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CHARACTERIZATION OF THE UNDERLYING MECHANISMS OF VULNERABILITY IN COMPLEX PROJECTS USING DYNAMIC NETWORK SIMULATION

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ABSTRACT

The objective of this study was to investigate the underlying mechanisms of vulnerability in complex construction projects using simulation experiments. Specifically, two hypotheses related to project vulnerability were tested: (1) project schedule performance is negatively correlated with vulnerability; (2) the level of project vulnerability is positively correlated with project exposure to uncertainty and organizational complexity. In the proposed dynamic network simulation methodology, construction projects are modeled as heterogeneous meta-networks. Project vulnerability is assessed by the decrease in meta-network efficiency due to uncertainty-induced perturbations. Project schedule deviation is used as a measure for quantifying the impacts of vulnerability on project performance outcomes. The proposed simulation methodology was implemented in three case studies of real-world construction projects. Monte-Carlo simulation experiments were conducted under different simulation scenarios consisting of varying levels of uncertainty and project planning strategies to test the hypotheses.

1 INTRODUCTION

Performance inefficiency such as cost overrun and schedule delay continues to be a major concern in the construction industry. One of the major reasons of the unpredictability of construction project performance is the high level of risk and uncertainty in modern construction projects. While the traditional approaches in dealing with risk and uncertainty in construction projects mostly focus on the identification and evaluation of risk factors, recent studies have started looking into the internal weakness of project systems (i.e., vulnerability) in uncertain environments (e.g., Zhang 2007; Vidal and Marle 2012). According to Zhang (2007), vulnerability analysis and management can complement currrent approaches of analysing and managing risk events, and can more proactively improve project's adaptability, robustness, and flexibility.

Despite the ongoing efforts, the theory of vulnerability in complex construction projects is still underdeveloped. First, the majority of existing studies on project vulnerability are qualitative (e.g., Zhang 2007; Dikmen et al. 2008). A quantitative method for the assessment of project vulnerability and its impact on project performance outcomes is still missing. Second, the determinants and their influence on the level of project vulnerability are not identified in existing studies. Without these key theoretical constructs, a systematic understanding and management of project performance based on vulnerability assessment is hard to achieve.

Zhu and Mostafavi (2015) proposed a meta-network framework for assessment of project vulnerability. In the proposed framework, projects are conceptualized as meta-networks consisting of different types of nodes (i.e., human agents, information, resources, and tasks) and links. Various sources of uncertainty are translated as perturbations in project meta-networks. Project vulnerability is quantified as the decrease in meta-network efficiency due to uncertainty-induced perturbations. The proposed meta-network framework provides a quantitative approach for capturing the dynamic interdependencies in projects and assessing project vulnerability in the face of uncertainty. Based on the meta-network framework, this study further developed a simulation methodology to investigate the correlation between project vulnerability and schedule performance as well as the influencing mechanisms of two factors (i.e., exposure to uncertainty, project organizational complexity) on project vulnerability.

Specifically, this study aims at testing two hypotheses related to vulnerability in complex construction projects: (1) There is a negative correlation between project vulnerability and schedule performance under uncertainty; and (2) The level of project vulnerability is positively correlated with project exposure to uncertainty and organizational complexity.

2 VULNERABILITY SIMULATION METHODOLOGY

A simulation approach for theory development is adopted in this study for hypothesis testing. In this section, the simulation methodology is introduced in different steps.

2.1 Step One: Development of Project Meta-Network

In the first step, a construction project is conceptualized as a meta-network (Zhu and Mostafavi 2017). Project meta-networks include four different types of nodes (i.e., human agent, resource, information, and task) and ten different types of links (Figure 1). The basis of this conceptualization is that construction projects can be seen as a group of interconnected human agents utilize resources and information to complete certain tasks. In order to develop a project meta-network, different types of node entities: human agent (A), information (I), resource (R), and task (T) involved in the project are identified. Then, based on the types of interdependencies between different nodes, ten different networks can be developed by building the links between nodes. Each network captures one specific type of interdependencies in construction projects. For example, human agent nodes and agent-to-agent links form the social network (AA). Human agent nodes, tasks nodes, and agent-to-task links form the task assignment network (AT). All the ten individual networks are binary (i.e., links are unweighted). The combination of the ten interconnected networks then forms the project meta-network. The complexity of a project organization can be measured by the total density of its project meta-network (Equation 1):

$$Project\ organizational\ complexity = \frac{l}{n(n-1)/2} \quad (1)$$

where l denotes the total number of links in a project meta-network, and n denotes the total number of nodes in a project meta-network.

