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Selecting risk response strategies considering project risk interdependence

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Abstract

In risk response analysis, risks are often assumed independently. In fact, however, risks in a project mutually affect and the independent risk seldom exists in reality. This paper provides an approach to quantitatively measure the risk interdependence. Based on the analysis of the risk interdependence, we construct an optimization model for selecting risk response strategies considering the expected risk loss, risk interdependence and its two directions. Further, the effects of the risk interdependence on risk response can be investigated. There are two major findings by the analysis of the case project. First, the expected utility would be more sensitive to the risk interdependence itself than to the directions of it. Second, the insufficient attention paid to or neglect of the risk interdependence would lower the expected utility and increase the implementation cost.

Keywords: Project risk management; Risk interdependence; Risk response strategy; Optimization; Expected utility

1. Introduction

Projects are, by nature, exposed to multiple risks in practice. If the risks are not dealt with effectively in the process of project management, the poor performance with increasing cost and time delays will appear. Therefore, project risk management (PRM) is an important topic for practitioners and academic scholars. In general, PRM consists of three phases (Buchan, 1994): risk identification, risk assessment and risk response. Risk identification is the process of recognizing and documenting associated risks. Risk assessment is the process of evaluating project risks according to their characteristics such as the probability and impact. Risk response refers to developing, selecting and implementing strategies in order to reduce risk exposure. The risk response plays a proactive role in mitigating the negative impact of project risks (Miller and Lessard, 2001). Appropriate risk response strategies must be selected to reduce global risk exposure in project implementation once the risks have been identified and analyzed (Zou et al., 2007). Therefore, the risk response analysis can be regarded as an important issue in PRM (Ben-David and Raz, 2001).

In risk response analysis, risks are often assumed independently and then analyzed according to their individual characteristics in response strategy selection (Fan et al., 2008; Seyedhoseini et al., 2009). In fact, however, project risks are not always independent (Adner, 2006; Kwan and Leung, 2011), and risks in a project mutually affect (Ren, 1994). This leads to the need to consider risk interdependences as a part of risk analysis (Ackermann et al., 2007). The interdependences, as one of important elements of defining project complexity (Baccarini, 1996), make projects are becoming increasingly complex (Loch and Terwiesch, 1998; Archer and Ghasemzadeh, 1999; Williams, 1999). With the growing complexity of projects, more and more issues in decision-making about the prioritization of risks and development of the strategies may arise (Marle et al., 2013). Thus, it can be said that if the risk interdependences can be correctly analyzed, the project managers will be able to make more effective risk response decisions (Kwan and Leung, 2011).

In this paper, we firstly provide an approach to measuring risk interdependence. The approach avoids the need to moderate divergences in evaluations of different experts or test the consistency of the evaluation results. Further, we propose an optimization model considering the risk interdependence and its

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two directions for selecting risk response strategies. On the basis of these, we can investigate the effects of the risk interdependence on the decisions about project risk response. The computation results and discussions through a case study show that the expected utility is more sensitive to the risk interdependence itself than to the directions of it. Moreover, more attention paid to the risk interdependence can increase the expected utility and reduce the implementation cost. The numerical and analytical results indicate that, in practical PRM, it is important to understand the interdependences between project risks.

The remaining of this paper starts from reviewing the previous studies related to the risk interdependence and project risk response. Then it moves to an introduction of the formulae and properties of the strength of risk interdependence. Subsequently, we propose an optimization model for selecting risk response strategies considering the risk interdependence. Thereafter, the application of the proposed methodology to an engineering project is illustrated and related results and discussions are here reported. Conclusions and perspectives appear in the last section.

2. Literature review

2.1. Relevant literature on risk interdependence

Project execution is always accompanied by risks and the studies on project risks and risk interdependence have always been the topics of concern in academia and practice. Some scholars study on the project risk interdependence from qualitative perspectives. Badenhorst and Eloff (1994) consider the risk dependence as one of the risk factors in the process of IT risk management. Adner (2006) points out that the success of a company's growth strategy hinges on the assessment of the ecosystem's risks of the company. And the ecosystem is characterized by three fundamental types of risks: initiative risks, interdependence risks and integration risks. Ackermann et al. (2007) develop the 'Risk Filter' which is a tool to evaluate risks in projects considering the interaction between risks as a part of risk analysis. The 'Risk Filter' has been used on many projects since its introduction. Kwan and Leung (2011) propose methods to estimate risks by taking account of risk dependence effects, and risk response strategies focusing on risk dependences should also be developed. Correa-Henaoa et al. (2013) describe a methodology for risk management in electricity infrastructures considering interdependences between the infrastructure assets. Cavallo and Ireland (2014) advocate the need for disaster preparedness strategies using a networked approach which can deal with interdependent risk factors. Besides, in the context of project portfolios, Keisler and Linkov (2010) describe what makes a set of risks worth considering as a portfolio. And they further point out that the ignorance of important risk interdependences can lead to underestimating the remaining portfolio risks or overlooking ways to eliminate more risks with a fixed budget, or otherwise getting the wrong answer. Teller (2013) points out that project risk management alone is insufficient in the context of project portfolios, and it is necessary to understand the interdependences and cross-portfolio risks within the project portfolio. An empirical investigation is also applied to show that it is necessary and important to understand the interdependences between projects and their risks for project portfolio success (Teller and Kock, 2013). Pajares and López (2014) argue that new methodologies should be developed in order to deal with project-portfolio interactions in terms of risk, schedule or cash-flow.

In addition, there are approaches quantitatively assessing risk interdependences, which can be mainly classified into the following categories: the Monte Carlo simulation approach, the nature language assessment approach, the matrix-based approach and the Delphi-based approach. The Monte Carlo simulation approach is mainly used to establish interdependence among different project risks (Rao and Grobler, 1995; Touran and Wiser, 1992). However, some major shortcomings have been mentioned (Wirba et al., 1996): the linear correlation is assumed to establish interdependences between random variables, but the linear correlation does not completely account for the interdependencies; it is not always practical to estimate the correlation because of the lack of readily available data, and the correlations are best used in situations where the necessary relationships must be developed empirically while this is hardly ever the case in risk analysis. To overcome these shortcomings, linguistic variables are used to assess the interdependence (Wirba et al., 1996). In the assessment process, linguistic variables have to be transformed into fuzzy numbers because the algorithms are designed to handle the mathematics of fuzzy set operations. After the computation, the obtained fuzzy numbers need to be transformed into linguistic variables once again since the results are difficult to understand. It can be seen that there are loss of information in the transformation. In recent years, the approach based on Design Structure Matrix (DSM) (Steward, 1981) which represents relations and dependences among objects, is developed (Fang and Marle, 2012; Fang et al., 2012, 2013; Marle and Vidal, 2011; Marle et al., 2013). The core of the approach is to capture and represent project risk interdependences by building up matrices. The approach mainly includes two steps. First, a binary matrix representing the existence of potential interdependence between each pair of risks is built. Secondly, the binary matrix is transformed into a numerical one to assess the strength of risk interdependence, in which a Likert scale using expert judgments or the Analytic Hierarchy Process (AHP) (Satty, 1980) is used. The last approach is based on the Delphi technique (Linstone and Turoff, 1975). In the approach (Aloini et al., 2012a, 2012b), questionnaire respondents are asked to assess the strength of interdependence among the risks. Then the experts' judgments are elaborated in order to define a unique map of relationships and the process is reiterated until a consensus is reached although it takes time to reach the consensus.

