discontinuity)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.13	Out of date labor, tax, insurance, trade and environmental laws	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
9.14	Lack of support from government	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

10. Environmental risk and opportunity events

No.	Environmental Risk and Opportunity Events	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
10.1	Adverse weather conditions (continuous rainfall, snow, temperature, wind)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.2	Force majeure (natural and man-made disasters that are beyond the control doing the risk analysis, e.g. floods, thunder and lightning, landslide, earthquake, hurricane, etc.)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.3	Adverse environmental impacts of the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.4	Pollution associated with construction activities (dust, harmful gases, noise, solid and liquid wastes, etc.)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.5	Strict environmental regulations and requirements	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.6	Changes in environmental permitting	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.7	Poor preliminary assessment and evaluation of environmental impacts of the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.8	Poor environmental regulations and control	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
10.9	Prosecution due to unlawful disposal of construction waste	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

11. Health and safety risk and opportunity events

No.	Health and Safety Risks/Opportunities	Risk Probability of Occurrence						Risk Impact on Work Package Cost						Opportunity Probability of Occurrence						Opportunity Impact on Work Package Cost						Cost of Work Package Affected in %
		NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	NA	VL	L	M	H	VH	
11.1	Accidents occurring during construction	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.2	Inadequate safety measures or unsafe operations	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.3	Poor construction safety management	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.4	Damage to persons or property or materials due to poor health and safety management of the project	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.5	Changed labour safety laws or regulations	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.6	Lack of safety insurance	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.7	Ineffective protection of surrounding environment (e.g., adjacent buildings and facilities)	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.8	Failure to comply with HS&E standards or security plan	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.9	Accidents caused by or to resident communities or third parties	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.10	Epidemic illness	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.11	Poor safety and environmental regulations	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.12	Poor performance of contractor in health and safety of work	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.13	Strict health and safety regulations	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.14	Poor planning of contractor for emergency measures	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
11.15	Public concerns related to health and safety of the project due to poor communication	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5	

Appendix E. Assessment of Causal Relationships between Risk and Opportunity Events

Please assess (i) the degree of causal influence of risk and opportunity event *i* (row) over risk and opportunity *j* (column) using the linguistic terms very low, low, medium, high, and very high (in addition to N/A-Not applicable); and (ii) the type of causal relationship between the risk and opportunity event as positive, negative, or not applicable (N/A).

Risk and opportunity Event	**1.1** Lack of experience and project management skills of the project team		**1.2** Poor coordination and communication among various parties involved in the project		**1.3** Inadequate project organization structure		**1.4** Poor relationship among various parties involved in the project		…
	Degree of causal relationship	Type of causal relationship	Degree of causal relationship	Type of causal relationship	Degree of causal relationship	Type of causal relationship	Degree of causal relationship	Type of causal relationship	…
1.1 Lack of experience and project management skills of the project team									…
1.2 Poor coordination and communication among various parties involved in the project									…
1.3 Inadequate project organization structure									…
1.4 Poor relationship among various parties involved in the project									…
1.5 Unavailability of sufficient professionals and managers									…
2.2 Unanticipated engineering and design changes									…
2.4 Delay in issuing construction drawing due to late approval									…
2.8 Unproven engineering techniques (the techniques adopted are immature and cannot fulfill the standards and requirements as expected)									…
3.1 Delays and interruptions causing cost increase to the work package/project									…

Risk and opportunity Event	**1.1** Lack of experience and project management skills of the project team		**1.2** Poor coordination and communication among various parties involved in the project		**1.3** Inadequate project organization structure		**1.4** Poor relationship among various parties involved in the project		…
	Degree of causal relationship	Type of causal relationship	Degree of causal relationship	Type of causal relationship	Degree of causal relationship	Type of causal relationship	Degree of causal relationship	Type of causal relationship	…
3.3 Unreasonably tight project schedule causing cost increase to the work package/project									…
3.4 Complexity of proposed construction methods/techniques									…
3.7 Adoption of improper, poor, or unproven construction methods/techniques									…
3.8 Conflicting interfaces of work items									…
3.9 Pressure to deliver project on accelerated schedule (pressure to crash project duration)									…
3.10 Strict quality requirements									…
3.12 Owner's improper intervention in construction phase									…
3.13 Delay in approving the contractor work by consultant or owner of the project									…
3.15 Vagueness of construction methods/techniques									…
4.1.1 Unavailability of sufficient amount of skilled labour in project region									…
4.1.5 Higher workforce attrition rates									…
4.2.1 Unavailability or shortage of expected material									…
…	…	…	…	…	…	…	…	…	…

Appendix F. Prioritized List of Risk and Opportunity Events for the Structural Work Package

Risk ID	Description of risk and opportunity events	Risk and opportunity event category	Net severity percentage ($\widetilde{NS}_{i1}^{Def}$)	Rank
R3_1	Delays and interruptions causing cost increase to the work package/project	Construction	4.11	1
R3_8	Pressure to deliver project on accelerated schedule (pressure to crash project duration)	Construction	1.52	2
R3_9	Strict quality requirements	Construction	1.38	3
R7_5	Change in tax regulation	Economic and financial	1.18	4
R1_4	Poor project quality management including inadequate quality planning, quality assurance, and quality control	Management	1.16	5
R10_2	Force majeure (natural and man-made disasters that are beyond the control of the firm doing the risk analysis, e.g. floods, thunder and lightning, landslide, earthquake, hurricane, etc.)	Environmental	1.14	6
R10_1	Adverse weather conditions (continuous rainfall, snow, temperature, wind)	Environmental	1.12	7
R4_3_1	Unavailability or shortage of expected Equipment	Resource-related	1.05	8
R4_3_2	Equipment breakdown	Resource-related	1.05	8
R4_1_1	Unavailability of sufficient amount of skilled labour in project region	Resource-related	1.04	10
R5_10	Finding historical objects during excavation process	Site conditions	0.95	11
R4_3_4	Delay in equipment delivery to the project site	Resource-related	0.91	12
R10_6	Changes in environmental permitting	Environmental	0.89	13
R3_12	Delay in approving the contractor work by consultant or owner of the project	Construction	0.83	14
R3_13	Failure to identify construction defects	Construction	0.83	14
R4_1_5	Higher workforce attrition rates	Resource-related	0.82	16
R6_3	Change in codes and regulations	Contractual and legal	0.81	17