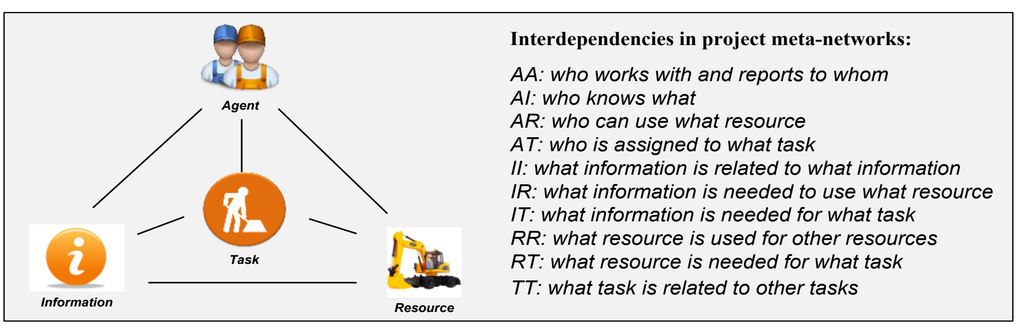


Figure 1: Conceptualization of construction project meta-networks.

Based on the project meta-network conceptualization, each task in a construction project is a subset of the project meta-network consisting of one task node and multiple agent, resource, and information nodes, fulfilling the needs for the completion of that specific task. Therefore, a conceptual model of construction project schedule can be developed (Zhu and Mostafavi 2016). As shown in Figure 2, the successful and timely completion of each task in the baseline plan is contingent on the availability and efficient interactions between the agents, resources, and information involved in the specific sub-network.

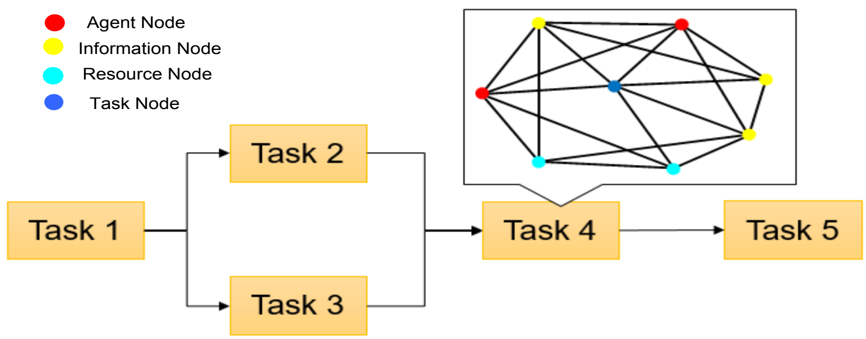


Figure 2: Modeling construction project schedule using meta-network conceptualization.

2.2 Step Two: Translation of Uncertainty

In the proposed framework, the impacts of uncertainty are translated into uncertain-induced perturbations in project meta-networks (Zhu and Mostafavi 2017). These perturbations are modeled through removal of the affected nodes and links in project meta-networks. There are three basic types of uncertainty-induced perturbations based on their nature: human-related (e.g., staff turnover, safety accident), information-related (e.g., unclear design information), and resource-related (e.g. equipment breakdown, delay in delivery of resources) (Zhu and Mostafavi 2015). Each type of perturbation, based on the magnitude of perturbation effects (i.e., duration of the removal of affected nodes and links), can be further defined at three different levels: high-, medium-, and low-disturbance. For example, both key staff turnover and regular staff turnover cause human agent nodes to be removed in project meta-networks. However, the turnover of key staff (e.g., project manager) has a more significant disturbance on projects. It leads to a longer duration of removal of the affected human agent nodes, since it is more difficult to eliminate the perturbation effects by finding qualified substitutions for key staff. Thus, the turnover of key staff leads to a high-disturbance human-related perturbation, while the turnover of regular staff leads to a low-disturbance human-related perturbation. Based on the perturbation type and level of disturbance, uncertain events are categorized (Table 1).

Table 1: Example of uncertain events and the resulting perturbations.

Perturbation Type	Disturbance Level	Examples of Uncertain Events
Human agent-related	High	Safety accident or injury, key staff turnover
	Medium	Shortage of manpower
	Low	Regular staff turnover
Information-related	High	Delay in processing key information, inaccurate design
	Medium	Limited access to required information, miscommunication
	Low	Unclear scope/design
Resource-related	High	Power supply issue
	Medium	Defective material, equipment breakdown
	Low	Late delivery of material

In the proposed simulation method, the uncertain environment in which a project operates is modeled by the likelihood of occurrence of each category of uncertain events and their perturbation effects. The likelihood of occurrence means at a given period of time (e.g., one day), out of all the human agents, resources, or information in the project jobsite, the percentage of them that would experience high-disturbance, medium-disturbance, or low-disturbance uncertain events. For a construction project, the information related to the likelihood of uncertain events can be obtained through interview and coding techniques. For example, if a project manager reports a daily likelihood of medium-disturbance resource-related uncertain events is 10% in the project, it means that in each day, 10% of the resources used might encounter medium-disturbance uncertain events such as defective material or equipment breakdown. Therefore, a project's exposure to uncertainty can be defined using Equation 2. Each parameter in Equation 2 represents the likelihood of one specific category of uncertain events. For instance, U_{h_h} denotes the likelihood of high-disturbance human-related uncertain events, and U_{r_m} denotes the likelihood of medium-disturbance resource-related uncertain events.