The above approaches have made significant contributions to risk interdependence analysis. However, from quantitative perspectives, there are some limitations in the existing approaches. For example, 0 and 1 are used to indicate whether the interdependence exists between two risks in the matrix-based approach and Delphi-based approach. This could lead to underestimation for relatively weak interdependence and overestimation for relatively strong interdependence. And it would be somewhat unrealistic that the complex risk interdependence is assigned either a numerical value in the matrix-based approach and Delphi-based approach or a linguistic variable in the nature language assessment approach. In addition, since different experts may get outcomes with differences in the process of assessment and they would rarely move far from their initial views, it could be difficult or even impossible to moderate this kind of confusion and divergence. In this paper, we try to propose an approach which can quantitatively measure the risk interdependence without the need to moderate the divergences in evaluations of different experts or test the consistency of the evaluation results.

2.2. Relevant literature on project risk response

It can be seen that some scholars have paid attention to the portfolio selection of risk response strategies from different perspectives (Hatefi and Seyedhoseini, 2012). The approaches involved in the existing studies can be mainly classified into four categories (Zhang and Fan, 2014): the zonal-based approach, the trade-off approach, the WBS-based approach and the optimization-model approach. Among the above methods, most closely related to this work is the stream of literature on the optimization-model approach. Therefore, the brief descriptions and comments on these optimization-model approaches will be given as follows.

Ben-David and Raz (2001) firstly put forward an optimization model aiming to minimize the sum of expected risk loss and risk response cost for obtaining the optimal risk response strategies. The main contribution of this work is in demonstrating that a practical and common problem can be treated with mathematical models. The above work is extended considering the interactions among risk response strategies as model constraints in (Ben-David et al., 2002). Kayis et al. (2007) develop a risk response selection model which minimizes the difference between the upper bound mitigation cost/risk ratio and the mitigation cost/risk ratio generated from the project within the limited budget. Fan et al. (2008) construct a mathematical model for selecting risk response strategies based on the analysis of the relationship between risk response strategies and relevant project characteristics. The model is to minimize the sum of risk-prevention and risk-adaptation costs under the acceptable risk level. Fang et al. (2013) construct a mathematical model to solve the risk response strategy selection problem. In the model, the budget requirement, response effect and risk response cost are considered in the objective function. And, two parameters are introduced into the objectives: one is to balance the tradeoff between the budget and response effect, and the other is to reflect the project manager's degree of aversion to budget overruns. Besides the risk response cost, budget constraints, and expected risk loss considered in the above studies, project time and project quality are included in the following models. Nik et al. (2011) propose a multi-objective model to determine the optimum set of risk response strategies. In the model, risk response cost, expected time loss and expected quality loss are respectively minimized as three objectives, and the three objectives are changed into a single one by assigning the weight to each objective. Zhang and Fan (2014) propose a WBS-based integrated mathematical programming model aiming to maximize the estimated risk response effects which considers project cost, project schedule, project quality and the trade-offs among them simultaneously.

Among the above literature, the methods for selecting project risk response strategies assume that the risks are independent, apart from one presented in Fang et al. (2013). Fang et al. (2013) propose a framework for risk response strategy selection considering the risk interactions, and the DSM method mentioned above is applied to identify the risk interactions. In their work, however, the effect of the risk interactions on the project risk response decisions is not analyzed, which produces a space guiding us to make deep thinking and conduct a further study in this aspect. In this study, we will try to fill this gap by proposing an optimization model for selecting risk response strategies and further analyze the effects of the risk interdependence on decisions about project risk response.

3. Methodology

In this section, we firstly provide an approach to measuring risk interdependence, in which the evaluations on the risk interdependence by all experts can be regarded as a discrete random variable with probability distribution and then the strength of risk interdependence can be measured by comparing the random variables. The approach avoids the need to moderate divergences in evaluations of different experts or test the consistency of the evaluation results. Further, we construct an optimization model for selecting risk response strategies considering the risk interdependence and its two directions. One direction of the risk interdependence refers to the situation that the risk takes precedence over other risks, and the other direction refers to the situation that other risks take precedence over this risk. The above work can lay the foundation for analyzing the effects of the risk interdependence on the decisions about project risk response in the next section.

3.1. Risk interdependence analysis

Risk identification, usually the first step for project risk analysis, is the process of determining risk events which could affect project objectives negatively or positively (PMI, 2008). Our study directly uses the set of risk events $R=\{R_1,\ldots,R_n\}$ previously identified by the project manager (PM) and his or her team, in which R_j is the jth risk event, $j=1,\ldots,n$. A risk event has two substantial attributes; these are the probability of occurrence and the impact, and the expected loss of the risk event can be defined as the product of the probability and the impact (Kwan and Leung, 2011). Here, we assume that the risks have been identified and analyzed, and the results of risk identification and risk analysis can directly serve as inputs for risk response analysis.

The risk interdependence is defined as the existence of a possible precedence relationship between two risks R_i and R_j (Fang et al., 2012; Marle et al., 2013). The analysis of the risk interdependence is performed on a direct link that means that there is no intermediary risk between the two risks (Fang et al., 2012). For example, when there is interdependence between risks *R1* and *R3* because *R1* is linked to *R2* and *R2* is linked to *R3*, this kind of interdependence is called indirect and it is not necessary to formalize interdependence between risks *R1* and *R3*. On the contrary, the interdependence between *R1* and *R3* is replaced by two direct interdependences, i.e., *R1* and *R2*, and *R2* and *R3*. In addition, the effect of the risk interdependence refers to an effect of one risk on the other risk arising from the direct interdependence. Specifically, there are two kinds of effects of risk interdependences considered in the paper which are unfavorable effects and favorable effects. The unfavorable effect will increase the expected loss by increasing the probability and/or the impact of the other risk, while the favorable effect will reduce the expected loss by lowering the probability and/or the impact of the other risk.

The experts with expertise and experience are generally invited for analyzing the risk interdependences since every new project is essentially unique with no previous data on it. The experts are firstly required to judge if there exist the risk interdependences between any two risks, and determine that the risk interdependences are favorable or unfavorable. Next, the strength of the risk interdependences needs evaluating. In practice, the experts often evaluate the strength of risk interdependence using phrases such as "*slightly weak*" or "*very strong*" for this kind of evaluation information is in the form of human language which can be naturally and easily expressed. For quantitative analysis of the risk interdependence, let $E=\{E_1,\ldots,E_l\}$ be a set of experts and $S=\{s_0,s_1,\ldots,s_T\}$ be a finite and totally ordered discrete linguistic term set with odd cardinalities in which $s_i>s_j$ $(s_i,s_j\in S)$ iff $i>j$ (Bordogna et al., 1997). The linguistic term s_0 can also be regarded that almost no interdependent relationship exists between the two risks. Each expert gives evaluations on interdependent relationship from R_i to R_j using the linguistic scale, where $R_i,\ R_j\in R$. The evaluation on the interdependence from R_i to R_j by expert E_k is denoted as x_{ij}^k, which satisfies $x_{ij}^k\in S$, $i,j=1,\ldots,n$, $i\neq j$, and $k=1,\ldots,l$. Further, the evaluations on the interdependence from R_i to R_j by all the experts can be denoted as X_{ij}. The vector X_{ij} can be regarded as a discrete random variable with probability distribution $f_{ij}(x)$, where $\sum_{x=s_0}^{s_T} f_{ij}(x)=1$. A brief example below can make this easier to understand.

