PGCS PROJECT AND PROGRAM MANAGEMENT SYMPOSIUM
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Modeling Risk Interdependencies to Support Decision Making in Project Risk Management:

Analytical and Simulation-based Methods

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Outline

1. **Introduction**
2. **Research Methodology**
3. **Case Studies**
4. **Contributions**
5. **Future Work**

1. Introduction

1.1. What is risk?

Definition 1

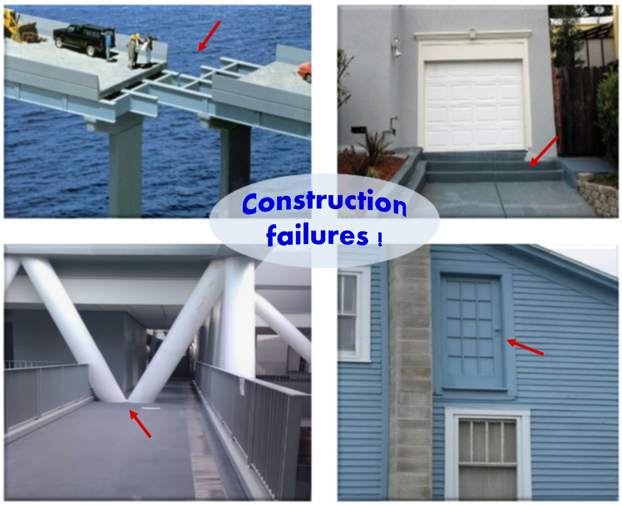
- Effect of uncertainty on objectives (*ISO 31000: 2018*)

Definition 2

- An uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives (*PMBOK, 2017*).

Risk Consequences

- Schedule delay
- Cost overruns
- Performance shortfall
- Loss of reputation
- Environmental damage



1.2. Project Risk Management


Risk management process
(ISO 31000: 2018)

Communication & Consultation

Scope, Context, Criteria

Risk Assessment

Risk Identification

Risk Analysis

Risk Evaluation

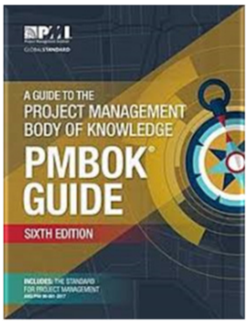
Risk Treatment

Monitoring & Review

Recording & Reporting

International Organization for Standardization ISO 31000 Risk-Management

STANDARDS Australia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Project Risk Analysis and Management Guide

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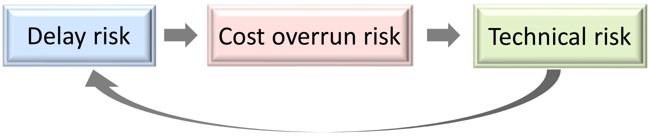
1.3. Project Risk Interdependency

- ❖ Cause-effect relationships among project risks.

  (“leads to” or “influences”)

- For example,


Delay risk ➡ Cost overrun risk ➡ Technical risk

- ❖ Risk interdependencies can cause a propagation from one upstream risk (e.g., **R1**) to numerous downstream risks or on the other side, a downstream risk (e.g., **R6**) may arise from the occurrence of several upstream risks.

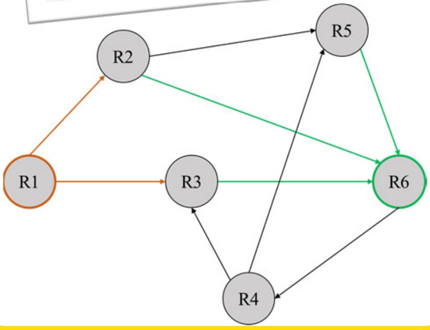


Fig. 1. Example of a risk interdependency network.

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1.4. *Probability–Impact* (*P–I*) Risk Model

※ **Classical two-dimensional risk assessment**

$$RC_i = P_i \times I_i$$

Risk *i*'s risk criticality

Risk *i*'s probability of occurrence

Risk *i*'s impact on project objectives

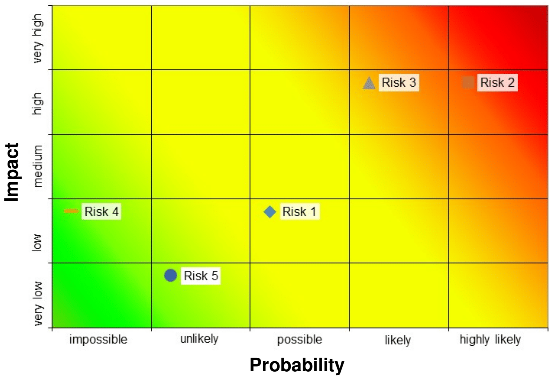

Fig. 2. Example of a *P–I* risk matrix.