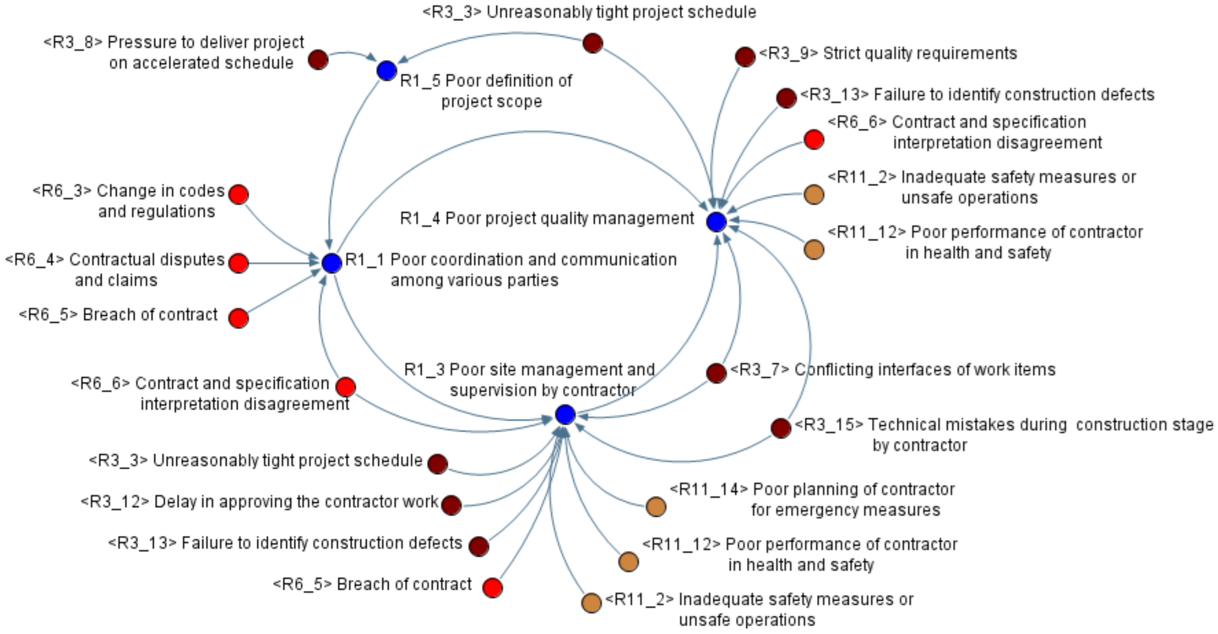
Risk ID	Description of risk and opportunity events	Risk and opportunity event category	Net severity percentage $(\widetilde{NS}_{i1}^{Def})$	Rank
R3_3	Unreasonably tight project schedule causing cost increase to the work package/project	Construction	0.79	18
R9_1	Changes in government laws, regulations, and policies affecting the project	Political	0.79	18
R3_15	Technical mistakes during construction stage by contractor	Construction	0.78	20
R11_1	Accidents occurring during construction	Health and safety	0.73	21
R6_4	Possibility of contractual disputes and claims	Contractual and legal	0.71	22
R6_5	Breach of contract by owner, contractor, or subcontractors	Contractual and legal	0.71	22
R6_6	Contract and specification interpretation disagreement	Contractual and legal	0.69	24
R1_5	Poor or incomplete definition of project scope	Management	0.59	25
R1_3	Poor site management and supervision by the contractor	Management	0.53	26
R1_1	Poor coordination and communication among various parties involved in the project	Management	0.51	27
R3_7	Conflicting interfaces of work items	Construction	0.46	28
R5_5	Late construction site possession	Site conditions	0.45	29
R5_9	Delays in right of way process	Site conditions	0.45	29
R11_2	Inadequate safety measures or unsafe operations	Health and safety	0.38	31
R11_12	Poor performance of contractor in health and safety of work	Health and safety	0.38	31
R11_14	Poor planning of contractor for emergency measures	Health and safety	0.38	31
R11_4	Damage to persons or property or materials due to poor health and safety management of the project	Health and safety	0.33	34
R5_15	Obstruction to surrounding business or others	Site conditions	0.31	35

Appendix G. Prioritized List of Risk and Opportunity Events for the Electrical Work Package

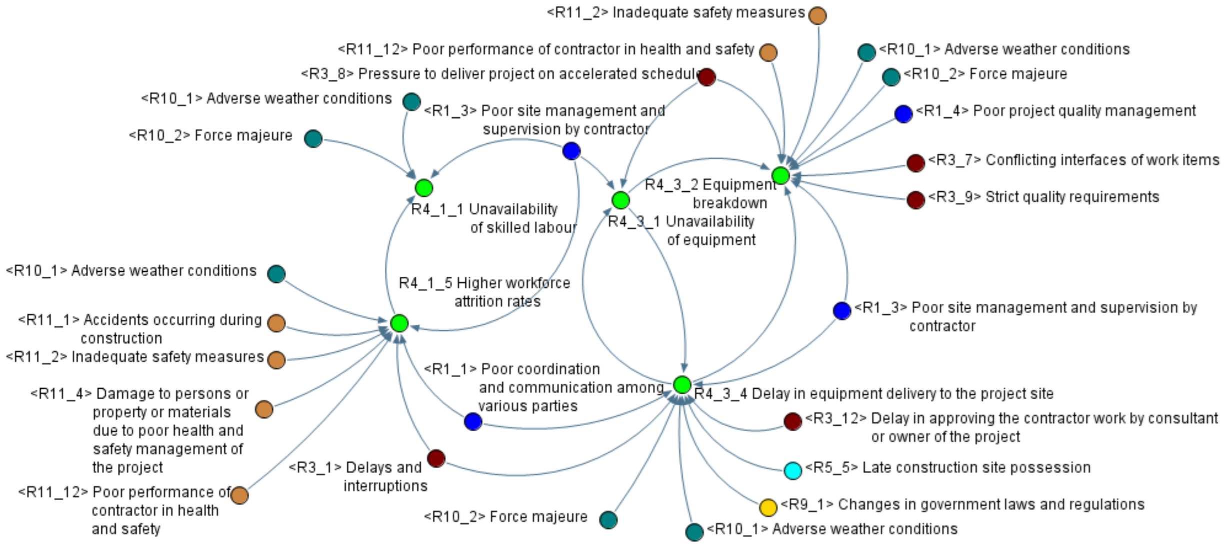
Risk ID	Description of risk and opportunity events	Risk and opportunity event category	Net severity percentage ($\widetilde{NS}_{i1}^{Def}$)	Rank
R5_7	Security problems at project site	Site conditions	2.43	1
R4_2_2	Delay in materials delivery	Resource-related	1.51	2
R3_7	Conflicting interfaces of work items	Construction	1.39	3
R3_1	Delays and interruptions causing cost increase to the work package/project	Construction	1.36	4
R3_8	Pressure to deliver project on accelerated schedule (pressure to crash project duration)	Construction	1.32	5
R1_4	Poor project quality management including inadequate quality planning, quality assurance, and quality control	Management	1.19	6
R10_2	Force majeure (natural and man-made disasters that are beyond the control of the firm doing the risk analysis, e.g. floods, thunder and lightning, landslide, earthquake, hurricane, etc.)	Environmental	1.19	6
R7_5	Change in tax regulation	Economic and financial	1.18	8
R10_1	Adverse weather conditions (continuous rainfall, snow, temperature, wind)	Environmental	1.10	9
R4_4_6	Delay in appointing subcontractor	Resource-related	0.98	10
R4_4_3	Poor performance of subcontractors	Resource-related	0.95	11
R2_2	Delay in issuing construction drawing due to late approval	Technical	0.94	12
R3_3	Unreasonably tight project schedule causing cost increase to the work package/project	Construction	0.94	12
R3_9	Strict quality requirements	Construction	0.94	12
R4_4_1	Unavailability of qualified subcontractors	Resource-related	0.94	12
R11_1	Accidents occurring during construction	Health and safety	0.87	16
R2_8	Gaps between implementation and specifications; incompatibility between construction drawings and methods	Technical	0.85	17
R4_2_1	Unavailability or shortage of expected material	Resource-related	0.82	18