$$Exposure\ to\ uncertianty = \{(U_{h_h}, U_{h_m}, U_{h_l}), (U_{r_h}, U_{r_m}, U_{r_l}), (U_{i_h}, U_{i_m}, U_{i_l})\} \quad (2)$$

The perturbation effects will be reflected at both project- and task- levels. At the project level, the uncertainty-induced perturbations cause topological changes in project meta-networks, by removing the affected nodes and links. At the task level, these perturbations cause delay in single tasks and ultimately result in project schedule deviation. The duration of delay caused by a perturbation is project-specific and task-specific. In the proposed methodology, for simplicity and the purposes of study, the average delay effects of different categories of perturbations in a project are captured (Equation 3). The methods for collecting data related to the delay effects include interview, observation, and report analysis. Each parameter in Equation 3 represents the average delay effect caused by one category of uncertain-induced perturbations in a project task. For instance, d_{r_l} denotes the duration of delay caused by a low-disturbance resource-related perturbation, and d_{i_m} denotes the duration of delay caused by a medium-disturbance information-related perturbation.

$$Delay\ effects\ of\ perturbations = \{(d_{h_h}, d_{h_m}, d_{h_l}),\ (d_{r_h}, d_{r_m}, d_{r_l}), (d_{i_h}, d_{i_m}, d_{i_l})\} \quad (3)$$

2.3 Step Three: Quantification of Project Vulnerability

Based on the theoretical underpinnings of network science, project vulnerability is measured by the changes in meta-network efficiency due to uncertainty-induced perturbations. The meta-network efficiency in the context of projects is quantified as the percentage of tasks that can be successfully completed (Zhu and Mostafavi 2017). Since the completion of a task is contingent on the presence of relevant human agents, information, and resources, any human-related, information-related, and resource-related perturbations will cause decreases in meta-network efficiency. Equation 4 shows the vulnerability of a project A when it is exposed to a set of uncertain-induced perturbations r.

$$Project\ vulnerability\ (V_r) = e(N_A) - e(N_A{}') \quad (4)$$

where e denotes the percentage of tasks that can be successfully completed based on the requisite human agents, information, and resources, N_A is the binary matrix representing the project meta-network without any perturbations, $N_A{}'$ is the binary matrix representing project meta-network after perturbations.

In order to quantify the vulnerability of a project exposed to an uncertain environment in which uncertain perturbations occur randomly, Monte Carlo simulation is used. Based on the identified project's exposure to uncertainty in step two, random numbers are generated using MATLAB rand function and the impacts of perturbations are reflected as changes in project meta-network matrices (Figure 3(a)). Then, project task completion after perturbations is evaluated (Figure 3(b)) and used to calculate project vulnerability. Multiple runs of Monte Carlo simulation experiments will be conducted and the average value of vulnerability will be used as an indicator of project vulnerability under a certain level of exposure to uncertainty.

Algorithm for human-related perturbation effects	***Algorithm for information-based task completion***

<pre>h=total number of human agents;
r=1;
while r<=h
    if perturbation happens to human agent r
       AI(r,:)=0;
       AR(r,:)=0;
    end
    r=r+1;
end</pre>
	<pre>failed task number=0;
	n=total number of tasks;
	r=1;
	while r<=n
	    if any required information for task r is not available
	       failed task number=failed task number+1;
	    end
	    r=r+1;
	end</pre>

(a)	(b)

Figure 3: Algorithms for assessment of perturbation effects (a) and their impacts on task completion (b).

2.4 Step Four: Assessment of Schedule Performance Deviation

Different levels of project vulnerability might lead to different performance outcomes. In order to assess the impacts of vulnerability on construction project performance, schedule deviation is selected as a measure of performance outcome. In the proposed methodology, a construction project consists of a set of tasks $E = \{1, \ldots, n\}$ with fixed precedence constraints $i \rightarrow j$ (i.e., task j cannot start before task i is completed). The constraints are defined by technical requirements (e.g., construction starts after design finishes, roof is constructed after wall). The start time (S_j) of task j then can be defined using Equation 5:

$$S_j = max\{S_i + t_i\},\ if\ i \rightarrow j \qquad i \in E, j \in E \tag{5}$$

where S_i denotes the actual start time of task i and t_i denotes the actual duration of task i. The total duration of the project (D) is then calculated in Equation 6:

$$D = S_n + t_n - S_1 \tag{6}$$

where n is the last task of the project, and 1 is the first task of the project. During the project, if uncertainty-induced perturbations occur and cause the removal of the requisite human agent, information, and resource nodes for a task, the actual duration of that specific task will increase. When multiple uncertainty-induced perturbations occur in the same task, the duration of delay will be determined by the most significant perturbation effect (Equation 7).

$$t_i = t_{ip} + \max(d_k) \qquad i \in E \tag{7}$$

where t_{ip} is the planned duration of task i, and d_k is the delay caused by perturbation k. In a project, if no uncertainty events occur, the actual total duration of the project will be the planned duration. Otherwise, the schedule performance deviation (SD) is assessed as the difference between the actual duration (D) and the planned duration (PD) of the project (Equation 8):

$$Schedule\ deviation\ (SD) = D - PD \tag{8}$$

Similar to vulnerability assessment in step three, Monte Carlo simulation will be conducted in this step to assess the project schedule deviation considering the randomness of uncertain events. Based on the identified level of exposure to uncertainty, stochastic computational models of project schedule developed in MATLAB will be run multiple times and the average outcome of project schedule deviation will be captured for measuring project performance under uncertainty.

