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EX-ANTE ASSESSMENT OF VULNERABILITY TO UNCERTAINTY IN COMPLEX CONSTRUCTION PROJECT ORGANIZATIONS

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Abstract: Modern construction projects are operated in extremely uncertain environments. Uncertainties affect the performance of projects. Despite an extensive body of literature in the area of performance assessment, there is a gap in knowledge pertaining to an integrated methodology for ex-ante evaluation of vulnerability of project organizations to the impacts of uncertainties. The objective of this paper is to address this gap in knowledge by creating a framework for ex-ante assessment of vulnerability in construction project organizations. In the proposed framework, construction project organizations are conceptualized as complex meta-networks and analyzed using dynamic network analysis. Accordingly, the impacts of the uncertain events (e.g., late design deliverables, equipment breakdown, safety accident and injury, and severe weather conditions) are translated into perturbations in different node entities (i.e., human agent, information, resource and task) and the corresponding links in project meta-networks. These uncertainty-induced perturbations cause transformations in the project topological structure, and thus, negatively affect the efficiency of project organizations' meta-networks. The extent of the variation in the efficiency is used as an indicator of a project organization's vulnerability to uncertainties. The application of the proposed framework is shown in a numerical example related to a tunneling project. Various scenarios related to different uncertain events were simulated to quantitatively investigate the vulnerability of the project and evaluate the impacts of different planning strategies on mitigating vulnerability. The results demonstrate the capability of the proposed framework for quantitative assessment of vulnerability and evaluation of planning strategies in construction projects. Hence, it provides a tool for proactive evaluation and mitigation of vulnerability in construction project organizations.

1 INTRODUCTION

Modern construction projects are complex and are executed in highly uncertain environments. Similar to other complex systems, construction project organizations have a greater likelihood for successful performance if they are less vulnerable to uncertainties. Despite a growing body of literature in the areas of performance assessment and risk analysis in construction projects, our understanding of the determinants of performance vulnerability in complex construction projects remains limited. First, the existing studies (e.g., Baloi and Price, 2003; Zou et al., 2007) mainly focus on identification of risks and uncertainties affecting the performance of construction project organizations. However, a better understanding on the extent and severity of performance variation in a project which also depends upon the vulnerability of the project organization is missing. Second, the majority of the existing risk and uncertainty assessment approaches (e.g., Nieto-Morote and Ruz-Vila, 2011) in construction projects are rather subjective and do not provide a robust quantitative basis for ex-ante evaluation of planning strategies to reduce the vulnerability of project organizations to uncertain events. Third, the existing methods for performance assessment and risk analysis in construction projects do not capture the complex interactions between human agents, information, resources, and tasks in project organizations. Capturing these complex interactions is a critical step toward development of an integrated methodology for performance assessment in complex construction projects (Zhu and Mostafavi, 2014). To address these methodological limitations and gaps in knowledge, an integrated framework for ex-ante assessment of vulnerability in complex construction project organizations is proposed in this paper.

In the proposed framework, project organizations are conceptualized as dynamic multi-node and multi-link meta-networks composed of different node entities (e.g., agents, information, resources and tasks) and their interdependencies. Accordingly, the uncertain events in construction projects are translated into perturbations in the node entities and links of the meta-network. Then, using stochastic simulation, the impacts of uncertainty-induced perturbations on the performance of project organizations are captured based on the changes in the efficiency of the meta-network. Finally, the proposed framework enables ex-ante evaluation of different planning strategies and their significance in mitigating vulnerability.

2 A FRAMEWORK FOR ASSESSMENT OF PROJECT ORGANIZATION'S VULNERABILITY

There are four components in the proposed framework: abstraction of project meta-network, translation of uncertainty-induced perturbations, vulnerability assessment, and evaluation of planning strategies. Figure 1 shows the four components in a workflow for integrated vulnerability assessment in complex construction projects. The details of each component are explained in this section.