R9_1	Changes in government laws, regulations, and policies affecting the project	Political	0.82	18
R3_4	Contractor's incompetence in executing the work package/project	Construction	0.76	20
R3_15	Technical mistakes during construction stage by contractor	Construction	0.76	20
R3_13	Failure to identify construction defects	Construction	0.72	22
R3_10	Contractor's lack of experience in similar projects	Construction	0.68	23
R3_12	Delay in approving the contractor work by consultant or owner of the project	Construction	0.68	23
R6_4	Possibility of contractual disputes and claims	Contractual and legal	0.66	25
R6_6	Contract and specification interpretation disagreement	Contractual and legal	0.66	25
R8_5	Insecurity and crime (theft, vandalism and fraudulent practices)	Social	0.66	25
R1_1	Poor coordination and communication among various parties involved in the project	Management	0.61	28
R9_4	Delay or refusal of project approval and permit by government departments	Political	0.59	29
R1_2	Poor relationship among various parties involved in the project	Management	0.58	30
R7_3	Escalation of material prices	Economic and financial	0.54	31
R2_4	Unpredicted technical problems in construction	Technical	0.51	32
R4_2_3	Defective or non-conforming materials that do not meet the standard	Resource-related	0.42	33
R4_2_5	Import restrictions on materials needed in construction	Resource-related	0.39	34
R5_9	Delays in right of way process	Site conditions	0.36	35

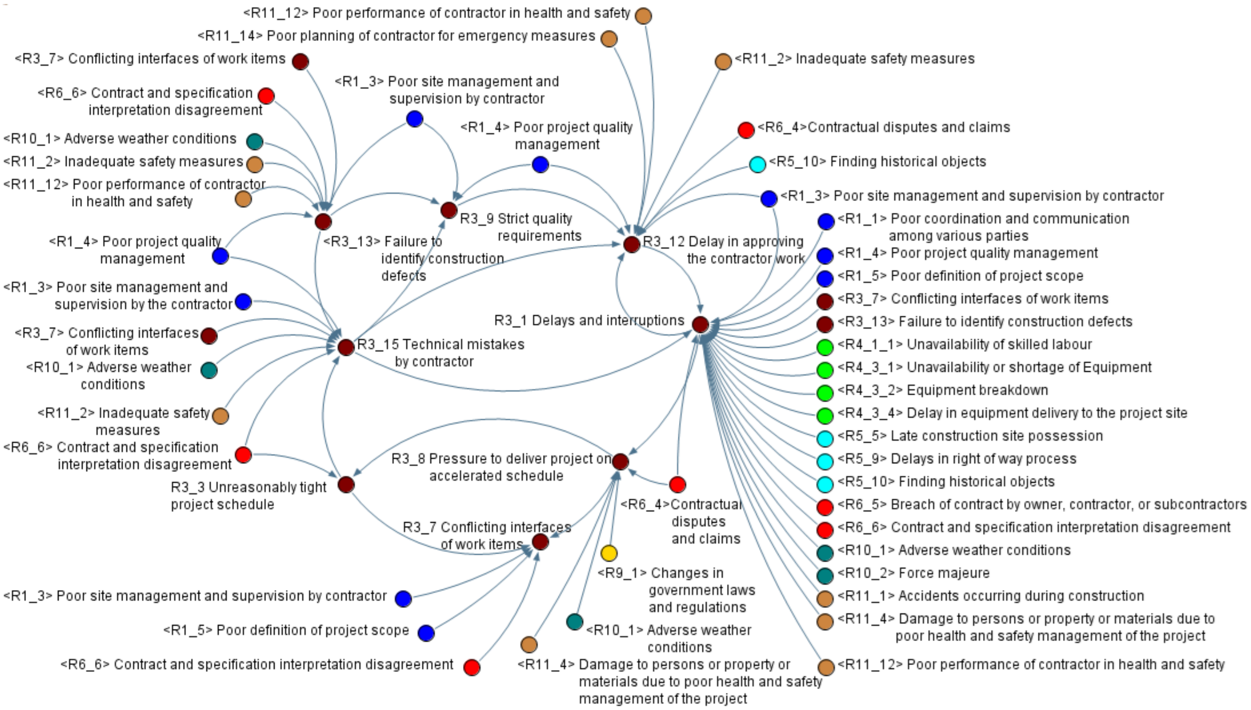
Appendix H. Causal Loop Diagrams of Risk and Opportunity Event Categories for the Structural Work Package



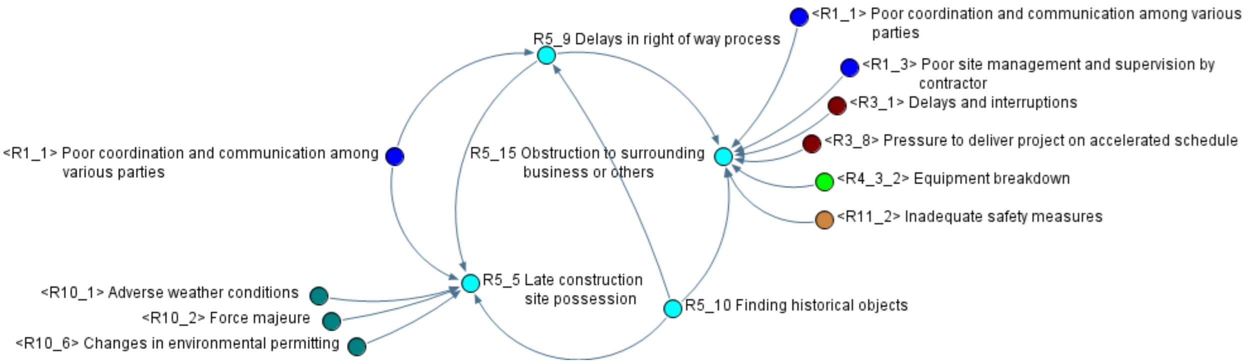
Causal loop diagram of the **management** risk and opportunity event category for the structural work package



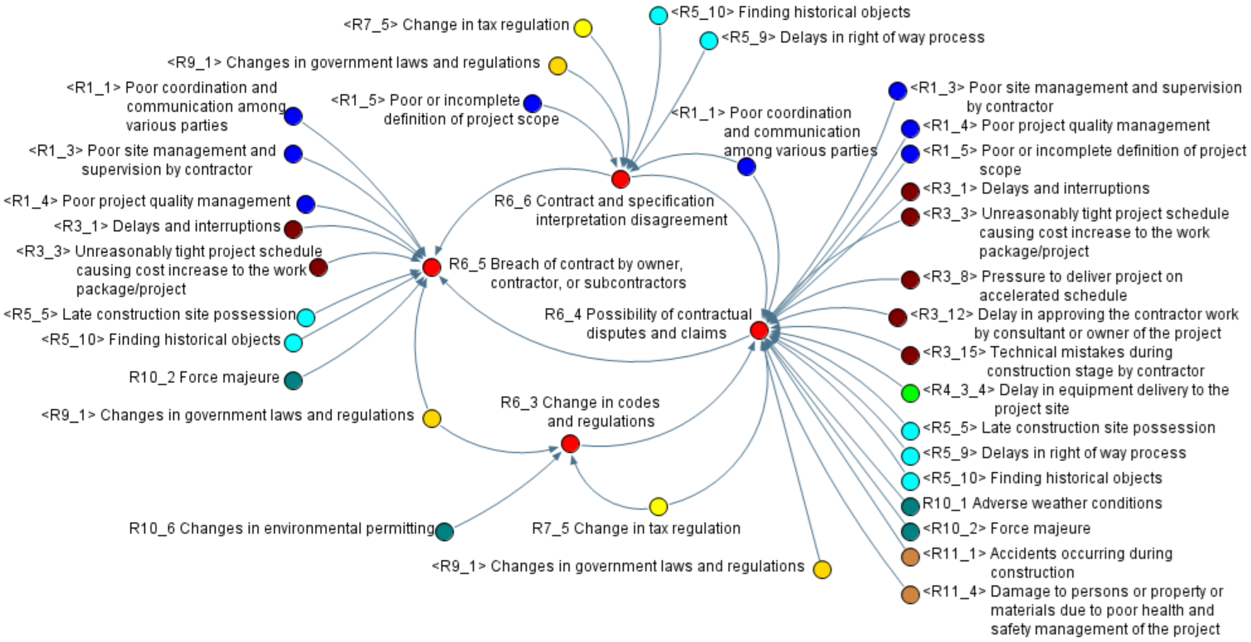
Causal loop diagram of the **resource-related** risk and opportunity event category for the structural work package