2.5 Step Five: Scenario Simulation Experimentation

In this step, simulation experiments are conducted in different scenarios to test the research hypotheses. Simulation scenarios are created based on the consideration of alternative planning strategies compared to the base scenario (i.e., the actual planning scenario in a project). Two types of planning strategies in construction projects will be considered. The first type of planning strategies affects a project's ability in coping with uncertainty by changing the topological structure of the project's meta-network. Examples of this type of planning strategies include considering redundancy in resources and division of labor. For instance, if redundancy of resources is considered in a project, additional resource nodes will be added in a project meta-network as backup resources. If any resource-related perturbations occur, the backup resources nodes can be used by human agents to complete tasks. In this way, project performance will be less or not affected by uncertainty. The second type of planning strategies focuses on reducing projects' exposure to uncertainty. By adopting this kind of planning strategies (e.g., supplier prequalification, training and teambuilding), a project's level of exposure to human-related, information-related, or resource-related uncertainty can be reduced, and thus, the possible uncertainty-induced impacts on project performance could be mitigated.

After simulation scenarios are created by considering one or multiple alternative planning strategies in a project, the project's meta-network model and exposure to uncertainty will change accordingly. Simulation experiments will be conducted to assess the project complexity, vulnerability, and schedule performance under these scenarios. Based on the results from different simulation scenarios, comparison and correlation analysis can be conducted to investigate the relationships between project complexity, exposure to uncertainty, vulnerability, and schedule performance.

3 CASE STUDY

Three case studies from two real-world complex construction projects were conducted to test the research hypotheses. Each case study unit is a project system related to one part of the whole project with independent work packages. Case study 1 and 2 are related to the elevator system and wall system in one commercial project, respectively. Case study 3 is related to the construction of pile caps in another commercial project. The three cases were selected based on their high level of complexity and uncertainty.

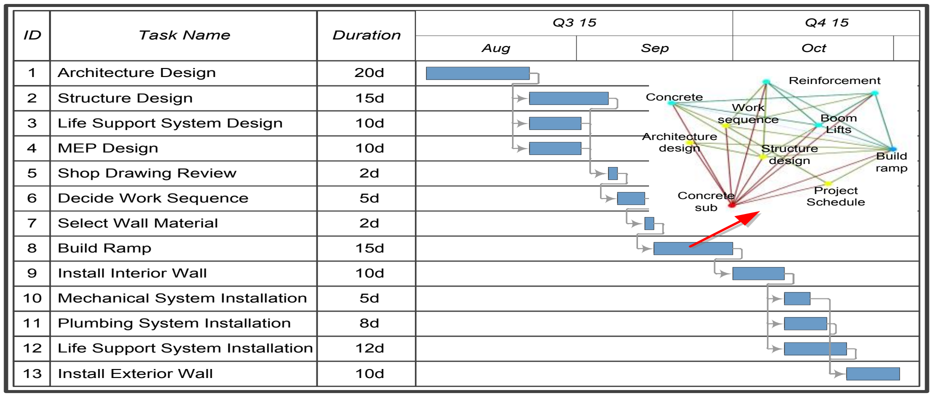
3.1 Data Collection

In order to develop the project vulnerability simulation models for the three case studies, various types of data were collected, including the project meta-network constitutes and their interdependencies, project task duration and sequence, and sources of uncertainty and their impacts on projects. During a six-month period, weekly visits were made to the job sites to collect the required data through document review, onsite observation, and interview with project personnel. Data validity was ensured by internal consistency checks of data from different sources.

