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Project Portfolio Risk Response Selection Using Bayesian Belief Networks

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Abstract

Risk identification, impact assessment, and response planning constitute three building blocks of project risk management. Correspondingly, three types of interactions could be envisioned between risks, between impacts of several risks on a portfolio component, and between several responses. While the interdependency of risks is a well-recognized issue, the other two types of interactions remain unacknowledged in the risk response planning literature. This research suggests a Bayesian belief network for modeling portfolio risks, their impacts, and responses. There are three kinds of nodes in this network: nodes representing portfolio risks, nodes corresponding to risk impacts on each objective of each portfolio component, and nodes showing response actions. The problem is to decide which responses are to be selected. For this purpose, an optimization model is proposed that minimizes the sum of both residual risk effects on portfolio component objectives and response implementation costs. Subsequently, a genetic algorithm is introduced to solve the model. A simple portfolio instance is also provided to illustrate the proposed model.

Keywords

Risk response selection, Project portfolio risk management; Bayesian belief network; Genetic algorithm.

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Introduction

Project portfolio management involves two cycles: definition (evaluating and selecting the right projects) and delivery (implementing the selected projects rightly). One of the essential practices in the delivery cycle is risk management (Office of Government Commerce, 2011). Risk is an uncertain event that may lead to reduced benefits, cost overruns, schedule delays, stakeholder dissatisfaction, or poor quality. Risk management enables an organization to adequately respond to emerging opportunities and threats. The goal of portfolio risk management is to reduce the probability and/or the effect of events which are disadvantageous to the value, strategic fitness, and balance of the portfolio. Risk management practice aims at consistently managing the portfolio's subjection to risks at both individual and collective levels. This management is essential to the effective delivery of change initiatives as well as the portfolio as a whole, and to attain the organization's strategic objectives.

There are three key elements in risk management (Project Management Institute, 2017, p. 90), namely risk identification, risk assessment, and risk response. Risk identification involves finding and recording associated risks. Risk assessment deals with examining the identified risks, improving the description of the risks, and appraising their corresponding probabilities and effects. Finally, risk response concerns evaluating, choosing, and executing actions so as to lessen the possibility of risk events and/or lower the negative outcomes of those risks.

In real life, three interactions in the risk response selection problem could take place:

a) The probability of a risk may be affected by other risks.
b) The total effect of risks on a portfolio may not be the sum of individual risk effects.
c) The effect of responses on a risk may not be the sum of individual responses.

The dependency of risks is a well-known issue in the literature, but few studies have considered the two other kinds of interactions. In this context, the so-called Bayesian belief network (BBN) can represent these interactions in a flexible manner. BBN is a strong means for knowledge representation and reasoning at times of uncertainty

(Cheng et al., 2002). It illustrates probabilistic relationships among a set of variables using a directed acyclic graph and a related set of probability tables. In a BBN, nodes represent random variables while arcs signify causal relationships between the variables. A conditional probability table (CPT) is related to each node in order to denote such causal influences. CPTs are completed by combining empirical data with expert judgment.

The proposed Bayesian network has three kinds of nodes which correspond to risks, impacts of risks on portfolio components (namely, projects and programs within the portfolio), and responses.

The decision-maker can control the state of response nodes. A set of responses must be selected so that the sum of response costs and residual effects of risks could be minimized. This paper introduces a mathematical model for this decision.

The remainder of this paper is structured as follows: Section 2 reviews the literature to show the contribution of our study to the existing body of knowledge; Section 3 defines the problem and presents its mathematical model; An optimization algorithm is proposed in section 4; the application of the model is demonstrated with an example in Section 5; and Section 6 draws some conclusions based on the results.

Background

Mathematical programming is one of the major approaches applied to risk response selection (RRS). The previous studies have addressed RRS in a single project context. In a pioneer research, Ben-David and Raz (2001) suggested mathematical programming for RRS. Modeling the RRS problem entails making decisions about its structure and assumptions. These assumptions may be described explicitly or considered implicitly in other papers.

a) Risk Interdependency

When there is an interaction between two risks, a causal relationship exists between them. Three approaches could be followed in dealing with this causal relationship. In the simplest case, risks may be considered independent and no interaction could be assumed between them. Ben-David, Rabinowitz, and Raz (2002) and Zhang and Fan (2013) have adopted this assumption. Most often, however, only one-to-one interaction between risks is evaluated and the effect of each risk on another risk is measured and quantified (Shoar & Nazari, 2019; Soofifard, Bafruei, & Gharib, 2018; Zhang & Zou, 2016; Zhang, 2016; Fang, Marle, Xie, & Zio, 2013). In this regard, design structure matrix (DSM) is widely used for modeling casual relationships between the risks (Fang et al. 2013; Soofifard et. al., 2018; Shoar & Nazari, 2019). The third approach evaluates the effect of multiple risks on each risk simultaneously. Thus, Zhang and Guan (2018) used bow-tie analysis to model risk interactions. The limitation of their approach is that it allows investigating only And/OR relationships between risks. The AND rule means that the occurrence of the risk event requires that all its related causes take place. The OR rule implies that the occurrence of the risk event entails the happening of at least one of its causes. As Table 1 shows, few studies have explored the third approach.