Example 1. Suppose that five experts are invited to analyze the risk interdependences with respect to three risks (R1, R2, R3) using a linguistic seven-term scale, i.e., $S=\{s_0=$ Very Weak (VW), $s_1=$ Weak (W), $s_2=$ Slightly Weak (SW), $s_3=$ Medium (M), $s_4=$ Slightly Strong (SS), $s_5=$ Strong (S), $s_6=$ Very Strong (VS)$\}$. By analyzing the three risks, the experts determine that there exist risk interdependences between risks R1 and R2, and the effect of R1 on R2 is favorable and that of R2 on R1 is unfavorable. From the evaluations on the interdependence from R1 to R2, it can be generalized that the evaluation VW is provided by three experts, W by one expert, and SW by one expert. Similarly, the evaluations on the interdependence from R2 to R1 are: VW is provided by two experts, SW by one expert, M by one expert, and SS by one expert. Thus, the probability density functions $f_{12}(x)$ and $f_{21}(x)$ can be obtained as follows, respectively.

$$f_{12}(x)=\begin{cases}3/5, & x_{12}=VW\\ 1/5, & x_{12}=W\\ 1/5, & x_{12}=SW\\ 0, & x_{12}=M\\ 0, & x_{12}=SS\\ 0, & x_{12}=S\\ 0, & x_{12}=VS\end{cases},\ f_{21}(x)=\begin{cases}2/5, & x=VW\\ 0, & x=W\\ 1/5, & x=SW\\ 1/5, & x=M\\ 1/5, & x=SS\\ 0, & x=S\\ 0, & x=VS\end{cases}. \square$$

In practice, the interdependent relationship between risks is complex; meanwhile it is probable that the evaluations are divergent due to experts from multiple departments with different expertise and previous experience. More specifically, the evaluations in reverse direction between R_i and R_j may probably exist, i.e., the evaluations from R_j to R_i. Thus, we need to know which risk should be prioritized and the relative importance of each risk in project risk response. For this purpose, the strength of risk interdependence of R_i over R_j (or R_j over R_i) needs to be measured.

The strength of risk interdependence can be known by calculating the probabilities of $X_{ij}>X_{ji}$ and $X_{ij}<X_{ji}$. From the above analysis, it can be seen that X_{ij} and X_{ji} can be regarded as two independent discrete random variables, that is to say, there is no inherent relation between the evaluations from R_i to R_j and those from R_j to R_i. Further, the probability distributions of X_{ij} and X_{ji} are denoted as $f_{ij}(x)$ and $f_{ji}(x)$, respectively, where $\sum_{x=s_0}^{s_T} f_{ij}(x)=1$ and $\sum_{x=s_0}^{s_T} f_{ji}(x)=1$. Let x_{ij} and x_{ji} be outcomes of X_{ij} and X_{ji}, respectively. Here, event $x_{ij}=x_{ji}$ can be regarded as a situation where events $x_{ij}>x_{ji}$ and $x_{ij}<x_{ji}$ occur with the same probability simultaneously, i.e., in the situation of $x_{ij}=x_{ji}$, the probability that events $x_{ij}>x_{ji}$ and $x_{ij}<x_{ji}$ occur is 0.5. Based on the above analysis, we give Definition 1, and Properties 1 and 2 (Liu et al., 2011).

Definition 1. Let X_{ij} and X_{ji} be two independent discrete random variables with probability distributions $f_{ij}(x)$ and $f_{ji}(x)$, respectively, where $\sum_{x=s_0}^{s_T} f_{ij}(x)=1$ and $\sum_{x=s_0}^{s_T} f_{ji}(x)=1$. Then the strength of risk interdependence denoted as D_{ij} is given by

$$D_{ij}=\sum_{x_{ij}=s_0}^{s_T}\sum_{x_{ji}=s_0}^{x_{ij}} f_{ij}(x_{ij})f_{ji}(x_{ji})-0.5\sum_{x_{ij}=s_0}^{s_T} f_{ij}(x_{ij})f_{ji}(x_{ij}), \tag{1}$$

and accordingly, the strength of risk interdependence denoted as D_{ji} is given by

$$D_{ji}=\sum_{x_{ij}=s_0}^{s_T}\sum_{x_{ji}=x_{ij}}^{s_T} f_{ij}(x_{ij})f_{ji}(x_{ji})-0.5\sum_{x_{ij}=s_0}^{s_T} f_{ij}(x_{ij})f_{ji}(x_{ij}). \tag{2}$$

The strength of the risk interdependence in the above equations can be regarded as the probability that the possible outcome of one random variable is greater than the other. Thus, the following properties can be easily found.

Property 1. $D_{ij}+D_{ji}=1$.

Property 2. $0\le D_{ij}\le 1$ and $0\le D_{ji}\le 1$.

The following example can be used to show how to calculate the strength of risk interdependence.

Example 2. Using the probability density functions $f_{12}(x)$ and $f_{21}(x)$ obtained in Example 1, the strength of risk interdependence of R1 over R2 (denoted as D_{12}) can be calculated by Eq. (1) as follows.

$$D_{12}=\frac{3}{5}\times\frac{2}{5}+\frac{1}{5}\times\frac{2}{5}+\frac{1}{5}\times\left(\frac{1}{5}+\frac{2}{5}\right)-0.5\times\frac{3}{5}\times\frac{2}{5}-0.5\times\frac{1}{5}\times\frac{1}{5}=0.3.$$

Similarly, the strength of risk interdependence of *R2* over *R1* (denoted as D_{21}) can be calculated by Eq. (2), and $D_{21}=0.7$. □

Further, let D_j be the strength of risk interdependence of risk R_j when risk R_j takes precedence over other risks, and D_j can be defined as

$$D_j=\eta\frac{1}{\left|\tau_j^-\right|}\sum_{\substack{i=1\\R_i\in\tau_j^-}}^{n}D_{ji}+(1-\eta)\frac{1}{\left|\tau_j^+\right|}\sum_{\substack{i=1\\R_i\in\tau_j^+}}^{n}D_{ji},\tag{3}$$

where $0\le D_j\le 1$, and the parameter η denotes the importance degree of the unfavorable risk interdependence relative to the favorable risk interdependence which satisfies $\eta\in[0,1]$. The set τ_j^- is composed of all the risks which risk R_j takes precedence over and the effects of the risk interdependences are unfavorable, and $|\tau_j^-|$ denotes the number of elements in the set τ_j^-. Similarly, the set τ_j^+ is composed of all the risks that risk R_j takes precedence over and the effects of the risk interdependences are favorable, and $|\tau_j^+|$ denotes the number of elements in the set τ_j^+. The set τ_j^- or τ_j^+ can be the empty set $\varnothing$ if there are no unfavorable or favorable risk interdependences with respect to risk R_j. And accordingly, let $\overline{D}_j$ be the strength of risk interdependence of risk R_j when other risks take precedence over risk R_j, and $\overline{D}_j$ can be defined as.

$$\overline{D}_j=\gamma\frac{1}{\left|\upsilon_j^-\right|}\sum_{\substack{i=1\\R_i\in\upsilon_j^-}}^{n}D_{ij}+(1-\gamma)\frac{1}{\left|\upsilon_j^+\right|}\sum_{\substack{i=1\\R_i\in\upsilon_j^+}}^{n}D_{ij}.\tag{4}$$

where $0\le\overline{D}_j\le 1$, and the parameter γ denotes the importance degree of the unfavorable risk interdependence relative to the favorable one which satisfies $\gamma\in[0,1]$. The set υ_j^- is composed of all the risks that take precedence over risk R_j and the effects of the risk interdependences are unfavorable, and $|\upsilon_j^-|$ denotes the number of elements in the set υ_j^-. Similarly, the set υ_j^+ is composed of all the risks that take precedence over risk R_j and the effects of the risk interdependences are favorable, and $|\upsilon_j^+|$ denotes the number of elements in the set υ_j^+. The set υ_j^- or υ_j^+ can be the empty set $\varnothing$ if there are no unfavorable or favorable risk interdependences with respect to risk R_j.