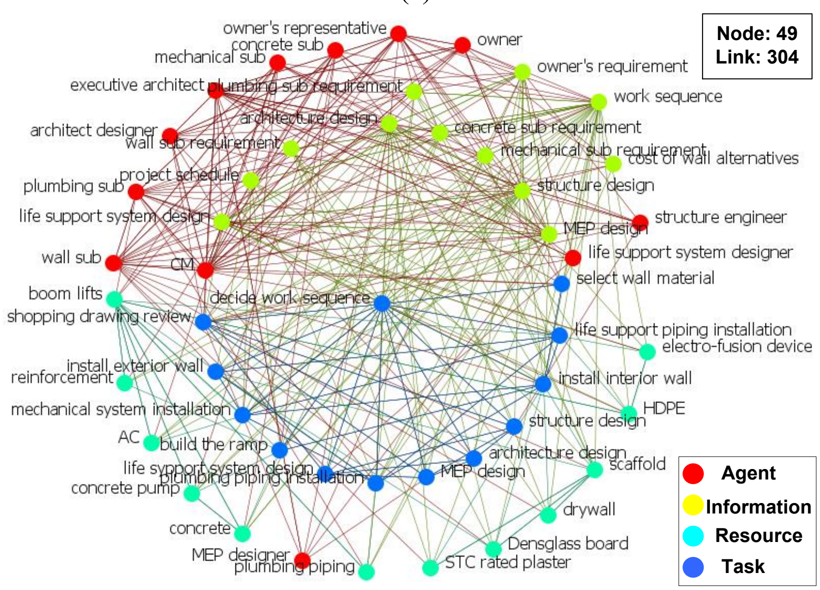
3.2 Case Modeling and Simulation

In this section, different steps of project meta-network modeling and vulnerability simulation in case study 2 are given as an example of implementation of the proposed methodology.

First, project meta-network model of case study 2 was developed. In case study 2, there were 13 tasks in total related to the design and construction of a wall system (e.g., architecture design, shop drawing review, installing interior wall, and installing exterior wall). Figure 4(a) shows the original schedule of case study 2. The planned schedule of all the tasks in case study 2 was 91 days. Each task in the case study was implemented by certain human agents with needed information and resources. For example, as shown in Figure 4(a), the task of "build ramp" was implemented by concrete subcontractor with relevant information (e.g., structure design, work sequence) and resources (e.g., concrete, boom lifts). Figure 4(b) shows the project meta-network including all the human agent, information, resource, and task nodes and their interdependencies. In total, there were 49 nodes of four different kinds and 304 links of ten different kinds in this project meta-network. The original project organizational complexity was 0.259. The developed meta-network model was shown to the project personnel and modified based on their comments and feedback in several rounds until a consensus that the meta-network completely and accurately represents the project was reached.



(a)



(b)

Figure 4: Schedule (a) and meta-network (b) of case study 2.

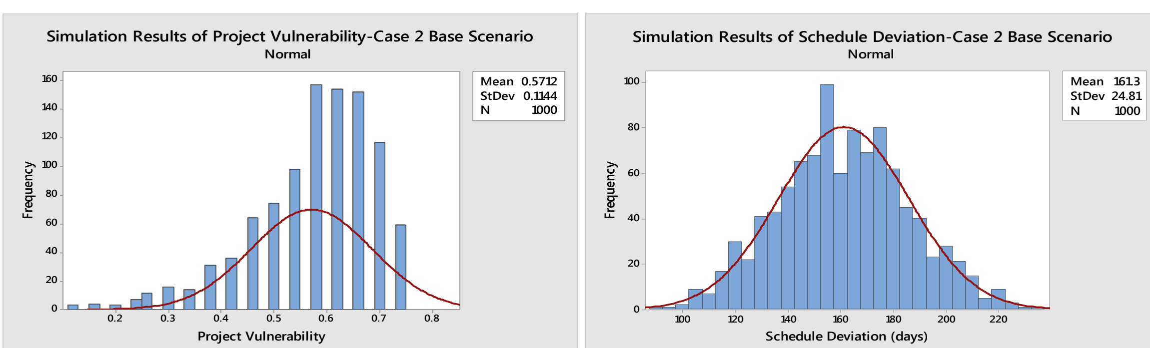
In step two, uncertainty in the operational environment of case study 2 was translated. The project's exposure to different uncertain events and the corresponding perturbation effects were captured through interviews with project personnel. The definition and examples of perturbations at different disturbance levels were provided to the interviewees. Three levels of exposure to uncertainty (i.e., high, medium, and low) defined based on the probability of occurrence of uncertainty events (i.e., 20%, 10%, 5%) were explained to the interviewees. Then, the interviewees were asked to give an estimation of the project exposure to each category of uncertainty and the corresponding delay effects on tasks based on their knowledge and experience on this specific project. For example, during the interviews, one set of questions related to high-disturbance human-related uncertainty was asked as follows: "*In this project, what is the level of exposure to high-disturbance human-related uncertain events that might have significant impacts on project delivery, such as safety incidents and key staff turnover? If these uncertain events happen, how many days they will cause delay in the ongoing tasks?*" Such interviews were conducted with multiple interviewees working at this case study project. Their responses were crosschecked and compiled in Table 2.

Table 2: Translation of uncertainty in case study 2.