In project portfolio, interaction between risks seems to be more complicated. Risks originating in organizational governance and project portfolio management processes affect many other risks.

b) Multiple Effects of Each Risk

In the context of a single project, a risk may affect several activities or work elements of the project (Zhang & Guan, 2018; Ben-David et al., 2002). In a project portfolio, risks associated with processes, operational departments, and common resources could influence several projects. Thus, a wrong policy in supplier selection, the failure of common equipment, inaccurate safety instructions, and weak management controls expose many projects to a common risk.

Zhang and Zou (2016), Zhang (2016), Fan, Lin, and Sheu (2013), and Fan et al. (2008) consider a single effect for each risk.

c) Risk Effects Aggregation Method

In a single project, each activity may be exposed to multiple risks. The problem is how to evaluate and aggregate their effects. A straightforward approach is to measure each effect separately and calculate the summation. As shown in Table 1, all of the reviewed papers have followed this approach. Nevertheless, this method does not consider the interaction of effects. Besides, a system is not the sum of its parts, that is to say, the concurrent occurrence of two risks may impact the project more than the sum of their individual effects. In the context of a portfolio, projects could be at once affected by several risks.

d) Response Strategy

Risk mitigation involves various types of responses: reducing the occurrence probability of the event, and/or lessening the impact of the event if it takes place. Some studies do not distinguish between probability and impact reduction (Zhang & Zou, 2016; Zhang, 2016; Soofifard & Bafruei, 2016; Soofifard et. al., 2018) and consider the expected impact as a parameter. When there is an interaction between various risks, separating the probability and impact of risks will be a necessity.

e) Multiple Effects of Each Response Action

Implementing safety standards in the organization or establishing appropriate portfolio governance could affect all of the portfolio projects involved. Shoar and Nazari (2019), Zhang and Zou (2016), Zhang (2016), and Fan et al. (2008) consider a single effect for each response.

f) Response Effects Aggregation Method

Here, the question is how to assess the overall effect when several responses target a risk or its impact. So far, only Soofifard et al. (2018) and Soofifard and Bafruei (2016) have addressed the synergy of responses. However, their method involves a number of limitations as well. For instance, synergy is separately considered between each pair of responses.

Application of BBN in Project Risk Management

BBN has been used for analyzing the risks of projects in different contexts such as software projects (Fan & Yu, 2004; Hu, Zhang, Ngai, Cai, & Liu, 2013), new product development (Chin, Tang, Yang, Wong, & Wang, 2009), or large engineering projects (Lee, Park, & Shin, 2009). Some BBN applications involve using discrete BBNs to compute the risk of having an overall schedule delay (Luu, Kim, Tuan, & Ogunlana, 2009), using a BBN to estimate the risk of exceeding budget and schedule and of having insufficient specifications (Lee et al., 2009), and using BBNs to estimate the project costs based on the causes of costs (Khodakarami & Abdi, 2014).

BBNs have been more extensively employed in software engineering projects. Examples include proposing a framework that continuously assesses and manages risks in different areas of software development (Fan & Yu, 2004), using discrete BBNs to assess risks and predict delays in software maintenance projects (Melo & Sanchez, 2008), and applying constraint-based structure learning algorithms to BBNs to identify causal relations and make predictions about the risk factors of software (Hu et al., 2013).

Table 1 summarizes the literature review. To the best of our knowledge, no study has so far used BBN as a tool for RRS. The purpose of this study is to select an optimal combination of risk response actions to cope with portfolio risks using BBN.

Table 1. Literature on project risk response strategy selection

Authors	Risk Interaction Evaluation		Multiple Effects Aggregation		Multiple Effects for each Risk	Response Type			Multiple Response Effects Aggregation	
	One-to-One	Many-to-One	Sum	Flexible		Probability	(Expected) Impact	Multiple Effects for each Response	Sum	Flexible
Zhang and Guan (2018)		Limited to And/OR Relations	X		X	X	X	X	X	-
Shoar and Nazari (2019)	DSM	-	X		objectives of one activity	X	X	-	-	-
Soofifard et. al. (2018)	DSM	-	X		X	-	X	limited to each activity		Synergy
Zhang and Zou (2016)	X	-	X		-	-	X	-	X	-
Soofifard and Bafruei (2016)	-	-	X		X	-	X	X		Synergy
Zhang (2016)	X	-	X		-	-	X	-	X	-
Fang et al.(2013)	DSM	-	X		-	X	X	X	X	-
Zhang and Fan (2013)	-	-	X		X		X	X	X	-
Fan et al. (2008)	-	-	-	-	-	X	X	-	-	-
Ben David et al. (2002)	-	-	X		X	X	X	X	X	-
This Research		X		X	X	X	X	X		X