Example 3. It is assumed that there also exist risk interdependences between risks R2 and R3 in Example 1, and the effect of R2 on R3 and that of R3 on R2 are both unfavorable. Thus, the strength of risk interdependences D_{23} and D_{32} can be calculated by Eqs. (1) and (2), respectively, and the calculation results are $D_{23}=0.8$ and $D_{32}=0.2$. Taking risk R2 for instance, D_2 and $\overline{D}_2$ can be obtained below by Eqs. (3) and (4), respectively.

$$D_2=\eta\frac{1}{2}(D_{21}+D_{23})=\eta\cdot 0.75,\overline{D}_2=\gamma D_{32}+(1-\gamma)D_{12}$$
$$=\gamma\cdot 0.2+(1-\gamma)\cdot 0.3.\ \square$$

3.2. Risk response analysis

3.2.1. Constructing the optimization model

For the convenience of quantitative analysis, the notations are firstly given below. Let b_j be the expected loss of the risk event R_j, and the expected loss b_j is the product of the likelihood of occurrence and severity of the impact of R_j. In order to mitigate the expected loss of each risk, candidate risk response strategies must be proposed and selected to cope with the risks in the project implementation. When the response strategies are formulated, the cost of implementing each strategy and the risk response effect after implementing the strategies need to be estimated. Let $A=\{A_1,\ldots,A_m\}$ be the set of candidate risk response strategies and c_h be the cost of implementing risk response strategy A_h, $h=1,\ldots,m$. Let a_{hj} be the estimated risk response effect (i.e., reduced expected loss of the risk event) after implementing risk response strategy A_h to cope with risk event R_j. The budget is the most basic guarantee for the PM to complete risk response tasks successfully, and let B be the budget for implementing risk response strategies.

Thus, an optimization model for selecting risk response strategies is constructed considering risk interdependence as follows.

$$V(y)=E[U(y)]=\sum_{h=1}^{m}\sum_{j=1}^{n}w_jU\left(y_{hj}\right),\tag{5}$$

$$\text{s.t.}\quad\sum_{h=1}^{m}\left(c_h\max_j y_{hj}\right)\le B,\tag{6}$$

$$y_{hj}\in\{0,1\}.\tag{7}$$

where y_{hj} is the binary integer decision variable, and y_{hj} is equal to 1 if risk response strategy A_h is implemented for risk event R_j and otherwise y_{hj} is equal to 0. In the model, objective function (5) aims at maximizing the PM's expected utility. Constraint (6) ensures that the cost of implementing risk response strategies meets the budget requirement, and " $\max_j$ " in constraint (6) can guarantee that the cost of implementing each risk response strategy cannot be counted more than once. Constraint (7) is a binary mode indicator.

In the following, the utility function $U(y_{hj})$ and weighting function w_j in the objective function (5) will be explained in detail, respectively.

3.2.2. Determining the utility function

In the above model, the optimization goal is to maximize the PM's expected utility. The PM's risk attitude is supposed to be risk aversion in this paper and a concave utility function is used since the concavity of the utility function may imply that the PM is risk averse. In project risk management, the PM needs to take measures to cope with the risks. The risks in projects that the PM intends to deal with, unlike those in gambling and lottery, are generally negative and manageable (March and Shapira, 1987), and the PM expects to gain benefits from implementing risk response strategies. Thus, the individual generally appears to be risk averse in the situation that possible outcomes of risky actions are generally good (Kahneman and Tversky, 1979) except for special cases. In some special cases, the PM's risk attitude may not be risk averse, for instance, the organization or project is "failing", the manager's own position or job is threatened (MacCrimmon and Wehrung, 1986). Among the concave utility functions, exponential utility can "satisfactorily treat a wide range of individual and corporate risk preference" (Howard, 1988), and indeed exponential utility is commonly used in decision analysis (Tsetlin and Winkler, 2005). Therefore, the exponential utility function which exhibits constant absolute risk aversion is used in this paper.

Thus, the utility function $U(y_{hj})$ in the objective function (5) can be expressed as follows.

$$U\left(y_{hj}\right) = 1 - e^{-\alpha\left(y_{hj}a_{hj}\right)}, \tag{8}$$

where $U(y_{hj})$ denotes the subjective assessment of the risk response effect $y_{hj}a_{hj}$. The parameter α is the coefficient of absolute risk aversion. In the light of a rule of thumb (Howard, 1988), the risk tolerance (the reciprocal of absolute risk aversion) tends to be about one-sixth of equity. Without loss of generality, $U(y_{hj})$ equals 0 at the zero point of $y_{hj}a_{hj}$, and $U(y_{hj})$ approaches 1 as $y_{hj}a_{hj} \to \infty$.

3.2.3. Defining the weighting function

The weighting function w_j denotes the severity of risk R_j, and satisfies $w_j \in (0, 1)$. In this paper, it is assumed that the severity of risk is related to two attributes: the strength of risk interdependence and expected loss of the risk. In the risk interdependence, two directions of the risk interdependence are both considered, i.e., the strength D_j when the risk R_j takes precedence over other risks and strength $\overline{D}_j$ when other risks take precedence over the risk R_j. Thus, the weighting function w_j can be expressed as follows.

$$w_j = \lambda\left(\theta D_j + (1-\theta)\overline{D}_j\right) + (1-\lambda)\frac{b_j}{\sum_{j=1}^{n} b_j}, \tag{9}$$

where the parameter λ denotes the importance degree of the risk interdependence relative to the normalized expected loss, and satisfies $\lambda \in [0, 1]$, and the parameter θ denotes the importance degree of the strength D_j, and satisfies $\theta \in [0, 1]$. Besides, $\frac{b_j}{\sum_{j=1}^{n} b_j}$ is the normalized expected loss since the expected loss and strength of risk interdependence are incommensurate.

Based on the above analysis, a research framework for project risk response decisions considering the risk interdependence is shown in Fig. 1.

4. Case study

In this section, we will show a substation renovation engineering project to illustrate the proposed approach to solving the problem of risk response strategy selection considering the risk interdependence. And we try to investigate the impact of the risk interdependence on the expected utility, costs of implementing strategies and risk response strategy selection.

4.1. Problem description and analysis

The substation was put into operation in 1996. Since the substation had been running for 18 years, the aging equipments made maintenance costs increasing and security risks more and more serious. Thus, the equipment reform and substation renovation become necessary and urgent. In the initial phase of the substation renovation project, an expert panel is established to evaluate project risks and risk interdependences. The expert panel includes fourteen experts, in which two experts on PRM, two experts on safety and quality management, two experts on substation maintenance, two experts on relay protection, two experts on high voltage electrical testing, one expert on vehicle management, one expert on contract management, one expert on electrical design, and one expert on civil design. By conducting a thorough analysis of the project and a brainstorming session, critical risk events are identified. Then, expected losses of the identified risks are estimated based on historical data and the experts' experiences and judgments. The project risks and expected losses of them in monetary form are shown in Table 1.

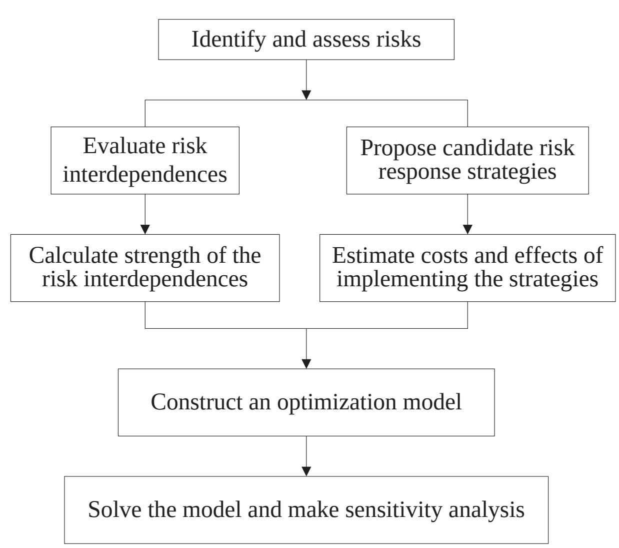

Fig. 1. Research framework.