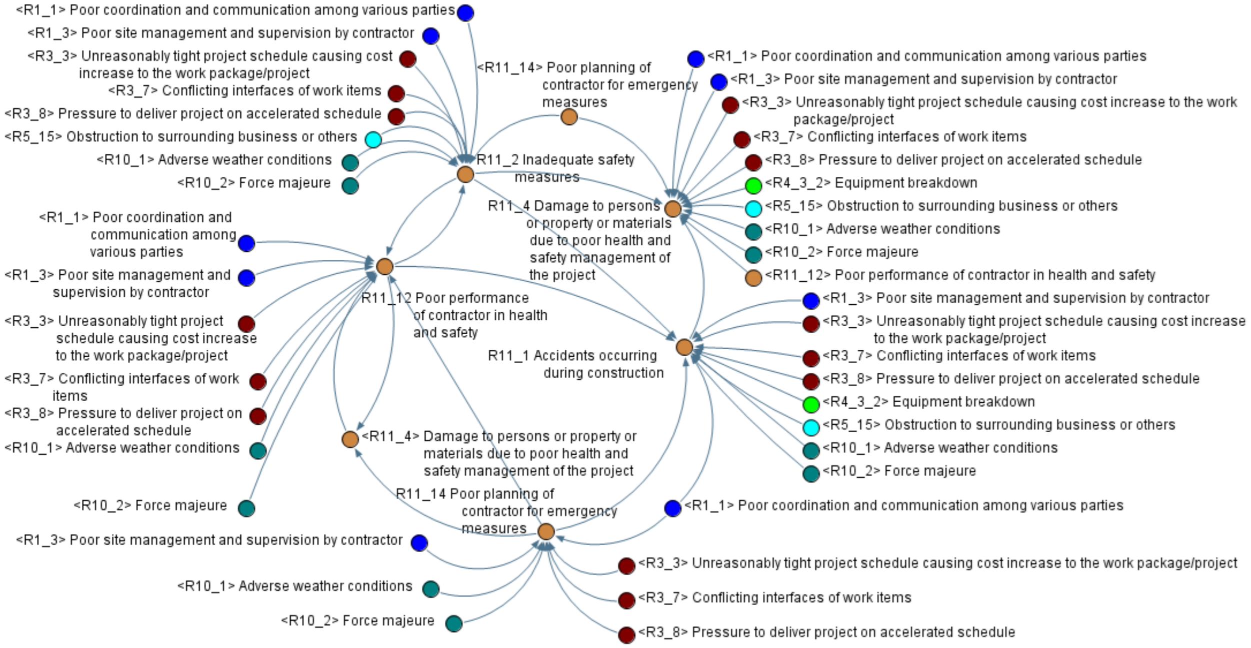
Causal loop diagram of the **construction** risk and opportunity event category for the structural work package



Causal loop diagram of the **site conditions** risk and opportunity event category for the structural work package

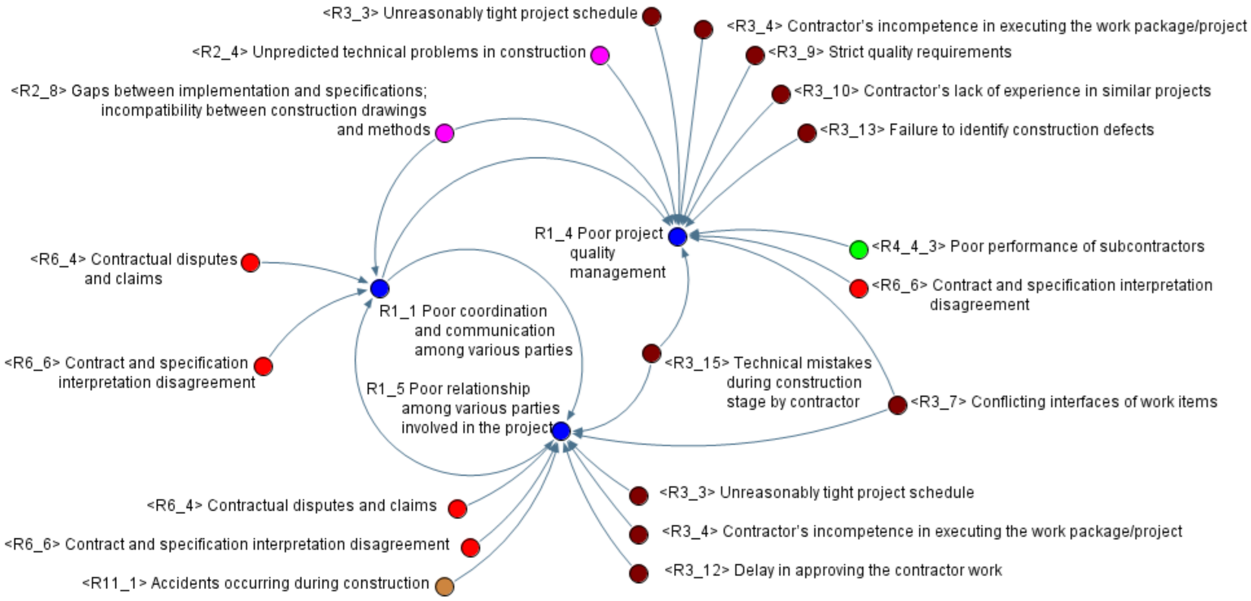


Causal loop diagram of the **contractual and legal, economic and financial**, and **political** risk and opportunity event categories for the structural work package

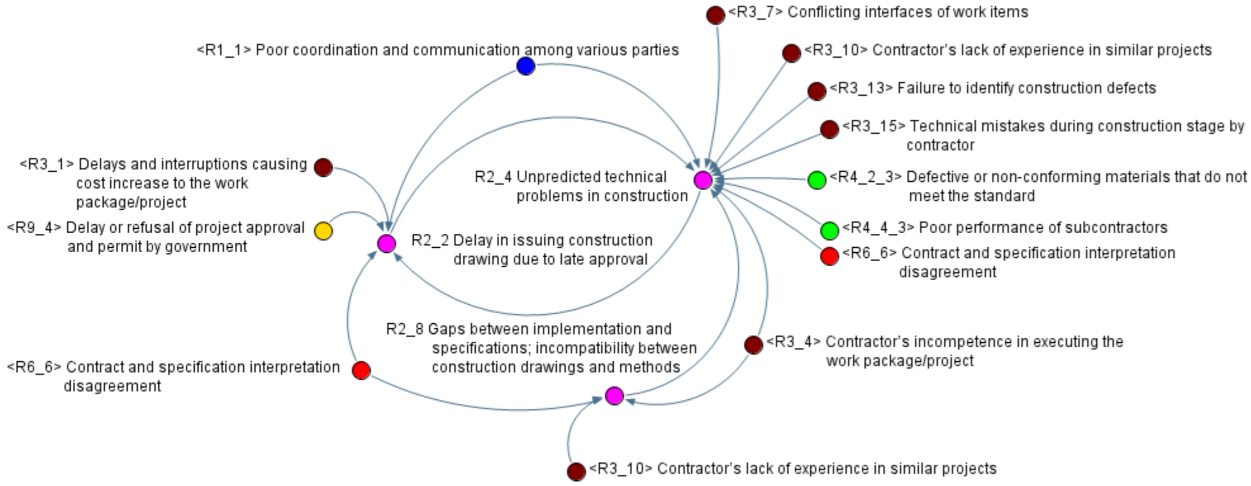


Causal loop diagram of the **health and safety** risk and opportunity event categories for the structural work package