Perturbation Type	**Disturbance Level**	**Exposure to Uncertainty** (Low: 5%; Medium: 10%; High: 20%)	**Delay Effects** (days)
Human-related	High-disturbance	U_{h_h}: Low	d_{h_h}: 21
	Medium-disturbance	U_{h_m}: Medium	d_{h_m}: 14
	Low-disturbance	U_{h_l}: Medium	d_{h_l}: 3
Information-related	High-disturbance	U_{i_h}: Medium	d_{i_h}: 28
	Medium-disturbance	U_{i_m}: Medium	d_{i_m}: 14
	Low-disturbance	U_{i_l}: High	d_{i_l}: 7
Resource-related	High-disturbance	U_{r_h}: Low	d_{r_h}: 21
	Medium-disturbance	U_{r_m}: Medium	d_{r_m}: 14
	Low-disturbance	U_{r_l}: High	d_{r_l}: 12

In step three, the vulnerability of case study project 2 was assessed using Monte Carlo simulation. Using a vulnerability simulation model developed in MATLAB and simulation variables captured in the previous steps, one thousand runs of Monte Carlo simulation experiments were conducted to quantify the vulnerability of cast study project 2 under the current condition of planning and exposure to uncertain. In each run of simulation, uncertainty-induced perturbations to the project meta-network occurred randomly, and thus, caused a decrease in project meta-network efficiency. The values of project vulnerability captured in the one thousand runs of simulation experiments were plotted in a histogram and fitted to normal distribution (Figure 5(a)). As shown in Figure 5(a), the mean value of vulnerability of case study project 2 was 0.57, which implied that around 60% of tasks in this case study project might not be successfully implemented according to the plan due to the current uncertain environment.

In the fourth step, the schedule deviation of case study project 2 under the impacts of uncertainty was quantified. Based on the algorithm proposed for assessing schedule performance deviation (Equations 5-8), computational model for schedule deviation assessment of case study project 2 was created in MATLAB. One thousand runs of Monte Carlo simulation experiments were conducted to assess the schedule performance of the case study project in the current uncertain environment. Each run of simulation produced one data point regarding the difference between the planned duration and the project duration as a result from the simulation experiment considering the impacts of uncertainty. Figure 5(b) shows the distribution of simulation results of schedule deviation in case study project 2. As shown in Figure 5(b), in average, the case study project might experience a delay of 161 days considering its exposure to uncertainty in the base scenario. In other words, when the average vulnerability was 0.57, the resulting schedule deviation in case study project 2 was around 161 days.



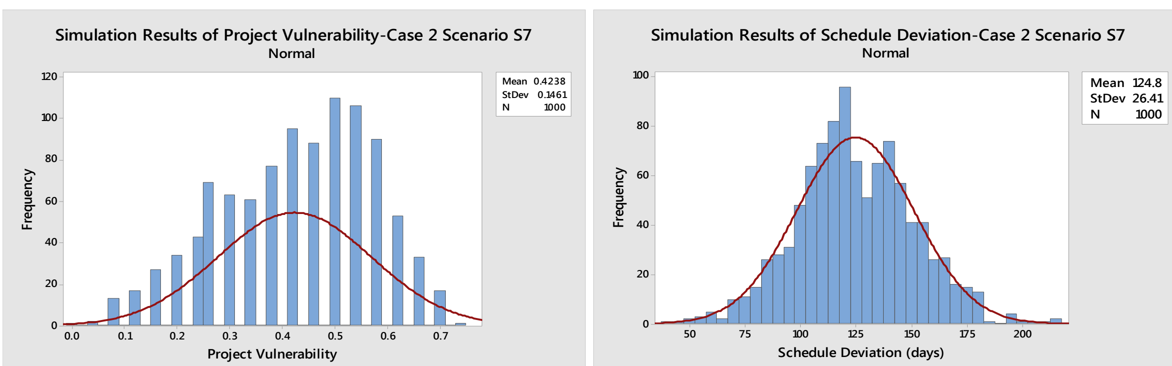
(a) (b)

Figure 5: Project vulnerability (a) and schedule deviation (b) of case study 2 under base scenario.

In the last step, different simulation scenarios were created and simulation experiments were conducted. Each simulation scenario consists of one or multiple alternative planning strategies identified through literature review. Table 3 shows some examples of simulation scenarios created in case study 2. For example, in scenario S7 of case study 2, redundancy in resource and adoption of information communication technologies (ICTs) were considered. The strategy of redundancy in resource would result in adding backup resource nodes in the original project meta-network, and the strategy of adoption of ICTs would result in reducing the project's exposure to information-related uncertainty. Figure 6 shows the simulation results of project vulnerability and schedule deviation in simulation scenario S7. Compared to the base scenario, the average project vulnerability of case study project 2 decreased by 26%, and the average schedule deviation decreased by 23%.

Table 3: Simulation scenarios.

Planning Strategies	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**
Division of Labor	x															
Redundancy in resource		x				x	x	x				x	x	x		x
Supplier prequalification			x			x			x	x		x	x		x	x
Adoption of ICTs				x			x		x		x	x		x	x	x
Training and Teambuilding					x			x		x	x		x	x	x	x



(a) (b)

Figure 6: Project vulnerability (a) and schedule deviation (b) of case study 2 under scenario S7.