Table 1
Project risk list.

Risk (R_j)	Expected loss (k$) ($b_j$)
Unqualified installation or construction craft (R_1)	665.04
Inferior quality of the goods and materials (R_2)	432.96
Substandard concrete construction (R_3)	181.08
Potential risk on traffic safety (R_4)	103.48
Delay in equipment delivery to the site (R_5)	264.36
Manpower shortage in the construction peak (R_6)	4.09
Accidentally touching the charged interval (R_7)	18.83
Special weather during the construction (R_8)	984
Disqualification of parameter debugging in the relay protection (R_9)	602.64
Personnel electric shock and injury (R_{10})	21.52
Misuse of new materials, new craft and new technology (R_{11})	32.96
Insufficient power supplies for major international conferences or events (R_{12})	22.44
Incompetent technical personnel when facing complex cases (R_{13})	132.24
Construction funds not in place timely (R_{14})	63.12
Bad inspection of the construction site (R_{15})	678
Unsuitable construction technology scheme (R_{16})	1140
Omissions and mistakes in the design drawing (R_{17})	670.56

Further, the risk interdependent relationships between the risks are basically confirmed based on the analysis and discussion by the experts, and the effects of the risk interdependences are determined to be unfavorable. Then, each expert is asked to give evaluations on the interdependent relationships between the risks using a linguistic seven-term scale, i.e., S={s_0= Very Weak (VW), s_1= Weak (W), s_2= Slightly Weak (SW), s_3= Fair (F), s_4= Slightly Strong (SS), s_5= Strong (S), s_6= Very Strong (VS)}. Thus, the strength of risk interdependence D_{ij} can be calculated using Eq. (1), and through Properties 1 and 2, we can know the value of D_{ji}. The project risk network based on the analysis of the strength of risk interdependence is built as shown in Fig. 2. Next, the strength of risk interdependences D_j and $\overline{D}_j$ can be obtained using Eqs. (3) and (4) when the values of parameters η in Eq. (3) and γ in Eq. (4) are determined.

On the basis of the analysis of the risk events and risk interdependences, the expert panel discusses and proposes 28 candidate risk response strategies according to their experiences

Table 2
Candidate project risk response strategies.

Proposed candidate risk response strategy (A_h)	Cost (k$) ($c_h$)
Reserving safety stock (A_1)	188.28
Signing a carriage contract with the logistics company with good credit standing (A_2)	78.42
Tracking the orders (A_3)	9.41
Developing contingency plans for labor shortage (A_4)	1.88
Making security cards (A_5)	0.94
Installing anti-misoperation devices (A_6)	0.38
Communicating with relevant departments (A_7)	0.14
Making the scheduling plan (A_8)	0.56
Hiring experienced site engineers (A_9)	244.8
Strengthening supervision of project quality (A_{10})	9.6
Taking preventive measures (A_{11})	12
Formulating emergency response plan (A_{12})	6
Improving the traffic safety management rules and regulations (A_{13})	5.76
Purchasing insurance (A_{14})	28.14
Setting up traffic safety facilities (A_{15})	25.8
Establishing safety incident emergency handling procedures (A_{16})	0.42
Enhancing safety awareness of construction site personnel by safety training (A_{17})	0.14
Providing PPE and the required training for its use (A_{18})	0.94
Installing leakage protectors (A_{19})	8.47
Establishing technical disclosure system (A_{20})	4.7
Doing well on-job training (A_{21})	6.24
Employing experienced practitioners (A_{22})	7.2
Developing financing channels (A_{23})	6.72
Reviewing and adjusting the scheme in time (A_{24})	36
Signing the supervision contract (A_{25})	306
Strengthening supervision and inspection (A_{26})	14.4
Taking remedial actions (A_{27})	18
Cooperating with large designing institute with strength (A_{28})	60

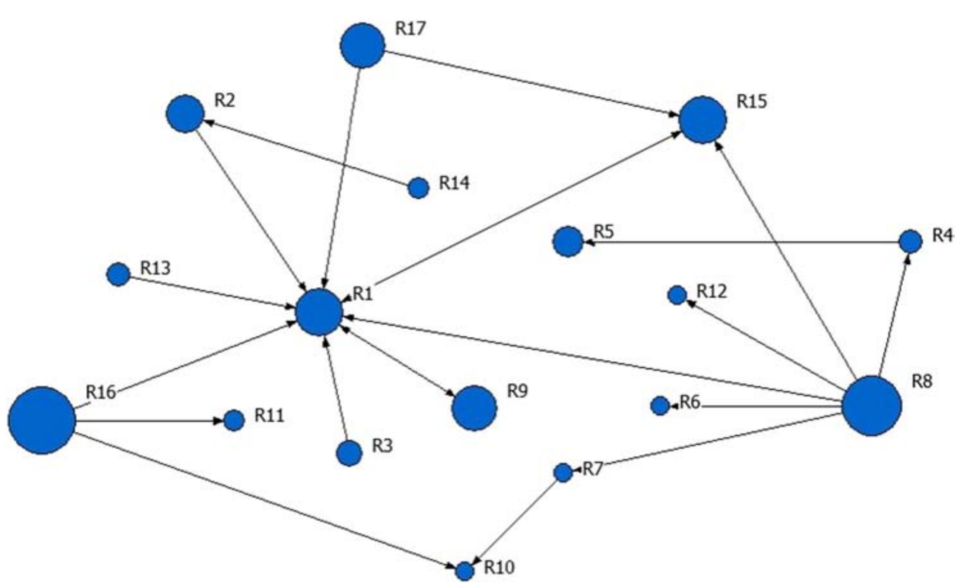

Fig. 2. Project risk network.

in similar projects or risk events before. The total budget or cost for implementing the strategies is no more than \$420K, and the parameter α is the reciprocal of one-sixth of the budget, i.e., $\alpha = 0.015$. Thus, Table 2 lists candidate risk response strategies and their estimated implementation costs. Furthermore, the estimated risk response effects after implementing the strategies in monetary form (K\$) based on the analysis of the risks and strategies are shown in Fig. 3. Lingo 14.0 is available and hence is used to solve the model. The results obtained by solving the given model as the parameters vary are presented in the following part.

