Methodology for Project Risk Assessment Using Bayesian Belief Networks in Engineering Construction Projects

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ABSTRACT

Engineering construction projects commonly suffer from cost and time overruns, for most of the time because of uncertainties that are not carefully considered during bidding for contracts and budget project planning. These uncertainties place the project at risk of poor quality delivery and also not adhering to the time and budget schedule within the original contractual agreement. A clear focus on risk analysis and its management from the onset is essential to guide project planning and also to achieve optimal performance in construction projects. The research carried out here presents a risk assessment methodology based on the Bayesian belief network, which is an effective tool for knowledge representation and reasoning under conditions of uncertainty, structural learning procedure, combination of different source of knowledge, explicit treatment of uncertainty and support for decision analysis and fast responses for risk assessment. Bayesian belief network therefore, is a scenario planning tool suitable for project risk management because of its systematic and integrated process approach to the analysis of key risk factors affecting project delivery, with a view to predict the worst and best case scenarios and thereby guide project planning. The proposed methodology developed in this study is partly based on knowledge and experiences acquired from experts who are in a position to provide information on the sources of uncertainty, and the causes of uncertain condition with a view to generate optimal response strategies to support a successful project outcome.

1. INTRODUCTION

Engineering construction is mostly characterised by designs prepared by engineers. These facilities are usually provided to public infrastructure and thus owned by public sector entities and funded through bonds, rates or taxes and a high degree of mechanization and the use of much heavy equipment and plant in the construction process.

Project inception, design, construction and project completion are the typical stages in a construction development [1]. However, for this process to pass from one stage to another, most often, it is usually fraught with problems. Construction works are implemented under the condition of risk, and the cost of risk is a concept many construction companies have never thought about despite the fact that it is one of the largest expense items.

Risk management is an important part of the decision-making process in construction industry to address risk factors as it determines the success or failure of construction projects [2]. Risk management helps the key project participants - client, contractor or developer, consultant, and supplier - to meet their commitments and minimize negative impacts on construction project performance in relation to cost, time and quality objectives.

To develop a systematic and integrated methodology of construction risk management, studies have suggested the use of process modelling and methodologies of construction risk management [3,4]. The use of diagrams such as cause and effect diagrams is one of the methodologies for construction risk management. These diagrams are useful in the modelling of conditional probability relationships among risks, and are very useful when handling risk variable.

Bayesian belief network are probabilistic models that represent system variables and their conditional relationships graphically as nodes and linkages in an influence diagram. Bayesian belief

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network is a useful methodology for construction risk management with a systematic and integrated process [3]. Therefore, this study presents a methodology for construction risk management process using the Bayesian belief network. This process is applied to a construction project in order to analyse key cost related risk factors affecting project delivery, with a view to predict the worst and best case scenarios and thereby improve engineering construction performance.

2. LITERATURE REVIEW

2.1. CONSTRUCTION RISK MANAGEMENT

The environment which decision-making takes place can be described in three methods, which include certainty, risk and uncertainty [2]. Certainty exist only when one can specify exactly what will happen during the period of time covered by the decision and conform to the specific requirements of certainty [2]. However, this does not happen in the engineering construction industry. Construction risk originates from the uncertainty that is present to a different extent in all construction projects. The project management book of knowledge describes construction risk as an uncertain event or condition that, if occurs, has a positive or a negative effect on at least one project objective, such as time, cost, scope, or quality. The causes or condition of risk, arise from but are not limited to: poor project definition during project planning, incomplete project designs at the design stage, unethical behaviours in the form of fraudulent practices, giving and taking kickbacks, undue delay of processes due to bureaucracy, delays from suppliers and poor site management.

Since, engineering construction projects are dynamic, risk management plays a relevant role in improving the performance of construction projects. Risk management is one of the nine knowledge areas propagated by the Project Management Institute. Zou et al [5] describe risk management in the construction project management context as a systematic way of identifying, analysing and dealing with risk as associated with a project with an aim to achieve the project objectives.

Risk management is a cyclical process, which is made up of; risk identification and assessment (also known as qualitative risk analysis), quantitative risk analysis, risk mitigation and monitoring. The risk management procedure described in Fig. 1 indicates a normal risk management system, which can start by planning and driven by reporting, with regard to not only obvious effectiveness but also significant improvement through its forward rolling process engine to implement a core risk management circle at different stages of construction project development so as to gradually reduce uncertainties and adverse impact [1].