※ **Fuzzy Set Theory (FST)** (*Zadeh, 1965*)

To handle the uncertainties of risk data due to the imprecision, vagueness & subjectivity of human thoughts.

1.5. Existing Project Risk Assessment (PRA) Methods

Assuming risks are independent

- Classical *P–I* risk assessment
- Analytical Hierarchy Process (AHP)
- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
- Fuzzy Synthetic Evaluation (FSE)
- Monte Carlo Simulation (MCS) [1]

Considering risk interdependencies

- Fault Tree Analysis (FTA)
- Bayesian Belief Network (BBN)
- Structural Equation Modeling (SEM)
- Design Structure Matrix (DSM) [2]
- Social Network Analysis (SNA) [2, 3]
- Interpretive Structural Modeling (ISM) [2, 3]

Research Gap

There is no systematic study that investigates the project risk management process considering multiple additional characteristics of project risks, e.g., risk stochastic behavior[1], complex risk interdependencies (including risk loops)[2], and risk position within a network[3].

1.6. Research Objective & Questions

Main Objective

To develop comprehensive & effective risk assessment indicators that can better reflect actual project risk conditions to provide decision makers with more objective, repeatable, & visible decision-making support for project risk management.

- **Question 1:** How to represent cause-effect relationships among project risks (i.e., risk interdependencies)?
- **Question 2:** How to consider risk stochastic behaviour, risk loops & risk position in network-based PRA?
- **Question 3:** What risk indicators considering risk interdependencies can be developed using analytical & simulation-based methods, respectively?

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2. Research Methodology

2.1. Identification of Project Risks & Risk Interdependencies

1 **Identifying individual project risks**

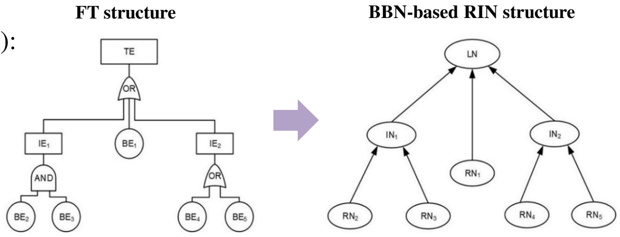
- ✓ Previous academic research on relevant project risks;
- ✓ Historical risk data of completed projects;
- ✓ Expert opinions on potential project risks.

2 **Identifying risk interdependencies**
(cause-effect relationships among individual risks)

- ✓ The interrelations among project objects, e.g., work-packages, tasks, or product components;
- ✓ Across different contexts or domains of the project, e.g., quality, cost or schedule.

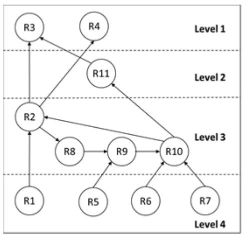
2.2. Representation of Project Risk Interdependency Network (RIN)

- ➢ Fault Tree (FT)-based Bayesian Belief Network (BBN):
  - 2.3.1. Fuzzy Bayesian Belief Network (FBBN)-based PRA model



- ➢ Interpretive Structural Modeling (ISM):
  - 2.3.2. ISM-MICMAC analysis-based PRA model
  - 2.3.3. Social Network Analysis (SNA)-based PRA model
  - 2.4. Monte Carlo Simulation (MCS)-based RIN model for PRA

ISM-based RIN structure



Nodes: project risks
Directed edges: risk interdependencies

2.3. Development of PRA Models Using Analytical Methods

2.3.1. FBBN-based PRA model

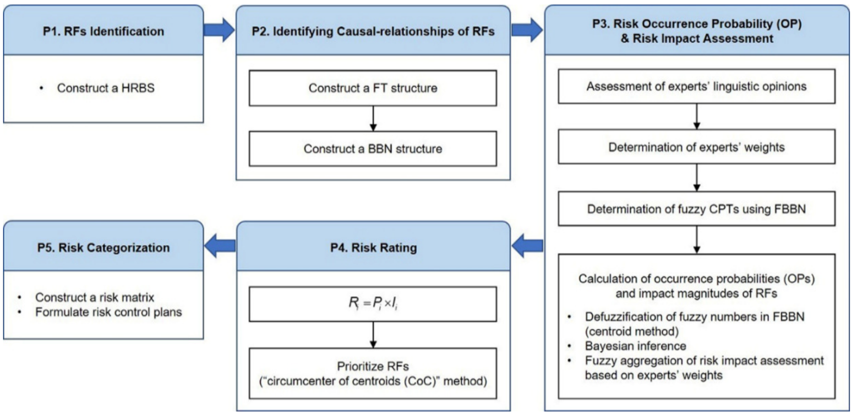


Fig. 3. Phases of FBBN-based risk assessment model (*Guan et al., 2020a*)**.**

Fuzzy Bayesian Belief Network (FBBN) method

Bayesian belief network (BBN)

Use Bayesian inference (causal & diagnostic inference) to evaluate risk occurrence probability in a directed acyclic graph (i.e., the RIN).