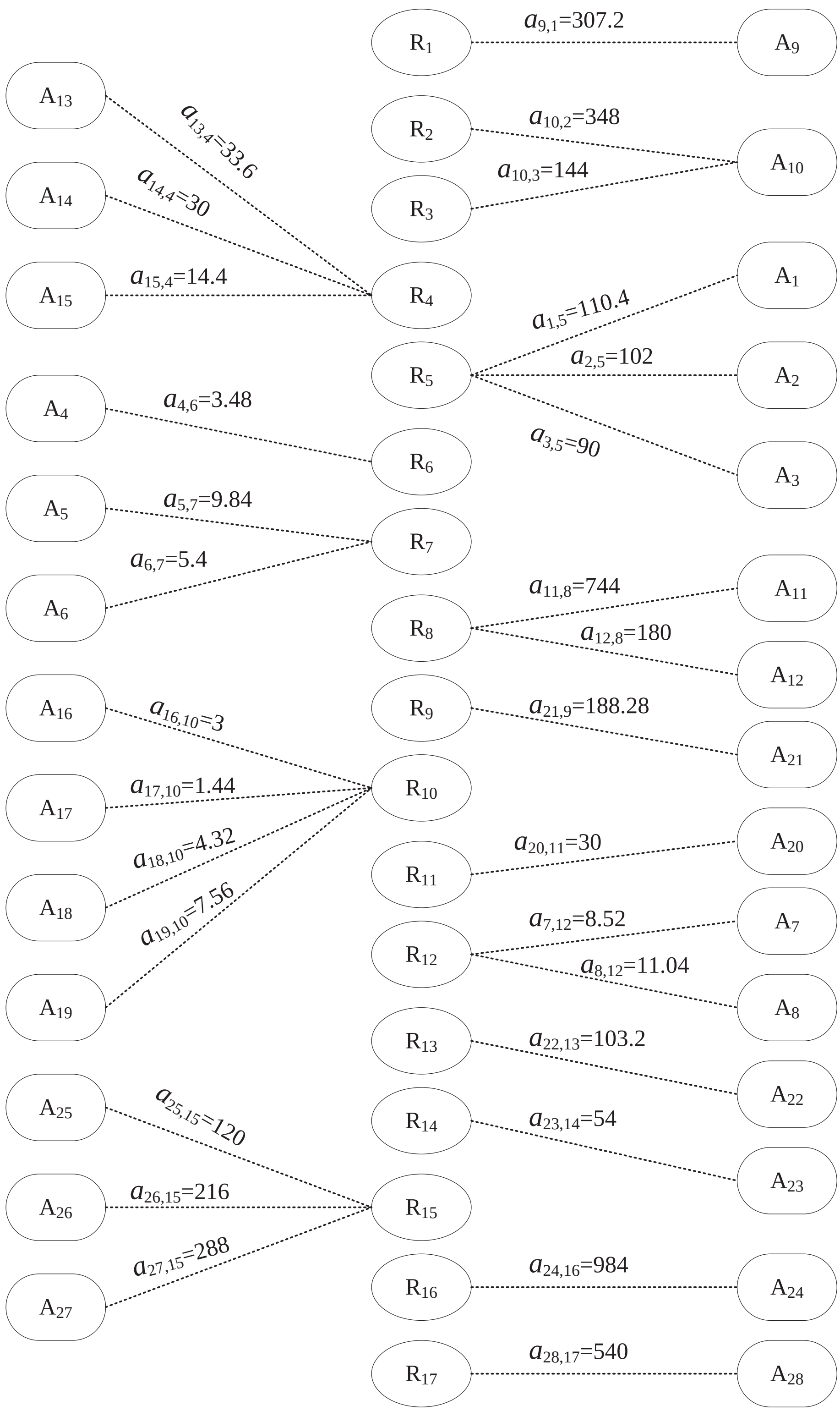

Fig. 3. Risk response effects.

4.2. Computational results and sensitivity analysis

In order to obtain the solutions to the model, we suppose that parameter η in Eq. (3) equals 1 since the effects of the risk interdependences in the project are unfavorable. Similarly, we suppose that parameter γ in Eq. (4) is equal to 1. Because different attentions paid to the risk interdependence and its directions can make the expected utility and the solution to the model different, the sensitivity analysis is performed as follows to elucidate the impact of parameter changes in λ and θ, respectively, on the robustness of the risk response effects.

Fig. 4 shows that the expected utility is sensitive to the variation of the parameter λ. Fig. 5 shows that the expected utility is sensitive to the variation of the parameter θ, and the sensitivity becomes more obvious as the value of λ gradually increases. By contrast, the slopes of the straight lines in Fig. 4 are greater than those of the lines in Fig. 5. From Fig. 6, it can be seen that the cost for implementing risk response strategies or the solution to the model is robust when λ and θ are, respectively, more than or equal to 0.04 and 0.3. The optimum solution to the model is $y_{1,5}=0$,$y_{9,1}=0$, $y_{25,15}=0$ and the other decision variables equal 1, respectively. Thus, the selected strategies are all the candidate strategies except A_1, A_9 and A_{25}, and the cost for implementing these strategies is \$285.237K and the maximum expected utility of 8.33 will be obtained. When λ and θ are, respectively, less than or equal to 0.03 and 0.3, the robustness is not good. For example, when λ and θ are, respectively, equal to 0.02 and 0.9, the cost for implementing risk response strategies increases to \$360.827K but the maximum expected utility decreases to 1.288. When λ and θ are, respectively, equal to 0.03 and 0, the solution to the model is $y_{9,1}=1$, $y_{10,2}=1$, $y_{10,3}=1$, $y_{13,4}=1$, $y_{11,8}=1$, $y_{12,8}=1$, $y_{21,9}=1$, $y_{22,13}=1$, $y_{26,15}=1$, $y_{27,15}=1$, $y_{24,16}=1$, $y_{28,17}=1$ and the other decision variables equal 0, respectively. Thus, the maximum expected utility decreases to 1.291 while the cost for implementing risk response strategies increases to \$360.827K.

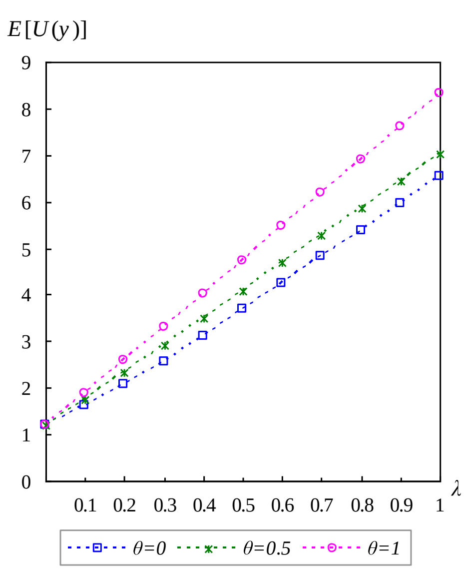

Fig. 4. The expected utility with different θ.

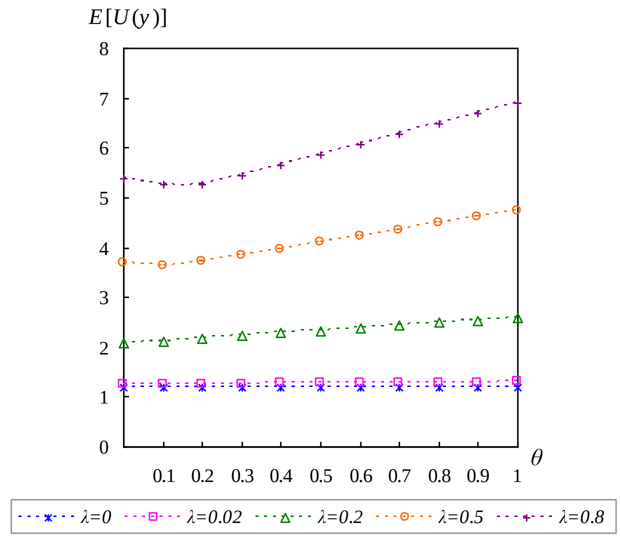

Fig. 5. The expected utility with different λ.

And the selected strategies are A_9, A_{10}, A_{11}, A_{12}, A_{13}, A_{21}, A_{22}, A_{26}, A_{27}, A_{24}, and A_{28}. This solution to the model is not feasible since risks R_7 and R_{14} are not coped with directly or indirectly.