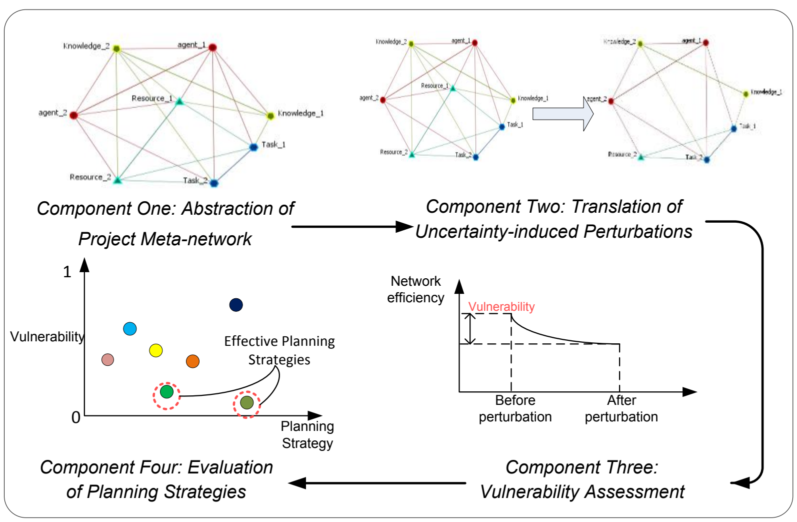


Figure 1. A Framework for Integrated Vulnerability Assessment in Construction Projects

2.1 Abstraction of Project Meta-network

Complex construction projects are systems-of-systems consisting of interconnected networks of human agents, information, resources and tasks (Zhu et al., 2014). The ability of project organizations to cope with uncertainty is an emergent property that arises from the interactions between different entities. Hence, for evaluating the vulnerability of a project organization to uncertainty, different entities and their interconnections should be properly abstracted. In order to facilitate the abstraction of the entities and their interactions in complex project organizations, Zhu and Mostafavi (2014a; 2014b; 2014c) proposed conceptualization of project organizations as systems-of-systems or meta-networks (Carley 2003). The meta-network of the construction project organization is composed of four types of node entities (i.e., agents, information, resources, and tasks) and ten types of links, as shown in Figure 2. To abstract the node entities and their interconnections, the first step is to identify the task nodes. A task node is an entity with a measureable outcome. In construction project, a task node could represent decision making, information processing or production work. A task is being implemented by one or more agent nodes which utilize information and resources to complete the task. After identification of the task nodes, the agent nodes can be identified. An agent node is an entity that implements the task. It could be an individual, a crew, or a team depending on the nature of tasks. Then, information and resource nodes can be identified accordingly based on the requirement of the tasks. The interdependencies and relationships between different node entities build the links in the project meta-network. Each type of links represents one type of relationship (e.g., agent-information link represents who knows what, agent-task link represents who is assigned to what task). One type of links and their corresponding nodes form an individual network [e.g., social network of agent-agent relationships (AA), assignment network of agent-task relationships (AT)]. Different networks are interconnected as a whole in the project meta-network. Changes in one node entity or network cascade into changes in the other node entities and networks.