Fuzzy set theory (FST)

- Fuzzy linguistic scales for risk probability & risk impact;
- Fuzzy conditional probability tables & fuzzy risk impact;
- Fuzzy risk ratings.

2.3. Development of PRA Models Using Analytical Methods

2.3.2. ISM-MICMAC analysis-based PRA model

❖ The Interpretive Structural Modeling (ISM) method (*Warfield, 1974*) aims to **identify the interrelationship** between complex factors within a system.

❖ The Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) analysis method (*Duperrin & Godet, 1973*) is a structural prospective analysis for **analyzing the influence and dependence degree** of model elements (four clusters).

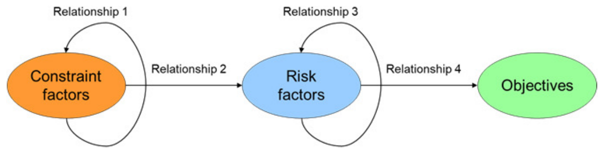


Fig. 4. Four types of investigated relationships among project constraints, risks & objectives (*Guan et al., 2020b*)**.**

❑ The weight of different levels (W_l) in a hierarchical ISM-based RIN:

$$W_l = \frac{1/l}{\sum_1^m (1/l)}$$

l: the numerical order of the partitioned levels (the smaller the l, the higher the level in a hierarchy).

m: the total number of levels.

❑ The importance of risk/constraint related to project objectives through the influence transmission:

$$I_{S_\sigma, O_\varphi} = W_l \left(\frac{1}{N_1+1}+\frac{1}{N_2+1}+\cdots+\frac{1}{N_i+1}+\cdots+\frac{1}{N_t+1}\right)$$

Ni: the number of intermediate nodes on the ith path.

2.3. Development of PRA Models Using Analytical Methods

2.3.3. SNA-based PRA model

Weighted distance → replaced with → **Path probability strength**

- **Evaluating risk interdependency:**

Normalized weighted edge betweenness centrality (WEB_e')

- **Evaluating risk:**

(1) Normalized out-degree centrality of node (NOD_i')

(2) Normalized betweenness centrality of node (NB_i')

(3) Normalized out-closeness centrality of node (NOC_i')

(4) Normalized hybrid structural centrality of node (NHS_i')

Social Network Analysis (SNA)-based measures

(5) Risk local significance (RLS_i)

(6) Risk global significance (RGS_i)

Probability-Impact (P-I) risk model-based measures

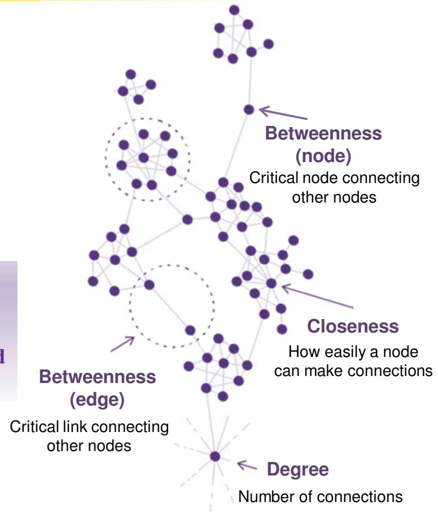


Fig. 5. General measures in the SNA method.

2.4. Development of a PRA Model Using Simulation-based Methods

MCS-based RIN model for PRA

Modeling the stochastic behaviour of risk occurrence

- The occurrence probability of R_i in the t^{th} simulation run ($COP_{i,t}$) is calculated as:

$$COP_{i,t} = 1 - [(1 - SP_i) \times \prod_{k=1}^{m} (1 - TP_k^i)], \quad m = 0, 1, 2, \ldots$$

where m is the number of risks that have occurred and can influence risk R_i directly in the t^{th} simulation run, and $TP_{k,t}^i$ represents the transition probability of the kth link to R_i in the t^{th} simulation run.