3.3 Results Analysis

In this section, simulation results from all three case studies were analyzed and compared to test the research hypotheses. First, the correlation between project vulnerability and schedule performance under uncertainty was examined. In each case study, the simulation results of project vulnerability and schedule deviation were studied to test whether there is a strong correlation between these two variables. The Pearson correlations of the two variables calculated from simulation results of the three case studies were 0.959, 0.945, and 0.977, respectively. The results showed a significant linear correlation between project vulnerability and schedule deviation. Figure 7 shows the fitted plots of project vulnerability and schedule deviation in the three case studies. As shown in Figure 7, when project vulnerability increases, the schedule deviation of a project increases too. In other words, the project schedule performance is negatively correlated with project vulnerability to uncertainty. Thus, the first research hypothesis of this study can be accepted.

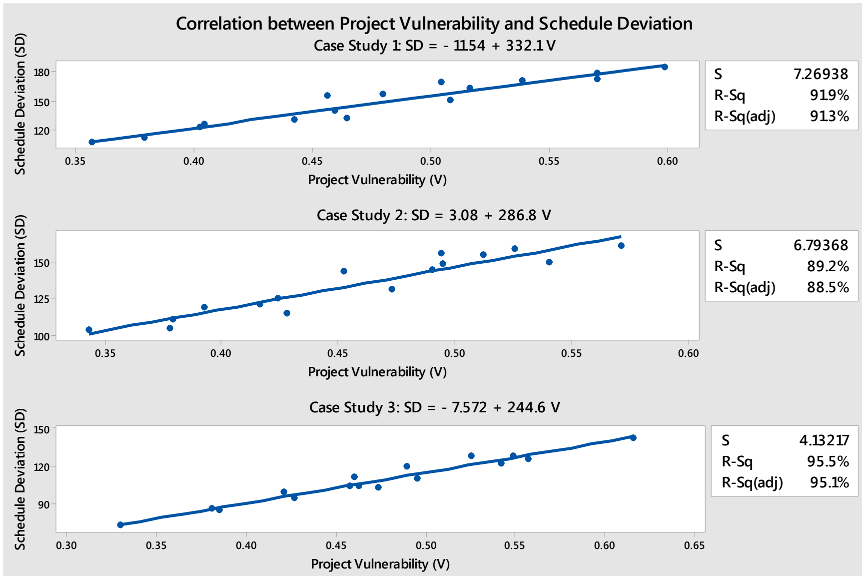


Figure 7: The correlation between project vulnerability and schedule deviation in three case studies.

The second hypothesis is related to the influencing factors of project vulnerability. Two sets of results were used to test the hypothesis. First, the impacts of exposure to uncertainty on project vulnerability were examined using results of vulnerability under different levels of uncertainty exposure in case study projects. As shown in Figure 8, in all three cases, when the uncertain environment of a project was modified deliberately to a higher level of exposure to uncertainty, the mean value of project vulnerability increased significantly compared to the base scenario. Accordingly, when the uncertain environment of a project was modified deliberately to a lower level of exposure to uncertainty, the mean value of project vulnerability decreased compared to the base scenario. Therefore, the hypothesis that project vulnerability is positively correlated with exposure to uncertainty can be accepted. In other words, the more exposed to uncertainty, the more vulnerable a project.

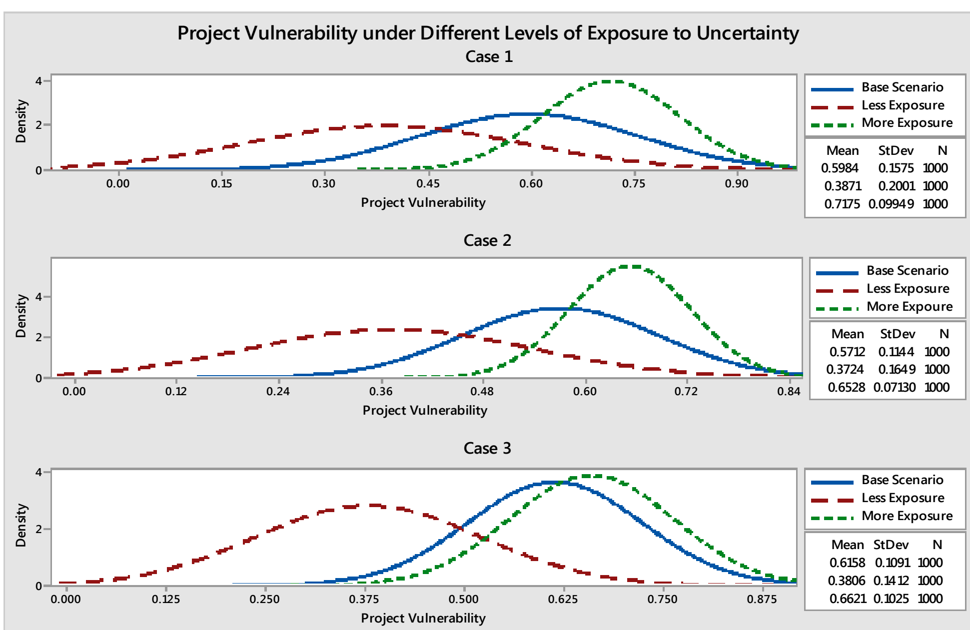


Figure 8: Project vulnerability under different levels of exposure to uncertainty in three case studies.