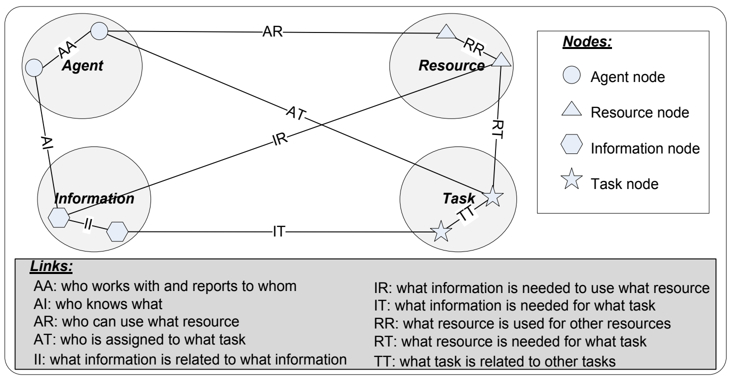


Figure 2. Nodes and Links in Project Meta-Networks

2.2 Translation of Uncertainty-induced Perturbations

Conceptualizing project organizations as meta-networks provides a novel perspective for understanding the uncertain events and their corresponding impacts on the performance. According to the principles of network science, perturbations in networks affect their topological structures and stability (Dalziell and McManus, 2004). Using the theoretical underpinnings of network science, in the proposed framework, the impacts of uncertain events are translated into perturbations in the node entities and links in a project organization's meta-network (Zhu and Mostafavi, 2015). Table 1 summarizes three main types of perturbations in construction projects (i.e., agent-related perturbations, information-related perturbations and resource-related perturbations) and examples of events corresponding to each type of perturbation. One uncertain event may cause perturbation in a single node entity (i.e., single-effect event) or multiple node entities (i.e., multi-effect event). For example, equipment breakdown on a jobsite may lead to a single-effect event, while the failure of the power system may cause multiple perturbations in different resource node entities. In the proposed framework, each uncertain event is abstracted using two attributes: its perturbation effect and likelihood of occurrence. The perturbation effect depends upon the node entities and links impacted due to the uncertain events. The likelihood of an uncertain event is determined using historical data or other probability encoding techniques (Clemen and Winkler, 1999).

Table 1: Perturbations in Project Meta-networks

Types of perturbation	Examples
Agent-related perturbation	Staff turnover, safety accident or injury, dereliction of duty
Information-related perturbation	Late design deliverables, unclear scope/design, limited access to required knowledge, miscommunication
Resource-related perturbation	Counterfeit/defective materials, equipment breakdown, late delivery of material

2.3 Vulnerability Assessment

The vulnerability of the project can be measured based on the extent of the changes in the relevant topological measure (i.e., task completion measure) of the meta-network before and after a perturbation (Holme et al. 2002, Criado et al. 2005). The greater the change in the topological measure due to uncertain-induced perturbations, the greater the vulnerability of the network. More specifically, network vulnerability denotes the decrease of network efficiency due to a selected removal of nodes or links. For example, a network is moved from its equilibrium state N to N'due to exposure to uncertain event(s) r. The corresponding vulnerability of the network to this exposure then can be defined using Equation 1:

[1] $v(r) = e(N) - e(N')$

where e denotes the performance efficiency (i.e., functionality) of the network. There are different approaches to assess the performance efficiency of a network depending upon its type. In project organizations' meta-networks, efficiency could be measured based on the percentage of tasks that can be completed by the agent assigned to them (i.e., based on whether the agents have the requisite information and resource to do the tasks) (Carley and Jeff, 2004). Equations 2-4 show the procedure for computation of information-based task completion. In Equations 2-4, binary matrices are generated based on the abstraction of the project meta-network (e.g., AI represents a binary matrix representing the agent-information relationships, with agent node entities as the row and information node entities as the column). Similarly, resource-based task completion can be calculated by replacing matrices AI and IT with matrices AR and RT in the equations. The overall performance efficiency of a project organization's meta-network is the average of information-based task completion and resource-based task completion values (Equation 5). Hence, the vulnerability of a project organization to uncertain events can be obtained using Equation 1 and by assessing performance efficiency of the meta-network (from Equation 5) prior and after perturbations. The value of vulnerability ranges from 0 to 1. A higher value means that the project organization is more vulnerable to the uncertain events.

[2] $Need = [(AT' \times AI) - IT']$

[3] $S = \{i | 1 \leq i \leq |T|, \exists j: Need(i,j) < 0\}$

[4] $Information\ based\ task\ completion = (|T| - |S|)/|T|$

[5] $e(N) = (Information\ based\ task\ completion + Resource\ based\ task\ completion)/2$

2.4 Evaluation of Planning Strategies

In the proposed framework, different planning strategies are translated to the addition/removal of node entities and/or links in the project organization's meta-network. Table 2 provides examples of planning strategies and their reflections in the project organization's meta-network related to task assignment, decision-making authority, as well as resource management. These different planning strategies can be translated to changes in the node entities and links in the meta-network. The same project could exhibit different levels of vulnerability under different planning strategies. The effectiveness of planning strategy is measured based on the reduction of vulnerability.