- In the proposed Monte Carlo Simulation (MCS) method, by comparing generated random values (between 0 and 1) with the updated risk occurrence probability ($COP_{i,t}$) of a risk, whether the risk occurs or not can be determined.

$$mc_{i,t} = \begin{cases} 1, & RN_{i,t} \leq COP_{i,t} \\ 0, & RN_{i,t} > COP_{i,t} \end{cases}$$

Solving the loop-phenomenon in RIN

- A hypothesis-test method is proposed to solve risk loops in a project RIN:

Assume one or more necessary risks would occur/not occur

↓

Proceed with the calculation in the designed program

↓

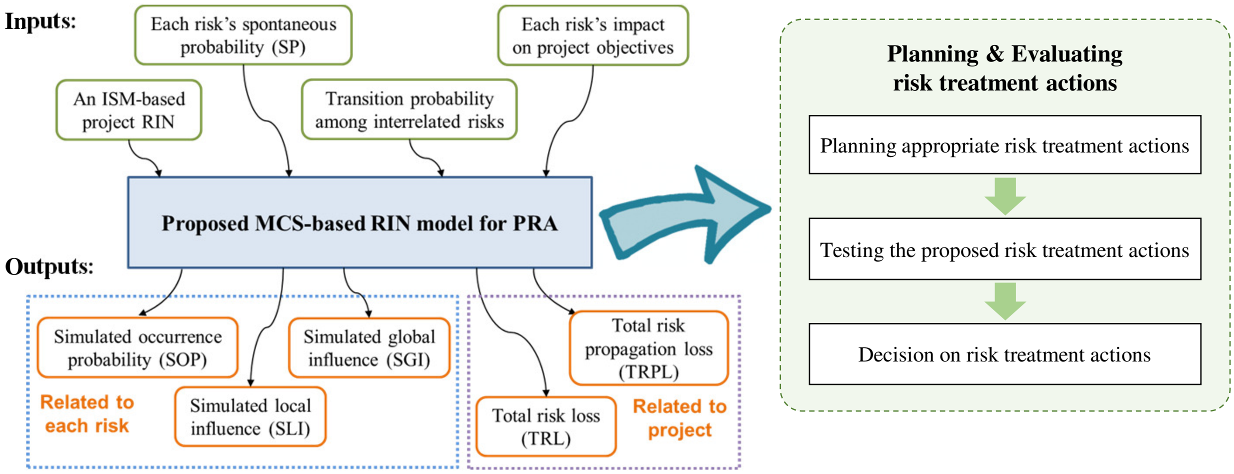
Evaluate whether the calculated status (occur or not) of the hypothesized risk is the same with the null hypothesis or not

↓

Discard the simulation runs with inconsistent cases

2.4. Development of a PRA Model Using Simulation-based Methods

MCS-based RIN model for PRA (Cont.)



Inputs:

Each risk's spontaneous probability (SP)

Each risk's impact on project objectives

An ISM-based project RIN

Transition probability among interrelated risks

Proposed MCS-based RIN model for PRA

Outputs:

Simulated occurrence probability (SOP)

Simulated global influence (SGI)

Simulated local influence (SLI)

Related to each risk

Total risk propagation loss (TRPL)

Total risk loss (TRL)

Related to project

Planning & Evaluating risk treatment actions

Planning appropriate risk treatment actions

Testing the proposed risk treatment actions

Decision on risk treatment actions

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3. Case Studies

3.1. Using FBBN-based PRA Model

Ankara-Istanbul high-speed railway project

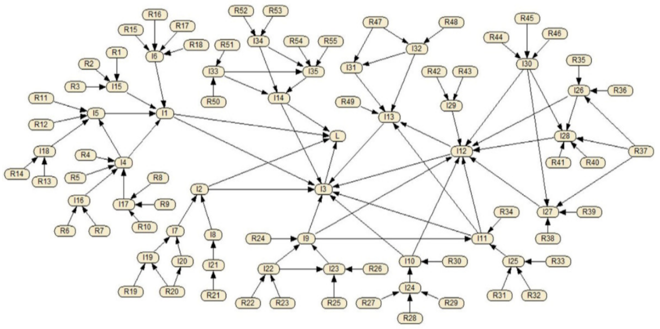


Fig. 6. The BBN structure of identified project risks (91 nodes and 111 edges) (*Guan et al., 2020a*)**.**

- **Most critical risks:** R_{42} *Different construction standards & measurement system*, I_3 *Project implementation risk.*

Table 1. Project risk categorization results.