Table 1. Literature on project risk response strategy selection (continued)

Authors	Tools/Techniques	Objective Function
Zhang and Guan (2018)	bow-tie analysis, fuzzy optimization, based on a single critical risk	response costs
Shoar and Nazari (2019)	optimization model and MCDM	remained effects
Soofifard et. al. (2018)	multi-objective	maximum response effects
Zhang and Zou (2016)		maximum utility of response
Soofifard and Bafruei (2016)	fuzzy multi-objective	maximum response effects
Zhang (2016)		maximum utility of response
Fang et al.(2013)		
Zhang and Fan (2013)		maximum response effects
Fan et al. (2008)	considers only one risk	risk handling cost
Ben David et al. (2002)		minimize the sum of expected risk loss and response cost
This Research	Bayesian belief networks	minimize remained effects and response costs

Problem Definition and Formulation

In real world, there is usually interdependency between the risks of a portfolio. Instead of an independent set of risks, organizations are faced with a network of interrelated risks. The portfolio components may have resource, technical, or benefit interdependency. A specific risk could affect several components. Several risks may impact the same objective of a component. For example, two risks could influence the time objective of a specific project. Hence, we propose BBN for modeling portfolio risks, impacts, and response actions.

Consider a portfolio that faces risks A, B, C, D, and E. Based on the experts' judgment, the relations between these risks could be modeled as in Figure 1.

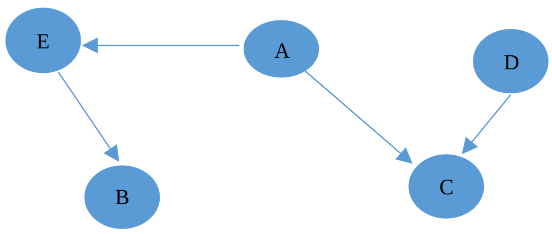

Fig. 1. Risk network

In this network, the nodes represent risk events and the arcs between nodes stand for the causal relationship between them. For each risk, we consider a random variable with the same name. Thus, $p(A = 1)$ will be the occurrence probability of risk A, and $p(A = 0)$ will be the probability that risk A will not take place. For each node impacted by other nodes, a conditional probability table (CPT) is used to express the effects. For example, for node E, the CPT is determined as in Table 2. In the first column of Table 2, one and zero values denote the cases where risk A will and will not occur, respectively. If we assume that $p(A = 1) = 0.4$ and $p(A = 0) = 0.6$, the probability of risk E to occur will be 0.45. In other words P(E=1) is 0.45.

Table 2. Conditional probability table for node E

A	P(E=1|A)
1	0.55
0	0.3833

Risks involved in a portfolio can affect portfolio component objectives such as time, cost, quality, and benefit, with benefit being defined as a measurable improvement achieved via a project or program which is regarded as an advantage by one or several stakeholders and which is conductive to one or multiple organizational objectives (Axelos, 2013). For example, if we show the risk impacts with letter “e”, then risks dependencies and their impacts may be modeled as in Figure 2. Assume that A has an impact on the cost of the first project. Figure 2 represents this effect with e1.

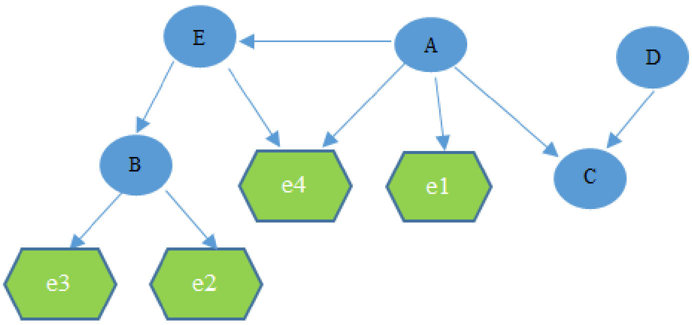

Fig. 2. Network of risks and their impacts

If A and E have a simultaneous effect on the time of the fourth project, as illustrated in Figure 2, the conditional impact table for the effect node e4 will be stated as in Table 3. Columns A and E show the values of risk random variables, and e4 column refers to the associated effect. The expected value of e4 would be 25.9.

Table 3. Risk impact table for node e4

A	E	e4
1	1	50
1	0	40
0	1	30
0	0	0

Risk responses are used for mitigating the probability and/or the impact of risk events. For example, if we show the responses with S, the relationships between actions and their effects will be modeled as in Figure 3.