[6] $effectiveness\ of\ planning\ strategy\ p = (v_p - v)/v$

where v denotes the vulnerability of the project to the uncertain events in the base scenario, and v_p denotes the vulnerability of the same project to the uncertain events with alternative planning strategies.

Table 2: Examples of Different Planning Strategies in Construction Project Organizations

Planning Strategies		Reflection in the Project Meta-networks
Task Assignment	Division of labor	One agent or crew is assigned to one task
	Generalization of labor	Agents or crews can be assigned to multiple tasks
Decision-making Authority	Centralized	Reservation of decision making power at top level
	Decentralized	Decision making authority is distributed
Resource Management	Redundancy	Backup resources are prepared for key resources
	No redundancy	No backup resources

3 NUMERICAL EXAMPLE

A hypothetical case related to a tunneling project is used here to illustrate the application of the proposed framework. In this example, a tunneling project constructed using New Austrian Tunneling Method (NATM) was modeled. Compared to the conventional tunneling method, which uses the suspected worst rock condition for design, NATM saves cost by adjusting the initial design during the construction phase (De Farias et al., 2004). In NATM, rock samples are collected by the geologist team during the early stage of design. After doing laboratory tests on the rock samples, the test results are compared with the rock quality designation index and the rock mass classification can be identified. The initial design is then conducted based on the identified rock type. The excavation crew performs excavation into the tunnel face based on the initial design, followed by loading explosives and blasting. Before blasting, the safety supervisor performs the safety inspection on the site and issues the safety approval. Right after the excavation work, the support installation crew starts working on the jobsite. Support installation crew applies shotcrete and installs the initial support (e.g., rockbolts, lattices girders or wire mesh) as the initial lining process. Measurement instrumentations are installed to observe the rock deformation behavior after the initial lining. The geologist team reads the data from the instrumentations and reports the rock deformation information to the designer. The designer team then makes the decision on whether a revision on the initial design is needed. The decision depends on whether the rock deformation is within the acceptable range. If no revision is necessary, a final lining process composed of traditional reinforced concrete is conducted; otherwise, the designer team revises the initial design for both initial lining and final lining. In this case, the support installation crew will use the revised design to implement the initial and final lining. The whole tunneling project is constructed in sections. At the end of each section, the project manager reviews the initial design, revised design, as well as the rock deformation, to assess the risks, and makes a decision on the step length for excavation of the next section. For example, if a relatively large deformation is observed, the project manager will decrease the step length to prevent the chance of collapsing. This tunneling project involves multiple dynamic and complex processes. A high level of interdependence exists between different agents, resources, information and tasks. Uncertain events could have negative ripple impacts on the project performance. For example, if a miscommunication happens between the geologist team and design team about the rock deformation information, not only will the task of revising design be directly affected, but also the succeeding tasks (e.g., installation of the final lining may not be performed appropriately due to lack of information related to revised design).

3.1 Integrated Vulnerability Assessment

The proposed framework was used for ex-ante analysis of vulnerability in the case study project. The four components of the proposed framework were all conducted in the context of the case. ORA-NetScenes 3.0.9.9 was used as the network analysis and modeling platform.

Abstraction of Project Meta-network

First, the meta-network of the project organization in the case study was abstracted. The project's meta-network includes 36 node entities (of four different types) and 118 links (of ten different types) in total. Table 3 provides examples of different node entities and links in the tunneling project meta-network.