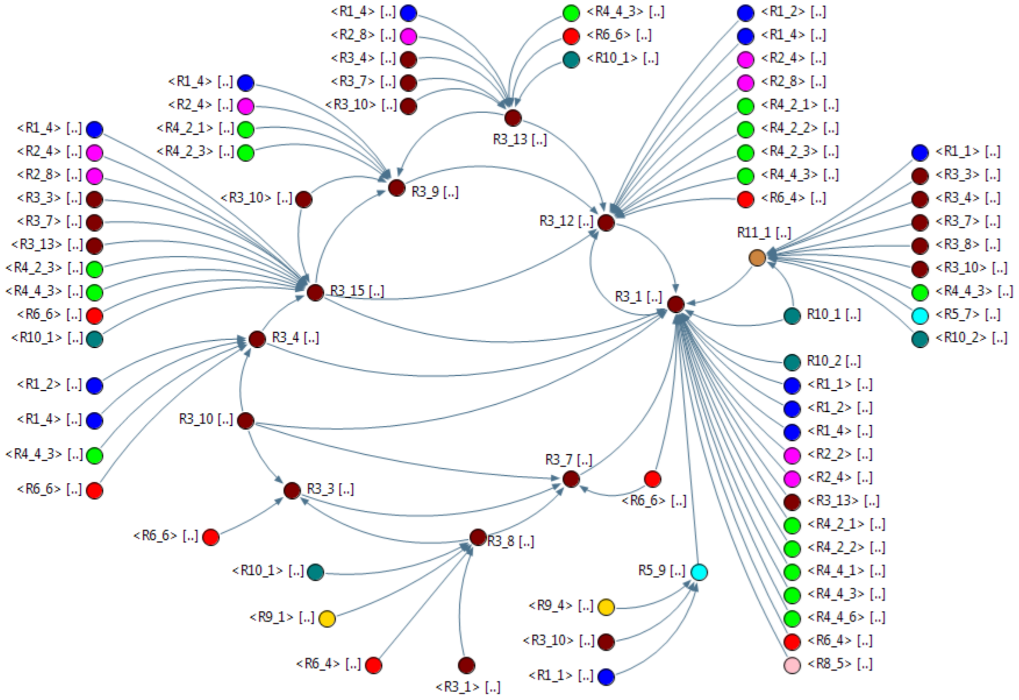
Appendix I. Causal Loop Diagrams of Risk and Opportunity Event Categories for the Electrical Work Package



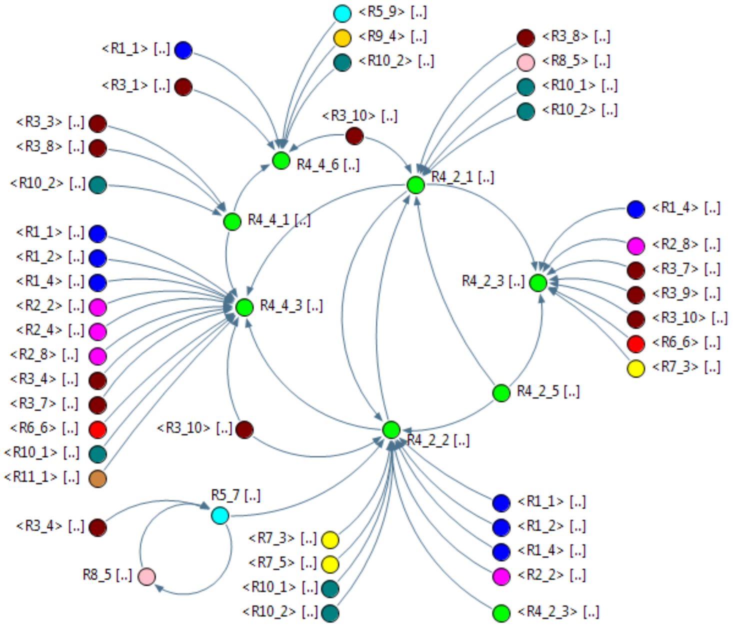
Causal loop diagram of the **management** risk and opportunity event category for the electrical work package



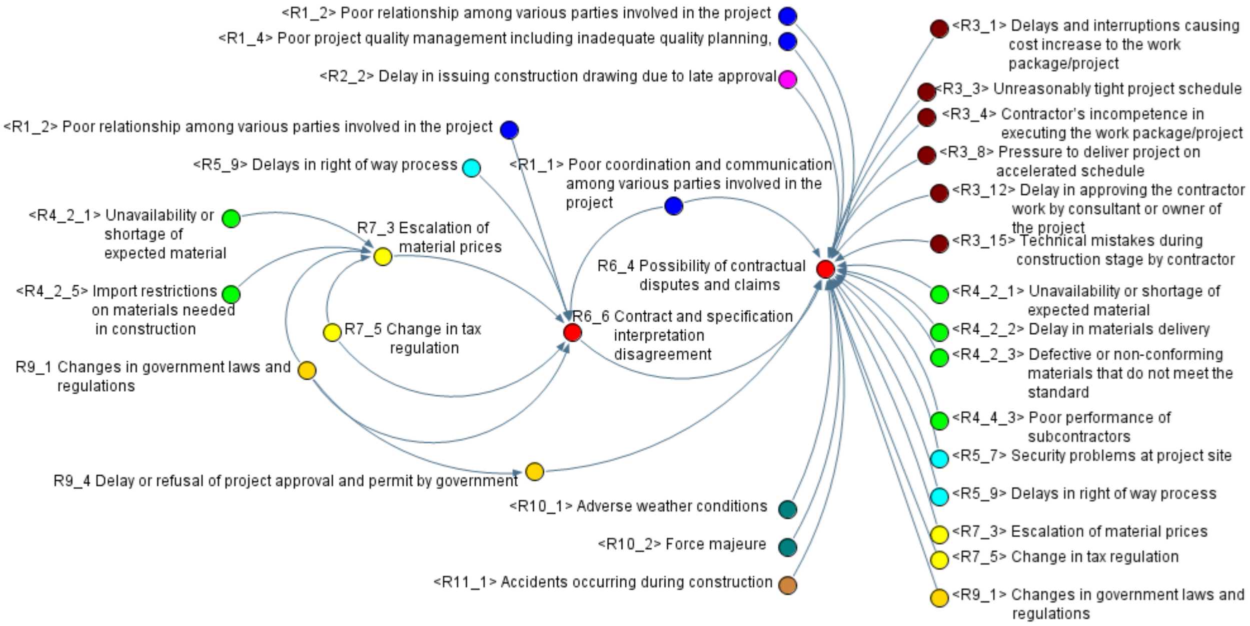
Causal loop diagram of the **technical** risk and opportunity event category for the electrical work package



Causal loop diagram of the **construction** risk and opportunity event category for the electrical work package