In summary, as shown in Figs. 4 and 5, the expected utility is more sensitive to the variation of the parameter λ than to the variation of the parameter θ on the whole. It means that the PM should first put emphasis on the interdependent relationship and then the directions of the interdependence in PRM for achieving greater expected utility. Fig. 6 shows that the solution to the model is robust when the value of λ is not particularly small. It also implies that more attention paid to the risk interdependence can lower the cost of implementing the risk response strategies.

4.3. Feedback and discussion

In order to carry out more effective project risk management, a feedback session was conducted to allow the PM and his team to review the computation results. During a two-hour session, we collected feedback through careful recording of the participants' reactions, responses, questions, and discussions. Participants' feedback on three main topics is presented below.

(1) The interpretation of the risk interdependence. The confusions and queries came primarily from the risk network (Fig. 2) and calculation of the risk interdependences. Some participants felt confused about the sizes of the circles in Fig. 2. Specifically, at first sight, the participants were very likely to consider that the larger circle indicated the higher level of the risk interdependence. In face of such misunderstanding, the researchers explained to the participants that the circle represents the risk and the size of the circle is related to the expected loss of the risk. The larger the size of the circle is, the higher the expected loss of the risk will be. The interdependent relationship is represented by the line and the direction of the interdependence is represented by the arrow. In addition, some participants also questioned the

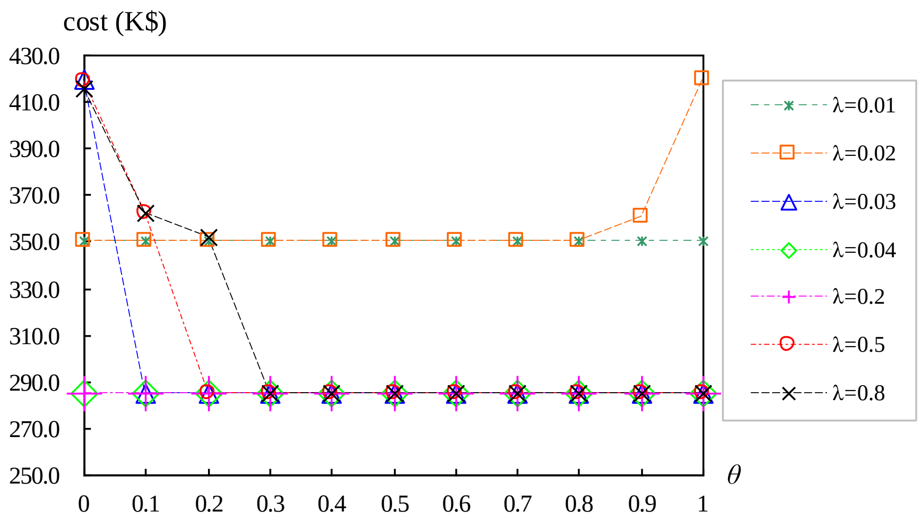

Fig. 6. The implementation cost with different λ.

calculation of the strength of the risk interdependence. For example, one participant said, "*I've noticed that in the network, some risk is intertwined with several other risks, but there're only two numerical values available with respect to the risk. How do you obtain the values?*" With regard to this question, the researchers explained in detail the calculation principle and process. The approach considers two directions of each risk interdependence. One direction of the risk interdependence refers to the situation that the risk takes precedence over other risks, and the other direction refers to the situation that other risks take precedence over this risk. The strength of the risk interdependence can be obtained by aggregating the experts' opinions in both directions, respectively. Through effective communication, the participants finally showed appreciation for our efforts. Some participants acknowledged that the phenomena of the risk interdependence do exist, but they did not consider the interdependence when they dealt with the risks in practice. According to the collected feedback, we noticed that one participant was quite impressed by the work. "*This network shows us the relationship between the risks intuitively. Besides, the network and the calculated strength of the risk dependence make me easily find out major risks so as to avoid greater loss*", said one participant.

(2) The effects of the risk interdependence. The participants agreed that most PMs are risk-averse in project risk management, and they approved that the risk response strategies obtained by solving the optimization model are necessary and feasible. However, they questioned that many selected strategies could also be implemented without consideration of the risk interdependence. With regard to this question, the researchers gave the relatively detailed explanation of the results shown in Figs. 4, 5 and 6. As shown in Figs. 4 and 5, the PM should put emphasis on the risk interdependence and the directions of the interdependence in PRM for achieving greater expected utility. Further, more attention paid to the risk interdependence can lower the cost of implementing the risk response strategies as shown in Fig. 6. The participants finally acknowledged that the model indeed can provide a quantitative decision support for their practical work, and expressed their opinions respectively. For instance, one participant said, "*The strategies A_{14}, A_{19} and A_{20} are indispensable for coping with the corresponding risks, but they don't get selected by solving the model when the attention to the risk interdependence is insufficient.*"

(3) The implementation of the method. With regard to the implementation of the approach, there are three main questions from the participants. The first question is how to calculate the strength of the risk interdependence since the equations look a bit complicated. The second one is how to solve the optimization model. The last one is whether the research results are applicable to all projects. With respect to the first two questions, the researchers explained that the simple program and commercial solver are easily available to them. The researchers also suggested that a decision support system (DSS) should be developed for project risk response. With respect to the last question, the researchers explained that similar conclusions were obtained from the study of one engineering project and one IT project previously. However, it is not sure whether the research results are applicable to all projects since the general conclusions from analytical solutions still need to be obtained in future studies.

5. Conclusions and perspectives

With the growing complexity of projects, phenomena of the risk interdependence become more universal. In this study, an approach to measuring risk interdependence is given, and then an optimization model considering the risk interdependence and its two directions for selecting risk response strategies is constructed. The computation results of the model as the parameters vary show that the risk interdependence has significant effects on decisions on risk response. The contributions of this paper are discussed as follows.

In the proposed methodology, the approach to calculating the strength of risk interdependence is firstly given. The approach for measuring the risk interdependence avoids the need to moderate divergences in evaluations of different experts or test the consistency of the evaluation results. For selecting risk response strategies and further investigating the effects of the risk interdependence on the decisions about project risk response, an integer programming model is constructed. In the model, we consider the expected risk loss, risk interdependence and its two directions by defining the weighting function. The computation results obtained by solving the given model through a case project demonstrate the necessity of the consideration of the risk interdependence in risk response analysis in pursuit of individual utility and organizational benefits maximization. Furthermore, it can be found that each risk response strategy can cope with multiple risk events, and on the other hand each risk event can be considered through several risk response strategies.

The management implication for practitioners in PRM is that the PM should first attach great importance to the risk interdependence and then put more emphasis on the risks that take precedence over others in the project system. The insufficient attention paid to or neglect of the risk interdependence would lower the expected utility, increase the implementation cost and even affect the overall benefits from project risk management.

The limitation of the study is that the results are obtained from the case project. It would be better to sum up the general conclusions on the impact of the risk interdependence on project risk response decisions, which needs to be studied with greater depth in the next step. Besides, the PM's risk attitude is assumed to be risk aversion and the exponential utility function is used in this paper. Although it is true in most situations from the perspective of behavior analysis, as previously mentioned, the PM's risk attitude may not be risk averse in some special cases. Therefore, in the situations of different risk attitudes and utility functions, the conclusions need to be further verified. In addition, it is worth considering whether the effects of a risk on all the other risks are favorable when the risk could affect the project objectives positively. It can be seen that, from the existing studies, the effects of a risk which could affect the project objectives negatively on the other risk are generally unfavorable. However, in actual projects, it is still common that the positive risks are not adequately managed, let alone their interdependent relationships with other risks. Therefore, more empirical field work is needed to study the positive risks and their interdependences.