Translation of Uncertainty-induced Perturbations

Potential uncertain events, their effects, and the likelihood in the case project were identified. The potential events include single-effect events related to agent, resource, and information (e.g., geologist or designer turnover, delay in obtaining rock deformation data, or excavator breakdown), as well as events with multiple effects (e.g., power system failure or severe weather). Each uncertain event was translated to perturbations in the project's meta-network. For example, if a turnover in the design team happens, the designer node is isolated in the project's meta-network (i.e., with no links to project resource or information). Thus, the design tasks cannot be completed successfully. The likelihood of uncertain events was identified based on three levels of uncertainty: low (10%), medium (20%), and high (50%) (van der Gaag et al., 2002). Table 4 depicts the identified uncertain events, their perturbation effects, and likelihood in the case. For example, the level of uncertainty related to the late delivery of material was identified as high, which implies that, for each type of material used in this project (i.e., explosive, initial support, concrete and reinforcement), there was 50% likelihood of late delivery.

Table 3: Examples of Node Entities and Links in the Tunneling Project's Meta-Network

	Types	Examples in the tunneling project case
Node	Agent (A)	geologist team, designer team, excavation crew, project manager, etc.
	Information (I)	rock condition, initial design, rock deformation, revised design, etc.
	Resource (R)	concrete, boomer, initial support, power system, excavator, etc.
	Task (T)	lab test, excavation, apply shotcrete, revise design, etc.
Link	A-A	geologist team reports to designer team
	A-I	excavation crew knows initial design information
	A-R	geologist team uses measurement instrument
	A-T	designer team is assigned to conduct initial and revised design
	I-I	revised design information depends on rock deformation
	I-R	initial design is needed for choosing initial support material
	I-T	rock deformation is needed for deciding step length
	R-R	concrete is used by shotcrete machine
	R-T	loader and trucks are needed for mucking
	T-T	safety inspection is conducted before blasting

Vulnerability Assessment

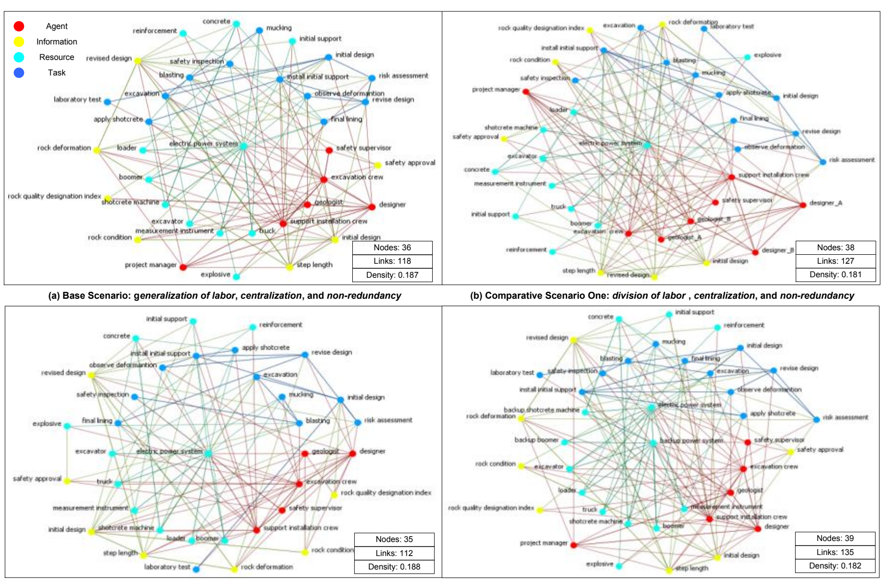
The perturbations related to the uncertain events were simulated as independent random events in the case study. Using Monte-Carlo experimentation, 30 runs of the simulation model were implemented. Since the likelihood of one event occurring does not affect the likelihood of the other events occurring, multiple uncertain events happen in each run of the Monte-Carlo simulation randomly. In each run of simulation, the vulnerability of the project organization to the perturbations of the uncertain events that occurred in that run was assessed. Then, a probability distribution related to the vulnerability of the project organization under the identified uncertainties (i.e., uncertain events, their effects, and likelihood) in this case was obtained from the outcomes of the total 30 runs.