As Figure 3 implies, S2 and S3 exert an effect on D and e1, respectively. Risk B is mitigated by S1 and S4 actions. Subsequently, CPT for node B is determined as in Table 4. If a response action is selected, we attribute a probability of 1 to it; otherwise, we consider the probability of 0 for it.

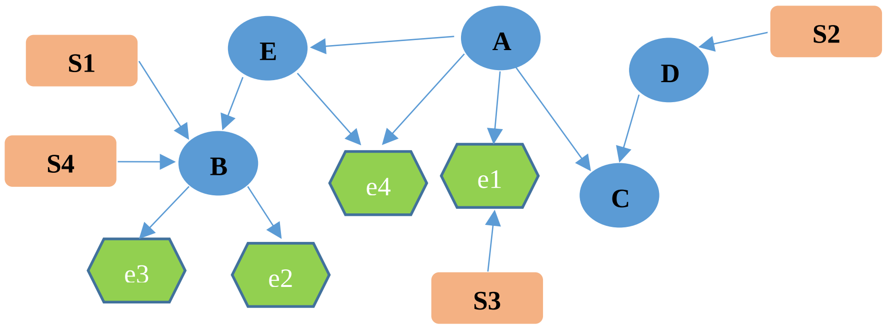

Fig. 3. Network of strategies and their effects

Table 4. Conditional probability table for node B

E	S1	S4	P(B=1 | E and S1 and S4)
1	1	1	0.1
1	1	0	0.15
1	0	1	0.2
1	0	0	0.3
0	1	1	0
0	1	0	0.06
0	0	1	0.05
0	0	0	0.1

Considering $p(\text{E} = 1) = 0.45$ (as calculated earlier) and assuming that S1 and S4 are not selected, the probability of B is given by 0.19. On the other hand, if only S1 is implemented, the probability of B will be 0.1005.

Incorporating response actions in CPTs automatically takes into account the interaction between response actions. Synergy or any other form of mutual effects could be reflected in CPTs. For example, in Table 4, the effect of simultaneous implementation of S1 and S4 is not equal to the sum of their individual effects. If E occurs, without any response, the occurrence probability of B is 0.3. By exclusively selecting S1 or S4, the probability of B to occur is respectively reduced by 0.15 (0.3 minus 0.15) and 0.1 (0.3 minus 0.2), whereas selecting both S1 and S4 will reduce this probability by 0.2 (not 0.25).

The main objective of this study is to select an optimal combination of risk response strategies to cope with portfolio risks. In the proposed model, zero–one decision variables are used to show whether or not each risk response action is implemented. Table 5 presents the related notations along with their definitions.

Table 5. Notations

Notation	Definition
X_i	Binary decision variable X_i is equal to 1 if risk response action *i* is implemented; otherwise, it is equal to 0, $i = 1,2, \dots, m$
C_i	Cost of resources needed for implementing response i
a_{ij}	Resource j required for implementing response *i*
K	Projects set
L	Objectives set (such as time, cost, quality, and benefit of projects)
B_j	Maximum access to resource j
d_l^k	Cost per unit deviation from *l*th objective of *k*th project (For the cost objective, d_l^k is equal to 1).
UE_l^k	Maximum allowable residual effect of risks on objective *l* of project k
UV_l^k	Maximum allowable variance of residual effect of risks on objective *l* of project k
$E_l^k(X_1, \dots, X_m)$	Expected residual effects of risks on *l*th objective of *k*th project after implementing strategies. (Calculations are made using the Bayesian Network)
$V_l^k(X_1, \dots, X_m)$	Variance of residual effects of risks on *l*th objective of *k*th project after implementing strategies. (Calculations are made using the Bayesian Network)

Thus, an optimization model for selecting the risk response strategies of a project portfolio is developed as follows:

$$min\, Z = \sum_{i=1}^{m} C_i\, X_i + \sum_{\forall\, l \in L} \sum_{\forall k \in K} d_l^k . E_l^k \left(X_1, \dots, X_m \right) \tag{1}$$

$$s.t. \quad \sum_{i=1}^{m} a_{ij}\, X_i \le B_j \qquad j = 1, \dots, n \tag{2}$$

$$E_l^k \left(X_1, \dots, X_m \right) \le UE_l^k \qquad \forall k, l \tag{3}$$

$$V_l^k \left(X_1, \dots, X_m \right) \le UV_l^k \qquad \forall k, l \tag{4}$$

$$X_i \in \{0,1\}\ ,\ i = 1,2, \dots, m \tag{5}$$

The objective function (1) minimizes the cost of implementing risk response actions and the cost of residual effects of risks after implementing responses. Constraint (2) specifies that the resources required for implementing the responses should be less than the available resources. Constraints (3) and (4) ensure that expectation and variance of the residual effect of risks on each project objective will not exceed its corresponding upper limit. These constraints demonstrate the risk tolerance of the decision-maker. Lower levels of risk tolerance suggest lower degrees of allowable variance. In the investment portfolio literature, the variance of profits is considered a measure of risk. Constraint (5) is a binary mode indicator.