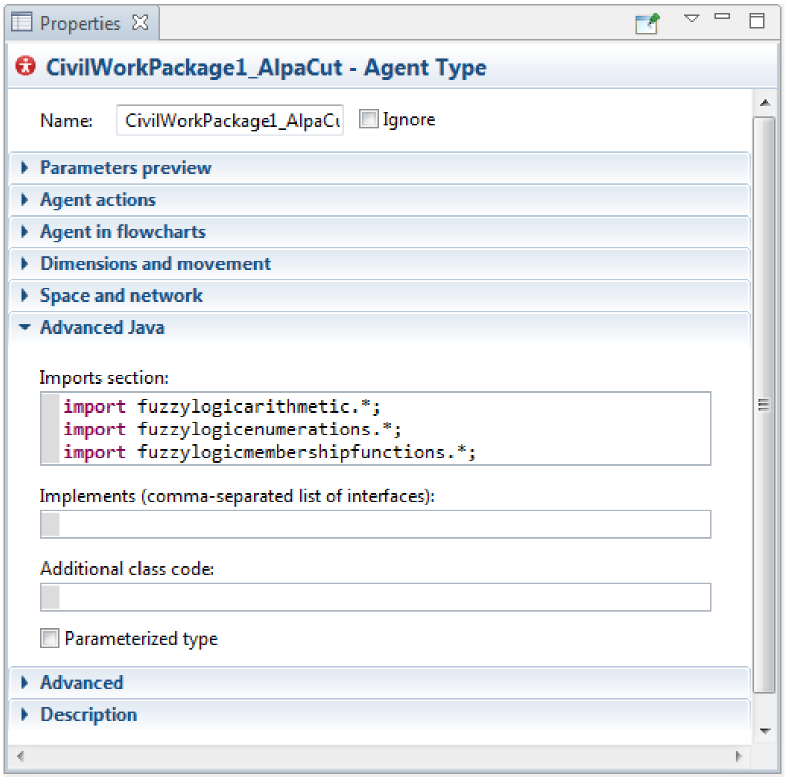
Causal loop diagram of the **resource-related** risk and opportunity event category for the electrical work package



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

Appendix J. Sample User Interfaces of the FSD model

Importing the fuzzy arithmetic library to AnyLogic®



Name: CivilWorkPackage1_AlpaCu ☐ Ignore

Imports section:

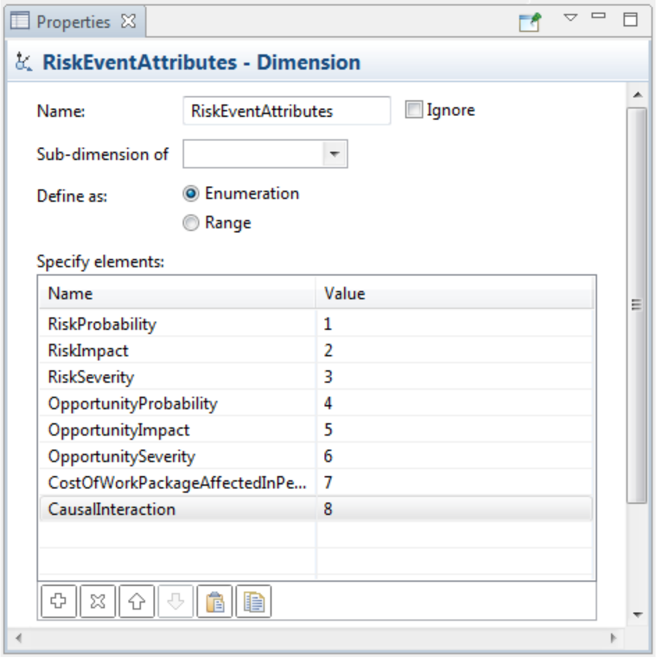
```
import fuzzylogicarithmetic.*;
import fuzzylogicenumerations.*;
import fuzzylogicmembershipfunctions.*;
```

Implements (comma-separated list of interfaces):

Additional class code:

☐ Parameterized type

Creating dimensions for arrays



Name: RiskEventAttributes ☐ Ignore

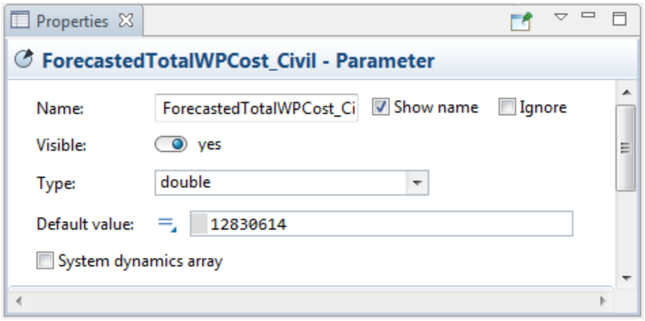
Sub-dimension of:

Define as: ● Enumeration ○ Range

Specify elements:

Name	Value
RiskProbability	1
RiskImpact	2
RiskSeverity	3
OpportunityProbability	4
OpportunityImpact	5
OpportunitySeverity	6
CostOfWorkPackageAffectedInPe...	7
CausalInteraction	8

Specifying crisp values of parameters in the model



ForecastedTotalWPCost_Civil - Parameter

Name: ForecastedTotalWPCost_Ci ☑ Show name ☐ Ignore

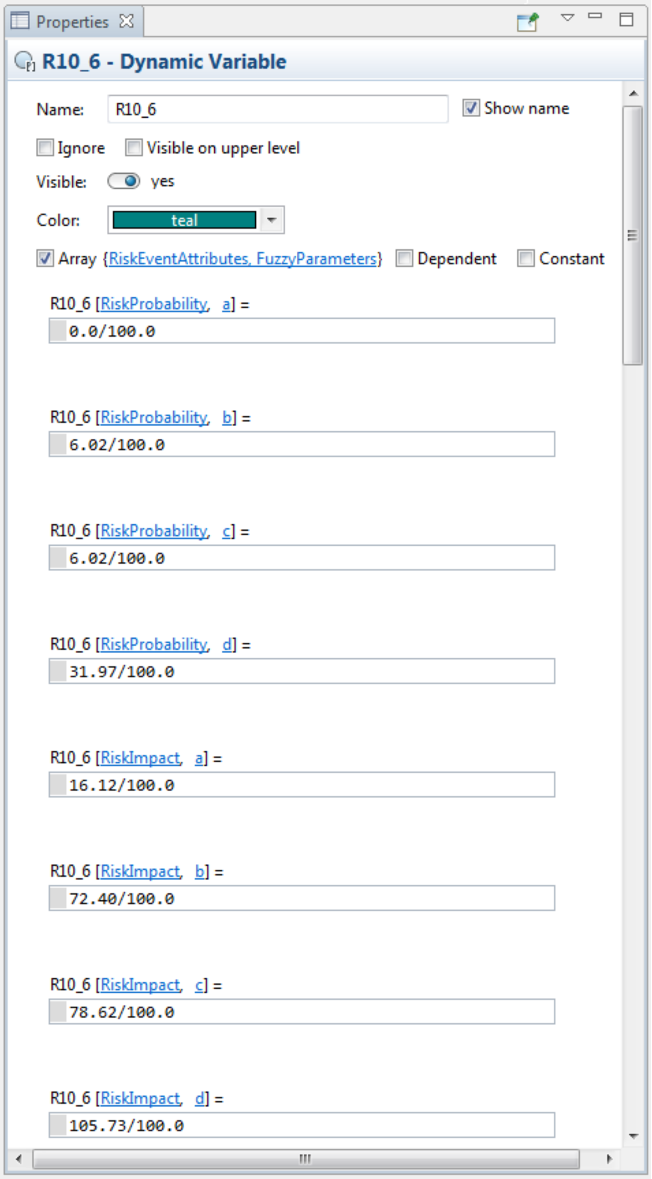
Visible: yes

Type: double

Default value: 12830614

☐ System dynamics array

Defining parameters of fuzzy numbers for probability and impact of risk and opportunity events