Table 4: Uncertain Events in the Tunneling Project's Meta-Network

	Uncertain Events	Perturbation Effect	Uncertainty
Single-effect Event	Dereliction of duty	Agent-related perturbation	Medium
	Staff turnover	Agent-related perturbation	Low
	Inadequate information	Information-related perturbation	Medium
	Equipment breakdown	Resource-relation perturbation	Medium
	Late delivery of material	Resource-related perturbation	High
Compound-effect Event	Power system failure	Multiple resource-related perturbation	Medium
	Severe weather	Agent and resource-related perturbations	Low
	Economic fluctuation	Agent and resource-related perturbations	Low

Evaluation of Planning Strategies

In the base scenario of the tunneling project studied, planning strategies of the generalization of labor, centralized decision making, and non-redundancy in resource management were adopted. To investigate the influence of different planning strategies on the project vulnerability, three comparative planning scenarios were developed. For comparative analysis, in each scenario, only one aspect of the planning strategy was different from the base scenario. In the first scenario, the planning strategy pertaining to task assignment was changed. In the base scenario, there was only one single agent node for the geologist team and one agent node for the designer team. Tasks of laboratory tests and observing rock deformation were both assigned to the same geologist agent, and tasks of conducting initial design and revised design were both assigned to the same designer agent. In scenario 1, two more agent nodes were added as geologist and designer. Thus, division of labor was achieved (i.e., tasks of laboratory tests and observing rock deformation were assigned to the different geologists, and tasks of conducting initial design and revised design were assigned to the different designers). In the second scenario, the planning strategy pertaining to the decision-making authority of the step length was changed. In the base scenario, the designer should report the corresponding information (e.g., initial design, revised design and rock deformation) in the current section to the project manager and wait for the project manager to make the decision on the step length for the next section. In scenario 2, the decision-making authority related to step length was given to the designer at the lower level, since he/she already holds all the required information for making the decision. Thus, in scenario 2, the project manager node and its corresponding links were removed from the project's meta-network. In the last scenario, the planning strategy of redundancy in resources was adopted. In the base scenario, no redundancy was considered in the resource management strategy. In scenario 3, nodes of the additional electrical power system, shotecrete machinery, and boomer were added as backup resources. These resource nodes were linked with other related nodes in the project's meta-network so that they could be used by the corresponding agents for specific tasks. Figure 3 shows all the meta-networks (without any perturbation) related to the four scenarios. Since different planning strategies were translated to different topologies of the project organization's meta-network, differences in the numbers of nodes, links, as well as the network densities of meta-networks under different planning strategies can be observed. For each scenario, vulnerability assessment was conducted following the same procedures. The effectiveness of different planning strategies was then evaluated.



(a) Base Scenario: *generalization of labor*, *centralization*, and *non-redundancy* (b) Comparative Scenario One: *division of labor* , *centralization*, and *non-redundancy*

(c) Comparative Scenario Two: generalization of labor, de*centralization*, and *non-redundancy* (d) Comparative Scenario Three: generalization of labor, *centralization*, and *redundancy*

Figure 3. Meta-networks of the Tunneling Project under Different Planning Strategies

3.2 Results

Figure 4 shows the results related to one run of vulnerability assessment for the tunneling project in the base scenario. In this specific run, no multiple-effect uncertain events happened. However, several single-effect uncertain events happened simultaneously. The safety supervisor left the position and the support installation crew failed to complete the tasks in the project. The geologist didn’t have access to the latest version of rock quality designation index, which led to difficulty in accurately determining the rock type. Also, there was a delay in the delivery of materials to the jobsite, including explosive, initial support, concrete and reinforcement. Finally, the boomer equipment which facilitates the tasks of applying shotcrete and installing support didn’t function properly during the project. In this specific circumstance, the project meta-network was pushed away from its original stable state, as shown in Figure 4. The network efficiency was decreased from 1 to 0.625, which means after the perturbations mentioned above, only 62.5% of the tasks could be completed if no adaptive or restorative actions were taken. Thus, the project vulnerability to the uncertain events assessed in this run is 0.375.