Risk level (based on risk ratings)	**Risks** (root/intermediate/leaf nodes)	
	Causal inference	**Diagnostic inference**
Category 5 (0.70929 – 0.96028)	R_{34}, R_{42}	R_{34}, R_{42}; I_3, L
Category 4 (0.54975 – 0.70928)	R_{41}, R_7, R_2, R_{11}, R_{23}, R_6, R_{33}, R_{13}, R_{20}, R_{45}, R_{25}, R_{22}, R_{54}, R_{16}; I_{26}, I_2, I_{24}, I_8, I_{25}, I_5, I_4, I_{30}, I_{28}, I_{10}, I_{16}, I_{14}, I_7, I_1, I_{12}, I_{35}, I_{11}, I_9, I_{22}, I_{29}, I_3, **L**	R_{41}, R_7, R_2, R_{11}, R_{23}, R_6, R_{33}, R_{13}, R_{20}, R_{45}, R_{25}, R_{22}, R_{54}, R_{16}; I_{26}, I_{24}, I_2, I_{25}, I_8, I_5, I_4, I_{30}, I_{28}, I_{10}, I_{16}, I_7, I_{14}, I_{12}, I_1, I_{11}, I_9, I_{35}, I_{22}, I_{29}
Category 3 (0.46600 – 0.54974)	R_{53}, R_9, R_{39}, R_{35}, R_4, R_{36}, R_{19}, R_{21}, R_{52}, R_5, R_{15}, R_{30}, R_{28}, R_{12}, R_{43}, R_{55}, R_{26}, R_{51}, R_{17}, R_{14}, R_{27}, R_{38}, R_{18}, R_{37}, R_3; I_{19}, I_{27}, I_{32}, I_{13}, I_{15}, I_{34}, I_{18}, I_{21}, I_{17}, I_{23}, I_{31}, I_{33}, I_6, I_{20}	R_{53}, R_9, R_{39}, R_{35}, R_4, R_{36}, R_{19}, R_{21}, R_{52}, R_5, R_{15}, R_{30}, R_{28}, R_{12}, R_{43}, R_{55}, R_{26}, R_{51}, R_{17}, R_{14}, R_{27}, R_{38}, R_{18}, R_{37}, R_3; I_{19}, I_{27}, I_{32}, I_{13}, I_{15}, I_{34}, I_{18}, I_{21}, I_{17}, I_{23}, I_{31}, I_{33}, I_{20}, I_6
Category 2 (0.42399 – 0.46599)	R_{48}, R_{31}, R_{10}, R_{47}, R_8, R_1, R_{40}, R_{44}, R_{50}, R_{29}, R_{24}, R_{46}, R_{49}, R_{32}	R_{48}, R_{31}, R_{10}, R_{47}, R_8, R_1, R_{40}, R_{44}, R_{50}, R_{29}, R_{24}, R_{46}, R_{49}, R_{32}
Category 1 (0.41708 – 0.42398)	Not identified	Not identified
Category 0 (0 – 0.41707)	Not identified	Not identified

3.2. Using ISM-MICMAC Analysis-based PRA Model

Green Building (GB) projects

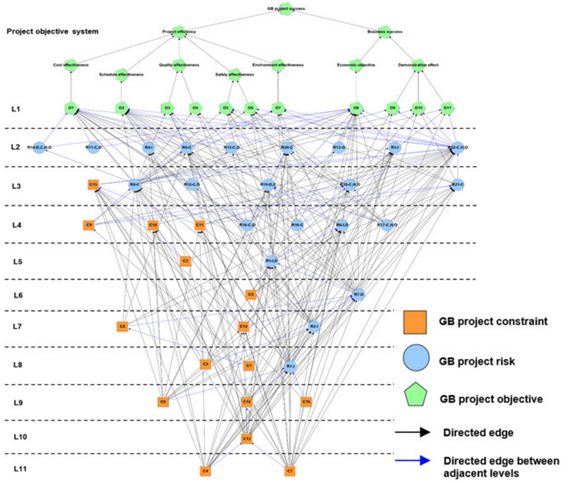


Fig. 7. The hierarchical ISM-based RIN of GB projects (16 constraints, 22 risks & 11 project objectives) (*Guan et al., 2020b*)**.**

Table 2. The importance of critical project risks & constraints associated with GB project objectives.

Constraints & Risks / **GB project objectives**	**C7**	**C4**	**C13**	**C6**	**C12**	**R1**	**C16**	**R2**	**C9**	**C14**	**Total influence** (all risks & constraints)
O1 Completed within budget	1.71	1.69	1.26	0.90	0.54	0.46	0.46	0.31	0.28	0.28	11.43
O2 Completed on time	2.92	2.86	2.15	1.51	0.90	0.79	0.55	0.52	0.28	0.47	17.26
O3 Comfort and artistry	0.74	0.72	0.56	0.41	0.27	0.25	0.16	0.18	0.11	0.13	4.33
O4 Long-term performance	0.39	0.39	0.30	0.23	0.14	0.15	0.09	0.11	0.04	0.06	2.26
O5 Safety in construction	1.07	1.07	0.78	0.58	0.32	0.26	0.18	0.18	0.25	0.15	7.10
O6 Safety in operation and maintenance	1.02	1.02	0.75	0.55	0.31	0.26	0.18	0.18	0.21	0.15	6.56
O7 Green certification	0.37	0.36	1.02	0.75	0.45	0.36	0.25	0.25	0.28	0.22	8.58
O8 Anticipated return on investment & payback period	2.50	2.49	1.84	1.28	0.78	0.67	0.49	0.45	0.28	0.44	15.96
O9 Customer satisfaction	0.93	0.93	0.67	0.50	0.26	0.20	0.15	0.13	0.21	0.15	5.96
O10 Promotion of brand image	0.98	0.98	0.71	0.53	0.28	0.20	0.15	0.13	0.25	0.15	6.42
O11 Promotion of new technologies and materials	0.93	0.93	0.67	0.50	0.26	0.20	0.15	0.13	0.21	0.15	5.96
GB project success (O1–O11)	14.54	14.42	10.71	7.74	4.49	3.82	2.67	2.58	2.38	2.34	-
Influenced objectives	11	11	11	11	11	11	11	11	11	11	-