In general, we believe that this work provides an important building block for project risk response decisions. The simplicity and computational ease of the proposed approach to measuring the risk interdependence make it promising for practical application to improve the effectiveness of project risk management. It is expected that the proposed methodology can be applicable to a wide set of engineering projects for risk management.

Conflict of interest

The author declares that there is no conflict of interest.

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References

Ackermann, F., Eden, C., Williams, T., Howick, S., 2007. Systemic risk assessment: a case study. J. Oper. Res. Soc. 58, 39–51.

Adner, R., 2006. Match your innovation strategy to your innovation ecosystem. Harv. Bus. Rev. 1–11 (April).

Aloini, D., Dulmin, R., Mininno, V., 2012a. Modelling and assessing ERP project risks: a Petri Net approach. Eur. J. Oper. Res. 220, 484–495.

Aloini, D., Dulmin, R., Mininno, V., 2012b. Risk assessment in ERP projects. Inf. Syst. 37, 183–199.

Archer, N.P., Ghasemzadeh, F., 1999. An integrated framework for project portfolio selection. Int. J. Proj. Manag. 17, 207–216.

Baccarini, D., 1996. The concept of project complexity—a review. Int. J. Proj. Manag. 14, 201–204.

Badenhorst, K.P., Eloff, J.H.P., 1994. TOPM: a formal approach to the optimization of information technology risk management. Comput. Secur. 13, 411–435.

Ben-David, I., Raz, T., 2001. An integrated approach for risk response development in project planning. J. Oper. Res. Soc. 52, 14–25.

Ben-David, I., Rabinowitz, G., Raz, T., 2002. Economic Optimization of Project Risk Management Efforts. The Israel Institute of Business Research.

Bordogna, G., Fedrizzi, M., Pasi, G., 1997. A linguistic modelling of consensus in group decision making based on OWA operators. IEEE Trans. Syst. Man Cybern. Part A Syst. Humans 27, 126–133.

Buchan, D.H., 1994. Risk analysis—some practical suggestions. Cost Eng. 36, 29–34.

Cavallo, A., Ireland, V., 2014. Preparing for complex interdependent risks: a system of systems approach to building disaster resilience. Int. J. Disaster Risk Reduction 9, 181–193.

Correa-Henaoa, G.J., Yusta, J.M., Lacal-Arántegui, R., 2013. Using interconnected risk maps to assess the threats faced by electricity infrastructures. Int. J. Crit. Infrastruct. Prot. 6, 197–216.

Fan, M., Lin, N.-P., Sheu, C., 2008. Choosing a project risk-handling strategy: an analytical model. Int. J. Prod. Econ. 112, 700–713.

Fang, C., Marle, F., 2012. A simulation-based risk network model for decision support in project risk management. Decis. Support. Syst. 52, 635–644.

Fang, C., Marle, F., Xie, M., Zio, E., 2013. An integrated framework for risk response planning under resource constraints in large engineering projects. IEEE Trans. Eng. Manag 60, 627–639.

Fang, C., Marle, F., Zio, E.J.B., 2012. Network theory-based analysis of risk interactions in large engineering projects. Reliab. Eng. Syst. Saf. 106, 1–10.

Hatefi, M.A., Seyedhoseini, S.M., 2012. Comparative review on the tools and techniques for assessment and selection of the project risk response actions (RRA). Int. J. Inf. Technol. Project Manage. 3, 60–78.

Howard, R.A., 1988. Decision analysis: practice and promise. Manag. Sci. 34, 679–695.

Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. Econometrica 47, 263–291.

Kayis, B., Arndt, G., Zhou, M., Amornsawadwatana, S., 2007. A risk mitigation methodology for new product and process design in concurrent engineering projects. Ann. CIRP 56, 167–170.

Keisler, J.M., Linkov, I.I., 2010. Managing a Portfolio of Risks, Wiley Encyclopedia of Operations Research and Management Science. John Wiley & Sons, Inc., pp. 1–24.

Kwan, T., Leung, H., 2011. A risk management methodology for project risk dependencies. IEEE Trans. Softw. Eng. 37, 635–648.

Linstone, H.A., Turoff, M., 1975. Delphi Method: Techniques and Applications. Addison-Wesley.

Liu, Y., Fan, Z.-F., Zhang, Y., 2011. A method for stochastic multiple criteria decision making based on dominance degrees. Inf. Sci. 181, 4139–4153.

Loch, C.H., Terwiesch, C., 1998. Communication and uncertainty in concurrent engineering. Manag. Sci. 44, 1032–1048.

MacCrimmon, K.R., Wehrung, D.A., 1986. Taking Risks: The Management of Uncertainty. Free Press, New York.

March, J.G., Shapira, Z., 1987. Managerial perspectives on risk and risk taking. Manag. Sci. 33, 1404–1418.

Marle, F., Vidal, L., 2011. Project risk management processes: improving coordination using a clustering approach. Res. Eng. Des. 22, 189–206.

Marle, F., Vidal, L., Bocquet, J., 2013. Interactions-based risk clustering methodologies and algorithms for complex project management. Int. J. Prod. Econ. 142, 225–234.

Miller, R., Lessard, D., 2001. Understanding and managing risks in large engineering projects. Int. J. Proj. Manag. 19, 437–443.

Nik, E.R., Zegordi, S.H., Nazari, A., 2011. A multi-objective optimization and fuzzy prioritization approach for project risk responses selection, Industrial Engineering and Engineering Management (IEEM). 2011 IEEE International Conference on IEEE, Singapore, pp. 888–892.

Pajares, J., López, A., 2014. New methodological approaches to project portfolio management: the role of interactions within projects and portfolios. Procedia Soc. Behav. Sci. 119, 645–652.

PMI, 2008. A Guide to the Project Management Body of Knowledge (PMBOK Guide). fourth ed. Project Management Institution.

Rao, G.N., Grobler, F., 1995. Integrated analysis of cost risk and schedule risk. Comput. Civ. Eng. 2, 1404–1411.

Ren, H., 1994. Risk lifecycle and risk relationships on construction projects. Int. J. Proj. Manag. 12, 68–74.

Satty, T., 1980. The Analytic Hierarchy Process: Planning, Priority Setting. McGraw-Hill.

Seyedhoseini, S.M., Noori, S., Hatefi, M.A., 2009. An integrated methodology for assessment and selection of the project risk response actions. Risk Anal. 29, 752–763.

Steward, D., 1981. The design structure matrix: a method for managing the design of complex systems. IEEE Trans. Eng. Manag. 28, 71–74.

Teller, J., 2013. Portfolio risk management and its contribution to project portfolio success—an investigation of organization, process, and culture. Proj. Manag. J. 44, 36–51.

Teller, J., Kock, A., 2013. An empirical investigation on how portfolio risk management influences project portfolio success. Int. J. Proj. Manag. 31, 817–829.

Touran, A., Wiser, E.P., 1992. Monte Carlo technique with correlated random variables. J. Constr. Eng. Manag. 118, 258–272.

Tsetlin, I., Winkler, R.L., 2005. Risky choices and correlated background risk. Manag. Sci. 51, 1336–1345.

Williams, T.M., 1999. The need for new paradigms for complex projects. Int. J. Proj. Manag. 17, 269–273.

Wirba, E.N., Tah, J.H.M., Howes, R., 1996. Risk interdependencies and natural language computations. Eng. Constr. Archit. Manag. 3, 251–269.

Zhang, Y., Fan, Z.-P., 2014. An optimization method for selecting project risk response strategies. Int. J. Proj. Manag. 32, 412–422.

Zou, P., Zhang, G., Wang, J., 2007. Understanding the key risks in construction projects in China. Int. J. Proj. Manag. 25, 601–614.