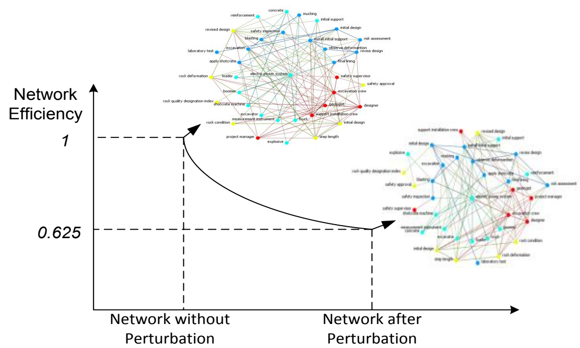
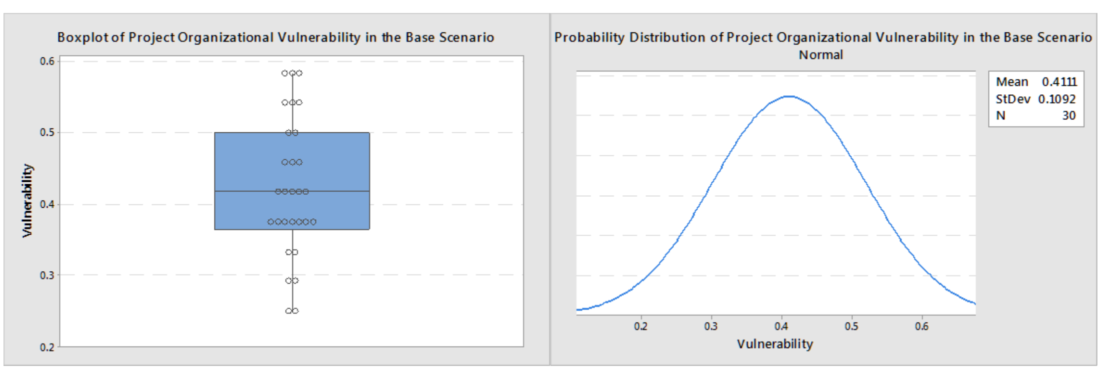


Figure 4. Changes in Network Efficiency in One Run of Monte Carlo Simulation for the Base Scenario

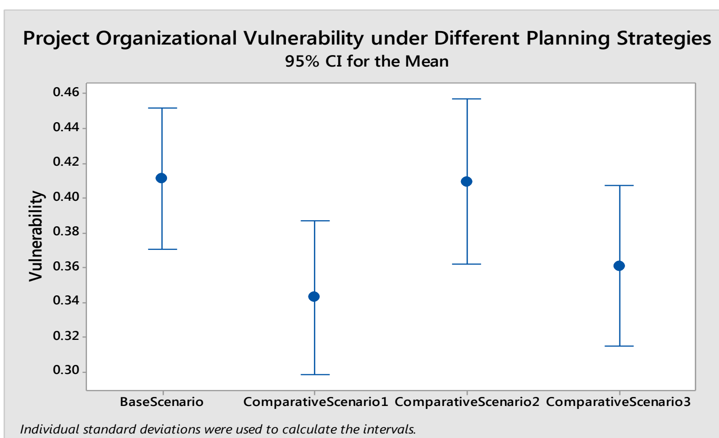
Figure 5 shows the results of vulnerability assessment in the total 30 runs of the Monte Carlo simulation for the base scenario. Figure 5(a) is a boxplot for the vulnerability values in different runs. Each data point shows the vulnerability obtained in one run. The interquartile range box indicates that 25% of the vulnerability values in the 30 runs are less than 0.3645, and 75% of them are less than 0.5. The boxplot also suggests the values of vulnerability obtained in the 30 runs are normally distributed. Figure 5(b) shows the bell curve of the distribution. With the mean value (0.4111) and standard deviation (0.1092) of the 30 samples, the average vulnerability of the project organization to the uncertainties in the case can be predicted. For example, with a 95% confidence interval, the average vulnerability of the tunnelling project under the base scenario to the identified uncertainties is between 0.3703 and 0.4519. A higher level of vulnerability implies more possible losses when facing uncertainties. Thus, construction project companies can use the results of the ex-ante vulnerability assessment to predict the possible disturbance magnitude of project against uncertain events and develop corresponding contingence plans.