3.2. Using ISM-MICMAC Analysis-based PRA Model

Green Building (GB) projects (Cont.)

MICMAC analysis: to analyze the drive/dependence power of each factor in the established ISM-based RIN.

The risk/constraint factors with higher drive power**:**

- ✓ Have stronger influence on project objectives;
- ✓ Located in the lower levels of the ISM-based RIN.

Top-3 GB project **risks**

R1 *Unclear requirements of a project implementation,*
R2 *Ambiguity in contracts,*
R7 *Design errors.*

Top-3 GB project **constraints**

C7 *Inadequate experienced designers/contractors/suppliers for GB projects,*
C4 *Limited GB benchmarks & shared information,*
C13 *Inadequate communication & cooperation among project stakeholders.*

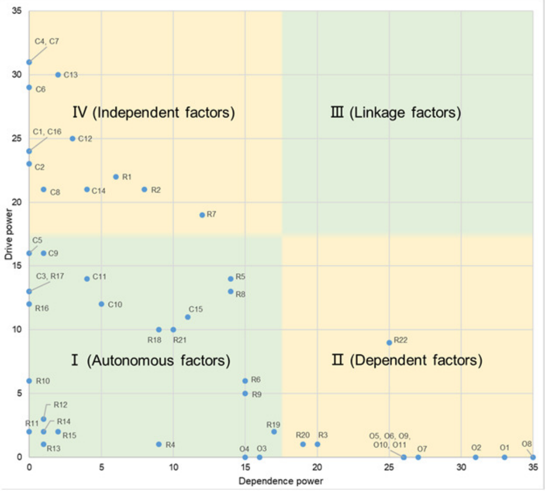


Fig. 8. The MICMAC diagram for GB project constraints, risks & objectives (*Guan et al., 2020b*)**.**

3.3. Using SNA-based PRA Model

Case project description

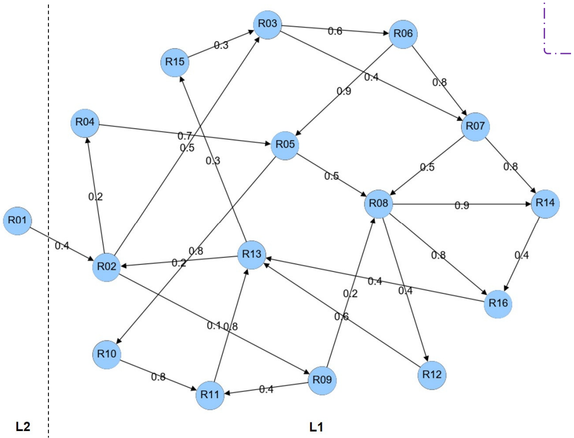


Fig. 9. A hierarchical ISM-based project RIN (16 risks & 26 direct risk interdependencies).

◆ This project concerns employing AI technology for predicting medical items, which belongs to a program related to logistics & healthcare (*Wang et al., 2020*).

Table 3. The identified project risks.

Risk No.	Risk	Risk No.	Risk
R01	Language problems & cultural conflicts	R09	Interfaces problem among the software platforms of different teams
R02	Communication problems between the teams	R10	Poor quality of the data from hospital & logistics company
R03	Unclear milestone & technical route	R11	Poor effectiveness & efficiency of the model
R04	Lack of professional medical knowledge	R12	Too much investigation
R05	Poor analysis of the factors regarding medical items	R13	Tense partnerships among the teams
R06	Poor selection of the medical items	R14	Overmuch tests on the model
R07	Poor selection of the existing database	R15	Project scope spread
R08	Building & training the model repeatedly	R16	Too much rework for the team in charge of the modeling

3.3. Using SNA-based PRA Model

Risk ranking results

Locally

Out-degree centrality
- R08 *Building & training the model repeatedly*
- R06 *Poor selection of the medical items*
- R05 *Poor analysis of the factors regarding medical items*

Risk local significance
- R03 *Unclear milestone & technical route*
- R16 *Too much rework for the team in charge of the modeling*
- R09 *Interfaces problem among the software platforms of different terms*

Globally

Betweenness centrality
- R13 *Tense partnerships among the teams*
- R02 *Communication problems between the teams*
- R03

Out-closeness centrality
- R06
- R05
- R03

Hybrid structural centrality
- R08
- R06
- R05

Risk global significance
- R03
- R04 *Lack of professional medical knowledge*
- R06

Table 4. The PRA results based on six proposed risk measures.