The structure of the proposed model makes it robust under various conditions. The objective function considers the trade-off between response costs and response impacts, and it guarantees that inefficient combinations of responses are not selected. If the expected savings earned from a set of responses are less than their implementation cost, they are not selected. The proposed objective function works successfully even if the decision-maker loosens the constraints on budget and residual effects. Also, if the decision-maker prefers to decrease portfolio uncertainty at the expense of high costs, he/she can tighten the residual effect constraints.

It might be expected that a pre-evaluation is thus carried out and inefficient responses are deleted. When there is no interdependency between risks and responses, it could be expected that decision-makers identify and omit inefficient responses, but when there is interdependency, evaluating the ultimate impact of a response will not be simple.

If only the response costs are considered as the objective function, setting an upper limit to residual effects will be mandatory and the model output quality will be highly dependent on the accuracy of that upper limit. On the other hand, if we consider maximizing the response effects as the objective function, a combination of responses might be selected that are inefficient and the decision quality will be highly dependent on the accuracy of the amount of budget.

Solution Method

Calculating the expectation and variance of the residual effect of risks (i.e., $E_l^k(X_1, \dots, X_m)$ and $V_l^k(X_1, \dots, X_m)$) requires the Bayesian network traversal. Therefore, the proposed mathematical model is highly non-linear and could not be solved by conventional optimization methods. Instead, a genetic algorithm (GA) is used to solve the model.

Genetic algorithm is basically inspired by the mechanisms of biological evolution. In a genetic algorithm, a population of strings (called chromosomes) evolves toward better solutions. Commonly, this evolution begins by a population of randomly created individuals and continues through generations. In each generation, the fitness of any individual in the population is assessed, and a number of individuals are stochastically chosen (according to their fitness) from the present population and subsequently changed (i.e. recombined and perhaps randomly mutated) to generate a new population. Afterwards, the new population is employed in the following iteration of the algorithm. An evaluation function is needed to evaluate the fitness of each chromosome, which determines the utility of the solution that a chromosome stands for.

Encoding

Each gene on the chromosome (individual) corresponds to a risk response strategy. The value in each gene represents whether the corresponding strategy is chosen or not. In other words, encoding becomes an array of 0 and 1 of risk responses.

GA Operators

Parents are selected through roulette wheel selection method, which chooses individuals based on their relative fitness in the current population. Single-point crossover generates two offspring from each pair of selected parents. Flip mutation replaces the value of a randomly chosen gene of the chromosome with its flipped value. Here, a crossover probability of 0.5 and a mutation rate of 0.4 have been considered. These configurations are the result of experimenting with different scenarios on a set of test problems.

Fitness Evaluation

The objective function in a mathematical model plays the role of GA fitness function. Fitness evaluation is a procedure that takes a chromosome as input and calculates its fitness using Bayesian network traversal. The values of the decision variable determine the status of response nodes in the Bayesian network. Since BBN is an acyclic graph, we begin from the response nodes and move forward according to the causal relationships between nodes. The probability of each node is calculated so as to reach the effect nodes. The expectation and variance of effect nodes determine the objective function.

Constraint Handling

Generating initial random solutions and imposing genetic operators may give rise to infeasible solutions. Constraints (2), (3), and (4) could be violated. For infeasible solutions, a penalty term is added to the objective function. This penalty is proportional to the number of violated constraints.

Illustrative Example

An example is presented to depict how to use the proposed approach in order to solve the risk response strategy selection problem by considering risk interdependencies. In this example, a project portfolio in a construction company is examined. This company has 10 construction projects (Table 6).

Table 6. Projects and their corresponding risks

Project	Category	Risks Affecting the Project Objectives		
		quality	cost	time
P1.Construction of Motahhari Underpass	Bridge	-	R3,R4,R8	R3,R6,R7,R8
P2.Construction of Etrat Bridge	Bridge	-	R3,R4,R8	R3,R6,R7,R8
P3. Construction of Omid sports hall	Buildings	R12	R5,R9	R1,R5,R9,R13
P4.Grade separation of Resalat-Kaveh	Bridge	-	R3,R4,R8	R3,R6,R7,R8
P5.Construction Street from Sohrevardi to Enghelab Park	Street	-	R2,R10	R2,R10
P6.Extension of Kashani Street	Street	-	R2,R10	R2,R10
P7.Construction of Andisheh study hall	Buildings	R12	R5,R9	R1,R5,R9,R13
P8.Grade separation U-turn of Azadi Bridge	Bridge	-	R3,R4,R8	R3,R6,R7,R8
P9.Asphalt overlaying on Imam Javad and Taleghani Street	Street	-	R2,R10	R2,R10
10.Construction of Saadi intersection Parking	Buildings	R12	R5,R9	R1,R5,R9,R13