(a) (b)

Figure 5. Project Organization’s Vulnerability for the Base Scenario

The other component of the analysis was to evaluate the effectiveness of different planning strategies in reducing vulnerability of project organization to the uncertainty-induced perturbations. Figure 6 shows the vulnerability of the tunneling project in different scenarios related to planning strategies. The interval plots in Figure 6 depict the mean values of multiple runs of the Monte Carlo simulation for each scenario with a 95% confidence interval. The effectiveness of the planning strategies related to task assignment, decision-making authority and resource management was evaluated by calculating the decreases of the project organization's vulnerability in different scenarios. From the results, it is obvious that division of labor adopted in scenario 1 is the most effective planning strategy which decreases the vulnerability of the project organization in the base scenario by 16.57%. This is due to the fact that when each agent or agent crew is assigned for one specific task and role, the impact of perturbations on single agent node is limited. The planning strategy of considering redundancy in resource also shows the capability in reducing the vulnerability of project organization. Compared with the base scenario, the mean value of the vulnerability assessed in the samples of scenario 3 is reduced by 12.16%. When the planning strategy of resource redundancy is considered, the project organization becomes more robust especially against resource-related perturbations, as the backup resource could help to maintain the efficiency of project network. The planning strategy related to decision-making authority doesn't show significant effectiveness in this case. The vulnerability is decreased only by 0.34% in average when adopting the planning strategy of decentralized decision-making authority in scenario 2 compared with the base scenario. As a conclusion, in this tunneling project, the planning strategies of division of labor and redundancy in resource have the most significant impact on reducing project organization's vulnerability. This kind of information can help the decision makers to select the most effective planning strategies from a list of options in order to decrease the vulnerability of the project organization. Adopting alternative planning strategies usually implies more input into the project (e.g., hiring more agents, ordering backup resource). Knowing the effectiveness of alternative planning strategies provides the basis for the decision makers to conduct cost benefit analysis and make the final decision on whether to adopt certain planning strategy or not.



	N	Mean	StDev	95% CI	effectiveness
Base Scenario	30	0.4111	0.1092	(0.3703, 0.4519)	-
Comparative Scenario 1	30	0.343	0.1186	(0.2987, 0.3873)	16.57%
Comparative Scenario 2	30	0.4097	0.1267	(0.3624,0.4570)	0.34%
Comparative Scenario 3	30	0.3611	0.1235	(0.3150, 0.4072)	12.16%

Figure 6. Project Organization's Vulnerability under Different Planning Strategies

4 CONCLUSION

Traditional methods of risk analysis in construction projects are based on qualitative, descriptive and reactive approaches. In this paper, an integrated framework for ex-ante assessment of vulnerability to uncertainties in complex construction project organizations is proposed. The proposed framework provides a novel approach for quantitative assessment of project vulnerability based on the theoretical underpinnings of network theory. It provides a quantitative basis for ex-ante assessment of vulnerability and evaluation of planning strategies. The results of the integrated vulnerability assessment can be used for analysis of the benefits of alternative planning strategies and selecting the most effective planning strategies for reducing vulnerability under uncertainty. The application of the proposed framework will facilitate a paradigm shift toward ex-ante assessment of performance vulnerability in complex construction projects. It enhances the design and management of project organization toward proactive reduction of vulnerability. It also will enable creation of novel theoretical constructs for a better understanding of the links between planning strategies, complexity, and vulnerability in construction projects. This understanding will provide prescriptive findings and flexible strategies that lead to predictive assessment and proactive management of performance in construction projects.

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