Risk No.	SNA-based measures				P-I risk model-based measures	
	Out-degree centrality	Betweenness centrality	Out-closeness centrality	Hybrid structural centrality $(*10^{-2})$	Risk local significance $(*10^{-2})$	Risk global significance $(*10^{-2})$
R01	0.027	0	0.098	0.024	0.267	1.505
R02	0.053	0.552	0.178	0.107	0.533	1.348
R03	0.067	0.471	0.254	0.194	1.167	3.238
R04	0.047	0	0.227	0.077	0.400	2.696
R05	0.087	0.410	0.260	0.436	0.100	1.829
R06	0.113	0.467	0.359	0.312	0.480	2.635
R07	0.087	0.048	0.146	0.146	0.267	1.383
R08	0.140	0.190	0.181	0.324	0.600	1.198
R09	0.040	0	0.107	0.076	0.800	1.653
R10	0.053	0.224	0.135	0.257	0.187	0.694
R11	0.053	0.267	0.105	0.237	0.533	0.341
R12	0.040	0	0.079	0.030	0.133	0.133
R13	0.033	0.557	0.067	0.125	0.400	0.490
R14	0.027	0	0.047	0.112	0.267	0.228
R15	0.020	0	0.094	0.034	0.427	0.745
R16	0.027	0.162	0.053	0.137	0.800	0.349

3.4. Using MCS-based RIN Model

Risk assessment results: the 16-risk project

Table 5. Risk prioritization by different risk indicators.

Risk ranking	Proposed MCS-based RIN model						Classical P–I risk model			
	SOP_i		SLI_i ($100)		SGI_i ($100)		SP_i		RC_i ($100)	
	Risk No.	Value	Risk No.	Value	Risk No.	Value	Risk No.	Value	Risk No.	Value
1	**R14**	0.895	R11	2.950	**R05**	18.574	R01	0.8	R03	1.75
2	**R05**	0.853	R16	2.516	R14	18.041	R03	0.7	R16	1.2
3	R16	0.839	R08	2.345	**R07**	17.256	R04	0.6	R09	1.2
4	R03	0.830	R03	2.074	R13	17.185	R09	0.6	R08	0.9
5	R13	0.825	R14	1.791	R01	17.095	R02	0.4	R01	0.8
6	R07	0.811	R02	1.321	R03	16.322	R06	0.4	R02	0.8
7	R01	0.799	R06	1.250	R16	16.243	R07	0.4	R11	0.8
8	R08	0.782	R09	1.246	R10	15.711	R13	0.4	R06	0.72
9	R11	0.737	R13	1.238	R08	15.546	R15	0.4	R15	0.64
10	R10	0.736	R10	1.031	R06	14.597	R16	0.4	R13	0.6
11	R06	0.694	R15	0.879	R11	14.049	**R05**	0.3	R04	0.6
12	R02	0.661	**R07**	0.811	R04	13.676	R08	0.3	R07	0.4
13	R04	0.651	R01	0.799	R02	13.442	R10	0.2	R14	0.4
14	R09	0.623	R12	0.746	R09	12.730	R11	0.2	R10	0.28
15	R15	0.549	R04	0.651	R15	11.423	**R14**	0.2	R12	0.2
16	R12	0.373	**R05**	0.427	R12	8.131	R12	0.1	R05	0.15