By analyzing the construction projects and holding a brainstorming session, experts identified critical risk events as shown in Table 7. The probability of identified parent risks is estimated based on historical data and experts' experience and judgment. Because of risk interdependencies, the probabilities of other risks are stated by experts using conditional probabilities in Bayesian networks.

Table 7. Portfolio Risks

Risk	Description
R1. Building construction budget is not in place on time	If the developers do not have sufficient financial capacity to develop the projects, the required budget might not be provided at the right time.
R2. Inappropriate maintenance planning in the construction of the street	If there is no proper planning for the maintenance of machinery and equipment, it will be extremely hard to prevent deterioration at the right time and, hence, the productivity of machinery will decline.
R3. Omissions and mistakes in the construction design of the bridge	The design team must be completely aware of the client's demand, organize comprehensive site investigation to acquire trustworthy design data, and facilitate efficient communication among individual designers. Making mistakes in the design of the construction causes dissatisfaction among clients.
R4. Inadequate site information for bridge construction (soil test and survey report)	This risk results in uninformative designs and further affects the progress of excavation, foundation, and footing construction.
R5. Lack of contractor's financial resources in building construction	In some cases, the contractor faces financial shortage. This may cause delays in project implementation and thus, it requires an appropriate response.
R6. Inadequate personal protective equipment in bridge construction	If the laborers do not have suitable equipment to protect themselves, they may face a lot of dangers in the workplace. This issue reflects a lack of perception of and/or commitment to construction safety among contractors and workers.
R7. Unfamiliarity of workers with safety principles in bridge construction	Unfamiliarity of workers with safety principles can pose irreparable risks to workers or the working environment.
R8. The dangers of destruction, thrust, etc. in bridge construction	Some risks such as inadequate personal protective equipment and the unfamiliarity of workers with safety principles can cause serious risks like fire, destruction, etc.

Table 7. Portfolio risks (continued)

Risk	Description
R9. Prolonged coordination time between agencies and organizations affecting the implementation of building construction	Sometimes, implementing projects requires acquisition of shared ownership of a property or state-owned private property. Therefore, prior to starting the project, the client must coordinate with and obtain the necessary permits from organizations such as the Natural Resources Agency, military centers, water organizations, power departments, and gas stations in order not to increase the project time and incur extra costs during the construction.
R10. The failure of equipment and machinery involved in the construction of the streets	Certain equipment and machinery are needed in multiple projects. If they break down, the construction time of the related projects could be affected.
R11. Unavailability of sufficient skilled maintenance staff in the street projects	Unskilled maintenance staff members are unfamiliar with their machines and equipment and cannot use them properly. This risk can result in the failure of (critical) machines involved in several projects.
R12. Unavailability of sufficient professionals and managers for building projects	Professional leaders are commonly necessary for prevailing over organizational inertia and resistance to change. As a result of a shortage in the number of skilled professionals or managers, decisions are not taken correctly and appropriate resolutions cannot be implemented in the face of significant uncertainties. This risk may prompt quality and safety problems in the construction phase.
R13. Limited access to machinery and equipment in building construction	If projects encounter resource deficiency, the access to machinery and equipment will be reduced and delays will occur in the implementation of the project.

On the basis of risk event analysis, experts discussed and proposed eleven candidate risk response actions according to their experiences in similar projects or previous risk events (Table 8).

Table 8. Candidate risk response actions

S1. Developing financing channels such as entering into a fixed rate loan contract with lending banks if nothing else helps;
S2. Choosing preventive maintenance strategy, meaning any planned activity on machinery that reduces the potential damage and prevents their early depreciation;
S3. Active cooperation with well-known designing organizations;
S4. Conducting the borehole soil test, surveying government agencies, and studying nearby buildings prior to any design scheme in order to ascertain the site conditions and reduce uncertainties;
S5. Early payment to the contractor;
S6. Considering safety measures such as purchasing safety equipment;
S7. Contractors should train all employees about safety knowledge and skills so that they can work accordingly;
S8. Insuring workers and major equipment located at the site of project (such as client's liability insurance, insurance of nearby buildings, etc.);
S9. Establishing a committee for handling disputes in all organizations (including the water organization, the electricity authority, etc.);
S10. Performing periodic inspection to identify potential breakdown points;
S11. Contractors should devise a robust construction plan and always map the construction progress to secure sufficient professionals, managers, or skilled maintenance staff ready to work.