Besides the level of exposure to uncertainty, another factor that could potentially affect a project's vulnerability is its organizational complexity. To test the hypothesis related to the relationship between project vulnerability and organizational complexity, the simulation results of vulnerability under planning scenarios with different levels of organizational complexity were analyzed. Figure 9 shows the analysis results in case study 2. In this case study, the original organizational complex was 0.259. In simulation scenario S1 (refer to Table 3), planning strategy "division of labor" was adopted and the topological structure of project meta-network was modified by adding additional human agent nodes and links between the added human agent nodes and other nodes. The organizational complexity of case project 2 under S1 was reduced to 0.243. Similarly, when considering the planning strategy of "redundancy in resource" in scenario S2 (refer to Table 3), the organizational complexity of case project 2 was reduced to 0.247. Thus, the organizational complexity in the base scenario was greater than scenarios S2 and S1 (0.259 > 0.247 > 0.243) in case study project 2. As shown in Figure 9, when under the current level of exposure to uncertainty, the average project vulnerability obtained from simulation under the base scenario was 0.57, while the average vulnerability under S1 and S2 was around 0.53. The similar impact of organizational complexity on vulnerability was observed in simulation results under scenarios with higher and lower levels of exposure to uncertainty (Figure 9). Thus, the hypothesis that vulnerability is positively correlated with organizational complexity can be accepted. In other words, the more complex, the more vulnerable a project. As an additional observation, the impact of complexity on vulnerability was more significant when a project was more exposed to uncertainty (Figure 9).

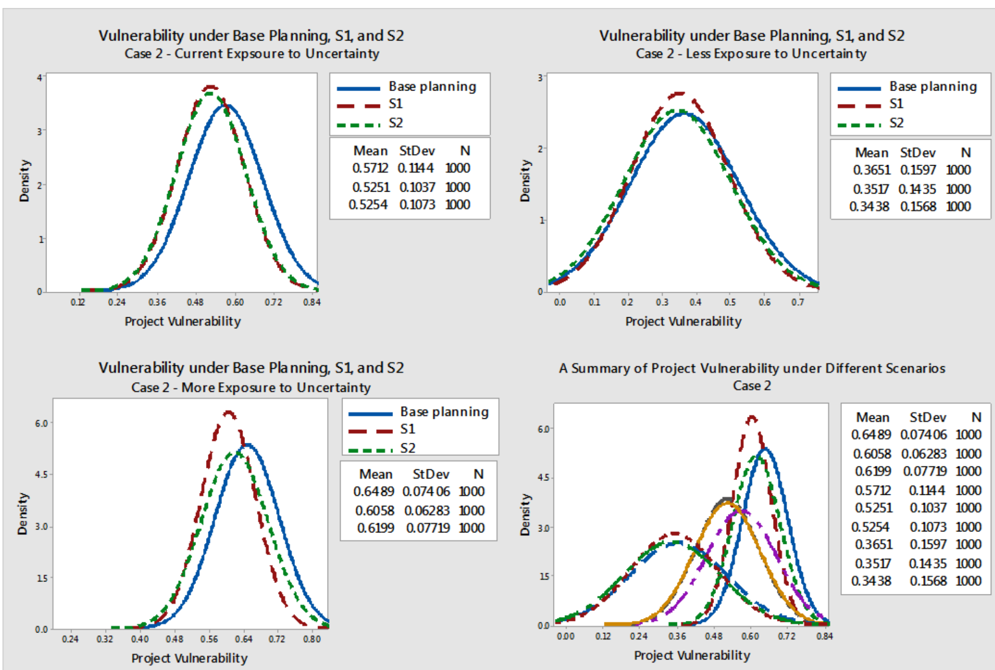


Figure 9: Project vulnerability under scenarios with different levels of project organizational complexity.

4 DISCUSSION AND CONCLUSION

In this study, an innovative conceptualization of construction projects as meta-networks and a simulation methodology for assessment of project vulnerability and its impact on project schedule performance were proposed. The simulation methodology was implemented in three real-world case studies. The simulation results confirmed the hypotheses that there is a negative correlation between project vulnerability and project schedule performance, and the level of project vulnerability is positively correlated with exposure to uncertainty and project organizational complexity.

The findings of this study help to build the theory of vulnerability in the context of complex construction projects by providing a better understanding of project exposure to uncertainty, complexity, vulnerability, and schedule performance. Project managers and decision makers can utilize the findings of this study to conduct vulnerability-based predictive assessment and proactive management (e.g., reduce exposure to uncertainty or organizational complexity) of project performance in the face of uncertainty.

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