Project level PRA indicators: TRL & TRPL

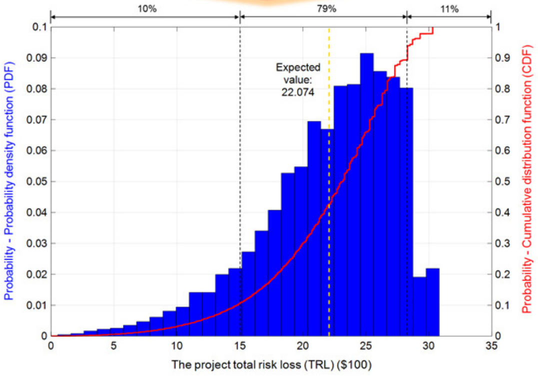
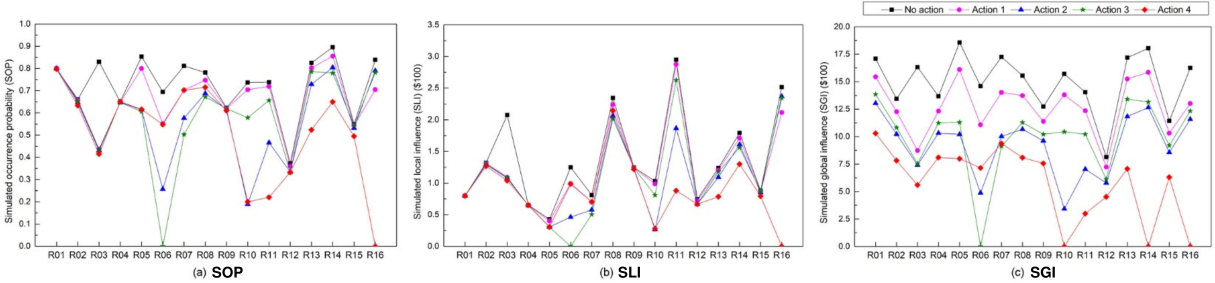


Fig. 10. Probability distribution of the project TRL (*Guan et al., 2021*)**.**

The project total risk propagation loss (TRPL): $24002

3.4. Using MCS-based RIN Model

Risk treatment results



(a) SOP (b) SLI (c) SGI

Fig. 11. Comparison of the values of risk indicators after different risk treatment actions (*Guan et al., 2021*)**.**

Table 6. The performance of different risk treatment actions from the project level.

Risk treatment actions **Performance**	**Action 1** (Classical *P–I* risk model)	**Action 2** (*Wang et al., 2019*)	**Action 3** (*Wang et al., 2020*)	**Action 4** (Proposed model)
Reduced value of project's TRL	$217	$489	$412	$826
Reduced value of project's TRPL	$3711	$9274	$7978	$14717

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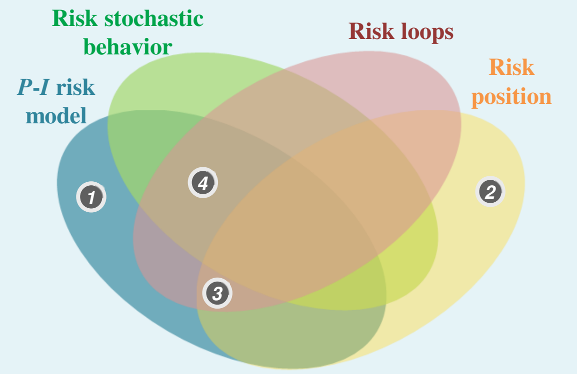
4. Contributions

4.1. Academic Contributions

- Effective analytical & simulation-based methods are investigated to develop project risk assessment (PRA) models considering the effects of risk interdependencies.
- More aspects related to the complexity of a project risk interdependency network (RIN) are taken into account, including the stochastic behavior of risk occurrence, risk loops & risk position within a project RIN.
- Proposed interdependency-based risk indicators can help planning of more appropriate project risk treatment actions.

Risk interdependencies



① FBBN-based PRA model

② ISM-MICMAC analysis-based PRA model

③ SNA-based PRA model

④ MCS-based RIN model for PRA

4.2. Managerial Implications

(1) Project practitioners can have more comprehensive perception of project risk through considering complex risk interdependencies in PRA from a ‘network’ perspective.

(2) The proposed PRA models try to mitigate the gap between theory and practice of the PRA, so the basic concepts of the classical *P–I* risk model (i.e., risk’s probability & impact), which are widely used by practitioners in managing project risks, are considered. Therefore, all related project practitioners can engage their knowledge & experience in the PRA process.

(3) The proposed PRA models have high universality & flexibility, which can be applied to projects in different fields (e.g., software, civil, or business), and even to large & complex projects. In particular, the proposed decision-support system for PRA developed using the MCS-based RIN model outperforms many existing analytical PRA methods that mainly rely on complicated calculations.

(4) The proposed PRA models can be used at the commencement stage of a project when there is high uncertainty about project risks, and the PRA results can update periodically to reflect risk conditions of the project over time when new risk information is captured.

5. Future Work

1 The MCS-based RIN model for PRA can be improved by integrating with Social Network Analysis method to incorporate more analysis of risk position in the RIN.

2 As projects are time-related dynamic systems, project risks & risk interdependencies may vary with project phases, so the dynamic behavior of project RIN throughout a project lifecycle will be further investigated under current PRA framework.

3 Additional parameters, such as project budget & cost of risk treatment actions, will be involved to further optimize risk treatment actions.

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Thanks for listening

Q & A

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