Figures 4, 5, and 6 show the identified risks, suggested responses, and their interactions, respectively.

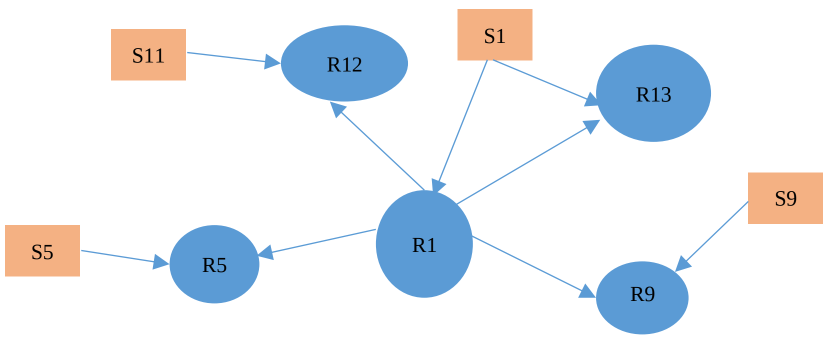

Fig. 4. Bayesian network of building construction projects

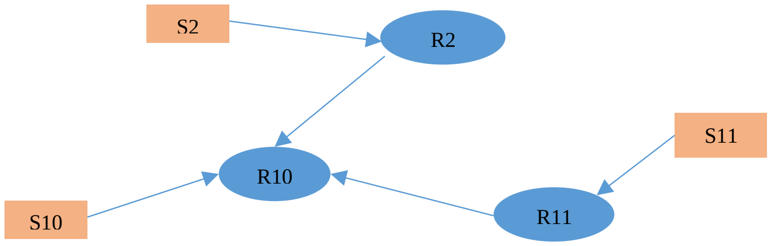

Fig. 5. Bayesian network of street construction projects

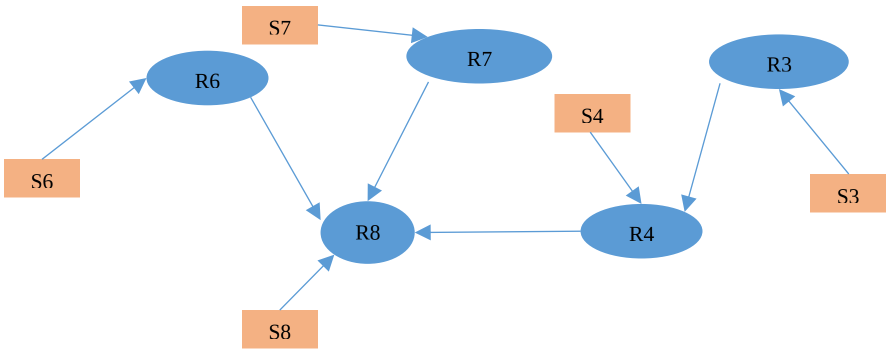

Fig. 6. Bayesian network of bridge construction projects

In this example, we consider three objectives of time, cost, and quality. Every risk can affect one or more project objectives. Table 6 shows risks affecting each project.

Eventually, we achieve a Bayesian network that has 47 nodes including 13 risks, 23 effects, and 11 responses.

Implementing risk response actions requires two kinds of resources, namely budget and management effort. The available budget and effort are assumed to be 20,000 (dollars) and 2,000 (hours), respectively.

Example Solution

The proposed GA was implemented in MATLAB and was used to solve this problem. The best solution and its objective function values are given in Tables 9 and 10, respectively. As Table 9 shows, S4, S8, and S10 have not been selected for implementation. The initial risk effect was about 382,140, which was reduced to 148,525 after the risk response process. The response costs given in Table 10 are the total costs of resource requirements for the selected responses.

Table 9. Optimal solution

Response										
S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**
1	1	1	0	1	1	1	0	1	0	1

Table 10. Objective function of the optimal solution

Residual effects	Response costs	Objective function
148,525	26,885	175,410

Investigating the Effect of Resource Availability

Figure 7 depicts the objective function for different levels of resource availability. Three effort levels (1000, 1500, and 2000) and 15 budget levels (ranging from 2000 to 30000) were considered. Figure 7 shows the trade-off between allocated resources and the residual risk effects. As available resources increase, marginal savings decrease. This kind of analysis helps the decision-maker to decide on the resources allocated to the risk response process.