R10_6 - Dynamic Variable

Name: R10_6 ☑ Show name

☐ Ignore ☐ Visible on upper level

Visible: yes

Color: teal

☑ Array {RiskEventAttributes, FuzzyParameters} ☐ Dependent ☐ Constant

R10_6 [RiskProbability, a] =
`0.0/100.0`

R10_6 [RiskProbability, b] =
`6.02/100.0`

R10_6 [RiskProbability, c] =
`6.02/100.0`

R10_6 [RiskProbability, d] =
`31.97/100.0`

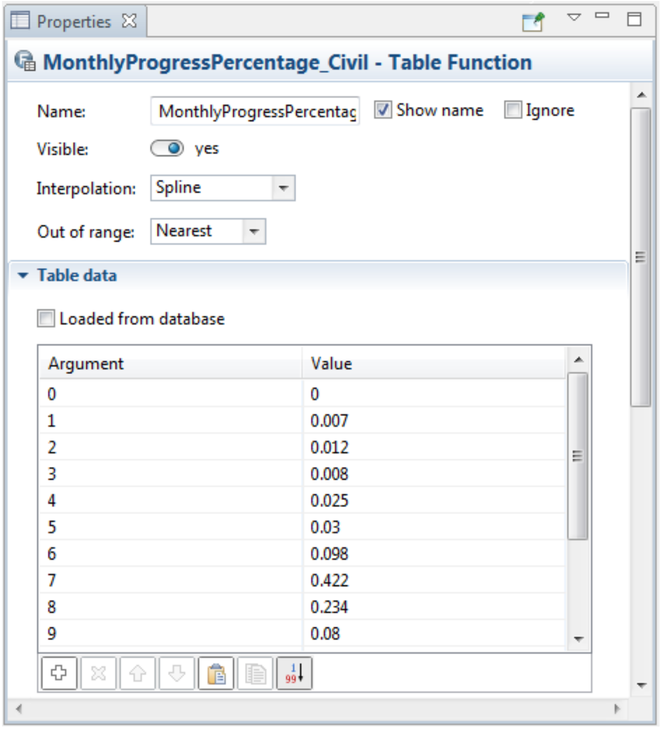
R10_6 [RiskImpact, a] =
`16.12/100.0`

R10_6 [RiskImpact, b] =
`72.40/100.0`

R10_6 [RiskImpact, c] =
`78.62/100.0`

R10_6 [RiskImpact, d] =
`105.73/100.0`

Creating table functions



Name: MonthlyProgressPercentag ☑ Show name ☐ Ignore

Visible: yes

Interpolation: Spline

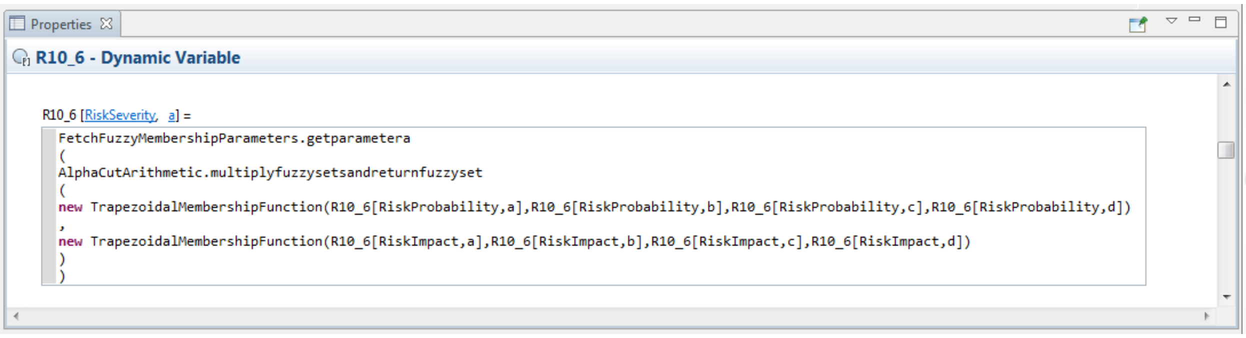
Out of range: Nearest

Table data

☐ Loaded from database

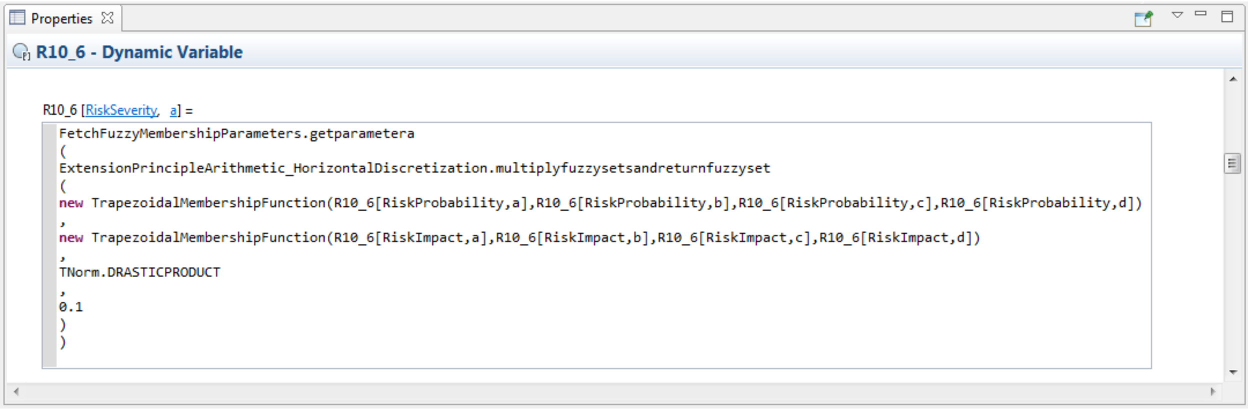
Argument	Value
0	0
1	0.007
2	0.012
3	0.008
4	0.025
5	0.03
6	0.098
7	0.422
8	0.234
9	0.08

Specifying fuzzy arithmetic method and type of operation



R10_6 [RiskSeverity, a] =

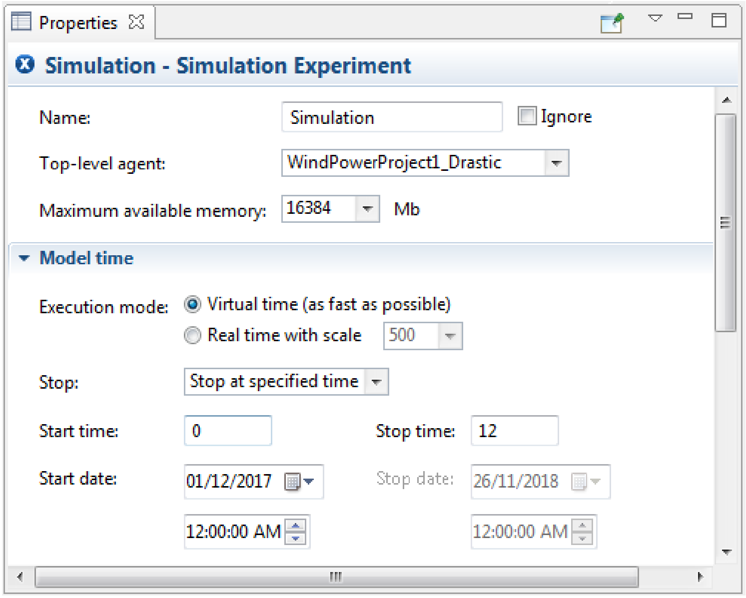
```
FetchFuzzyMembershipParameters.getparametera
(
AlphaCutArithmetic.multiplyfuzzysetsandreturnfuzzyset
(
new TrapezoidalMembershipFunction(R10_6[RiskProbability,a],R10_6[RiskProbability,b],R10_6[RiskProbability,c],R10_6[RiskProbability,d])
,
new TrapezoidalMembershipFunction(R10_6[RiskImpact,a],R10_6[RiskImpact,b],R10_6[RiskImpact,c],R10_6[RiskImpact,d])
)
)
```