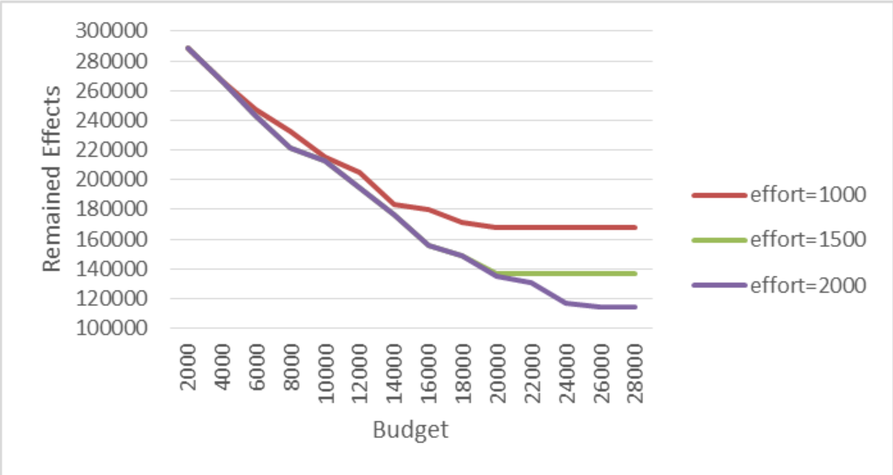

Fig. 7. Residual effects for different budgets and efforts

Table 11 shows the residual effect of risks for different available budgets and an effort of 2,000 hours. Each row of Table 11 corresponds to a budget level, shows which responses will be selected, and specifies residual risk impacts. Comparing each row's residual effect with that of the previous row determines the savings obtained through added budget.

Table 11. Selected responses in different levels of budget

Budget	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	Residual Effects
0	0	0	0	0	0	0	0	0	0	0	0	382140
2000	0	0	1	0	0	0	0	0	0	0	1	339824
4000	0	0	1	0	0	0	1	0	0	0	1	288492
6000	0	1	1	0	0	0	1	0	0	0	1	267328
8000	0	0	1	0	0	1	1	0	0	1	1	242793
10000	0	1	1	0	0	1	1	0	0	1	1	221583
12000	1	1	1	0	0	0	1	0	0	1	1	212597
14000	1	1	1	0	0	1	1	0	0	0	1	194510
16000	1	0	1	0	1	1	1	0	0	1	1	176539
18000	1	1	1	0	1	1	1	0	0	1	1	155329
20000	1	1	1	0	1	1	1	0	1	0	1	148525
22000	1	1	1	0	1	1	1	0	1	1	1	134696
24000	1	1	1	0	1	1	1	1	1	0	1	130292
26000	1	1	1	0	1	1	1	1	1	1	1	116463
28000	1	1	1	1	1	1	1	1	1	1	1	114019

Exploring the Objective Function

The proposed objective function has two terms: response costs and residual effects. As the last row of Table 11 shows, all the responses will be selected with a budget of 28,000 dollars. S4 is the last selected response. The saving obtained from S4 implementation equals 2,444 dollars (116,463 minus 114,019). If we increase the cost of S4 to more than 2444, S4 will not be selected at any level of budget. Alternatively, if we delete the first term of the objective function and solve the problem again, S4 will be selected. Therefore, the proposed objective function is more robust than other conventional functions.

Conclusion

This study presented a method for selecting project portfolio risk response actions. Each risk response can influence one or more portfolio risks, and the implementation of each action requires certain resources. In this research, a network of risks, risk effects, responses, and their interdependencies was developed. Considering their interdependencies, the probability of various risks was calculated on the Bayesian network. The findings of this research help project managers to provide an appropriate combination of actions consistent with available resources. Indeed, analyzing residual effects under different resource availabilities reveals the priority of risk responses for project management teams.

The approach proposed in this paper has some limitations that could be overcome in future studies.

I. Modeling the risks of a portfolio as a Bayesian network offers a portfolio management team invaluable insights. Meanwhile, preparing conditional probability tables and quantifying probabilities and impacts may be difficult due to the lack of adequate data and experience. To overcome this weakness of Bayesian networks, this research could be developed further by considering fuzzy probabilities and impacts.

II. Measuring the residual effect of risks on project objectives in monetary values might be difficult. An alternative approach is to consider each objective separately and model the problem as a multi-objective problem.

III. Disintegrating the project scheduling and RRS can have significant consequences when there are considerable parallel activities or when alternative resources could be assigned to each activity. In such cases, estimating the impact of risks on projects' time could be intricate. Hence, an alternative approach is to integrate the portfolio scheduling and RRS.

IV. One of the main parameters of the proposed model is risk response budget. The quality of the model output relies on its accuracy. If there is ambiguity in the amount of budget, we can consider the problem as a bi-objective model to have a more robust objective function. For this purpose, each term of the proposed objective function could be regarded as a separate objective, i.e. residual effects and response costs. The output of the new model would be a Pareto front that helps the decision maker to examine residual effects resulted from different response costs. In this case, the budget constraint could be deleted.

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