R10_6 [RiskSeverity, a] =

```
FetchFuzzyMembershipParameters.getparametera
(
ExtensionPrincipleArithmetic_HorizontalDiscretization.multiplyfuzzysetsandreturnfuzzyset
(
new TrapezoidalMembershipFunction(R10_6[RiskProbability,a],R10_6[RiskProbability,b],R10_6[RiskProbability,c],R10_6[RiskProbability,d])
,
new TrapezoidalMembershipFunction(R10_6[RiskImpact,a],R10_6[RiskImpact,b],R10_6[RiskImpact,c],R10_6[RiskImpact,d])
,
TNorm.DRASTICPRODUCT
,
0.1
)
)
```

Setting simulation properties of the model



Simulation - Simulation Experiment

Name: Simulation ☐ Ignore

Top-level agent: WindPowerProject1_Drastic

Maximum available memory: 16384 Mb

Model time

Execution mode: ● Virtual time (as fast as possible)
○ Real time with scale 500

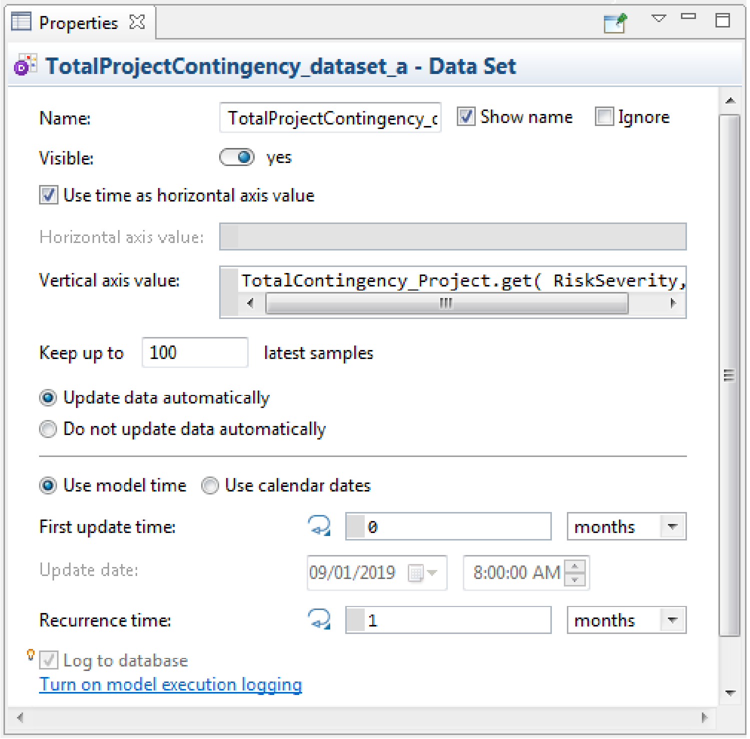
Stop: Stop at specified time

Start time: 0 Stop time: 12

Start date: 01/12/2017 Stop date: 26/11/2018

12:00:00 AM 12:00:00 AM

Collecting data instances (e.g., total project contingency) at each time step



TotalProjectContingency_dataset_a - Data Set

Name: TotalProjectContingency_c ☑ Show name ☐ Ignore

Visible: yes

☑ Use time as horizontal axis value

Horizontal axis value:

Vertical axis value: `TotalContingency_Project.get( RiskSeverity,`

Keep up to 100 latest samples

● Update data automatically
○ Do not update data automatically

● Use model time ○ Use calendar dates

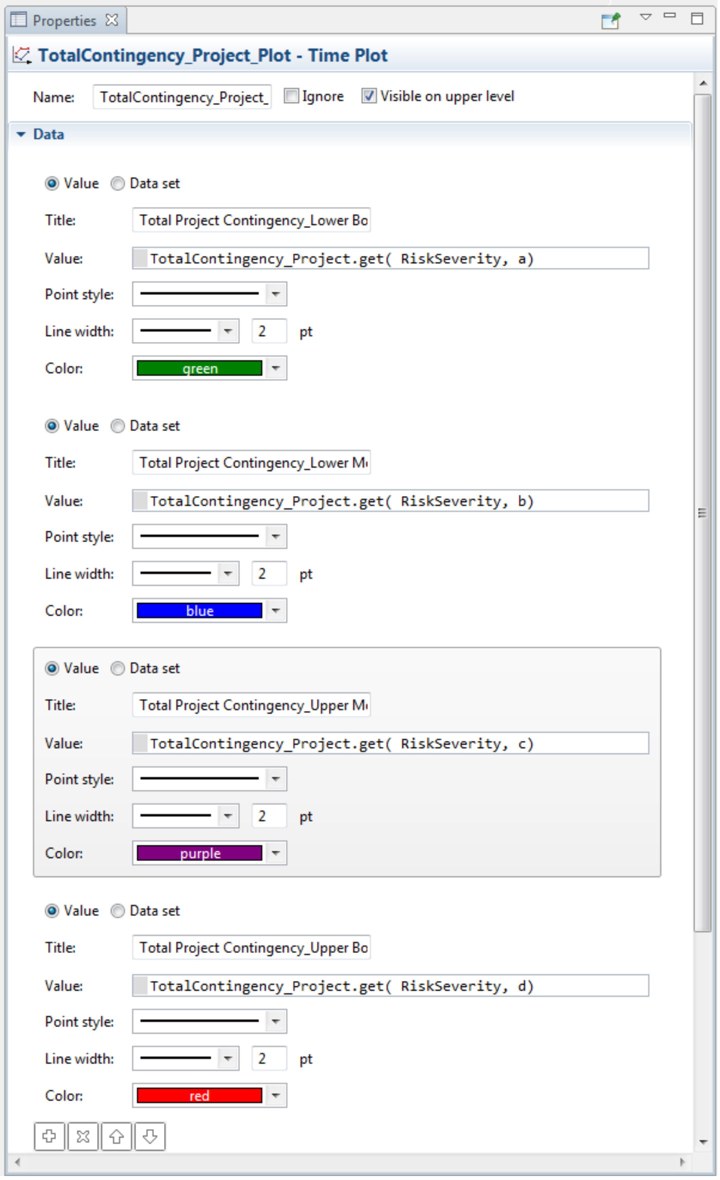
First update time: 0 months

Update date: 09/01/2019 8:00:00 AM

Recurrence time: 1 months

☑ Log to database
Turn on model execution logging

Plotting model outputs (e.g., total project contingency over the project duration)



Name: TotalContingency_Project_ ☐ Ignore ☑ Visible on upper level

● Value ○ Data set

Title: Total Project Contingency_Lower Bo

Value: `TotalContingency_Project.get( RiskSeverity, a)`

Line width: 2 pt

Color: green

● Value ○ Data set

Title: Total Project Contingency_Lower Mo

Value: `TotalContingency_Project.get( RiskSeverity, b)`

Line width: 2 pt

Color: blue

● Value ○ Data set

Title: Total Project Contingency_Upper Mo

Value: `TotalContingency_Project.get( RiskSeverity, c)`

Line width: 2 pt

Color: purple

● Value ○ Data set

Title: Total Project Contingency_Upper Bo

Value: `TotalContingency_Project.get( RiskSeverity, d)`

Line width: 2 pt

Color: red