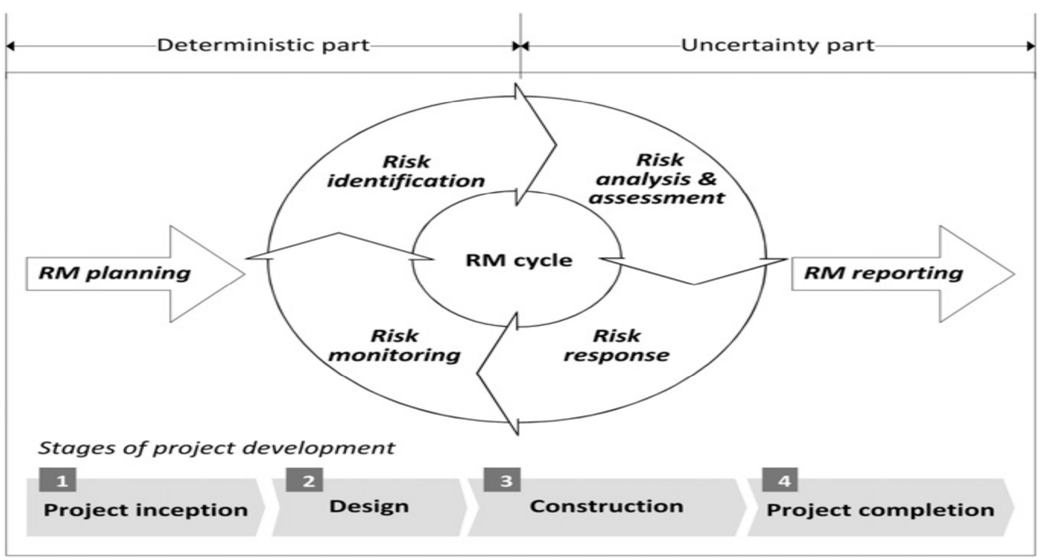


Fig 1. Risk management process for construction projects [1].

Risk management in construction is a tedious task as the objective functions tend to change during the project life cycle and if the risk management procedure is rightly applied, it will enhance the successful completion of construction projects and thereby make the projects more profitable.

However, if risk management is applied chaotically and arbitrarily, it can jeopardize the realization of the construction project, as most of the risks are very dynamic all the way throughout the project lifecycle.

2.2. BAYESIAN BELIEF NETWORK (BBN)

Bayesian belief networks (BBN) are multivariate statistical models, acknowledged for their unique probabilistic modelling approach and their high model transparency [6]. Bayesian belief network are used for knowledge representation and reasoning under conditions of uncertainty which has become increasingly popular for modelling complex domains for which knowledge and data are uncertain. They have proven effective for capturing and integrating quantitative and qualitative information from various sources [7], and they thus have the ability to strengthen decisions when empirical data are lacking. Due to the Bayesian nature of the approach, Bayesian belief networks provide both diagnostic and predictive capabilities and allow for updating the probability distributions with new evidence when such become available

Bayesian belief network consists of nodes, representing variables of the domain, and arcs, representing dependence relationships between nodes. Fig. 2 shows a simple belief network in which the node at the tail of the arrow, referred to as the parent node, directly affects the node at the head of the arrow, referred to as the child node [8]. An edge represents the cause-effect relationship between the parent node and the child node [8]. Child nodes are conditionally dependent upon their parent nodes [8].

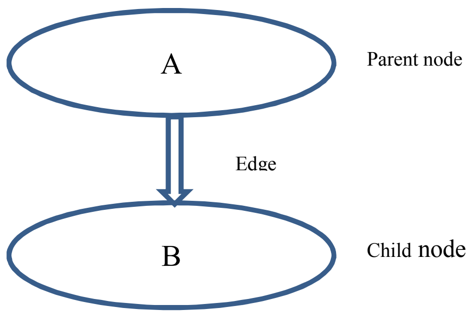


Fig 2. A simple Bayesian belief network [8].

A Bayesian belief network consists of a qualitative part and a quantitative part [3]. The qualitative part of a BBN is the graphical representation of interdependence holding among variables and has the form of a directed acyclic graph (DAG) in which nodes and directed arcs represent system variables and their conditional relationships [3,11]. The quantitative part of a Bayesian belief network finds the dependence relations as joint conditional probability distributions among variables using the cause and effect relationship from the quantitative part and variables [3].

Bayesian belief network is applied to construction risk management where a cause and effect diagram among risk is easily constructed, risk probability is obtained by calculating the joint conditional risks, and major risk, which affects project performance, can be identified [3].

3. METHODOLOGY FOR CONSTRUCTION RISK ASSESSMENT USING BAYESIAN BELIEF NETWORK

Bayesian belief network is based on Bayes' theorem, which has proven to be a coherent method of mathematically expressing a decrease in uncertainty gained by an increase in knowledge [9]. This is gained by combining probability distribution or functions of different outcomes and revising their probabilities when new information is obtained. According to Luu et al [8], Bayes' rule may be simply expressed as follows:

$$P(B/A) = \frac{P(A/B) \text{ X } P(B)}{P(A)} \quad (1)$$

Where P (A) is the probability of A, and P (A|B) is the probability of A given that B has occurred.

Based on Lee et al [3] and Zhang et al [9] a construction risk management process using Bayesian belief network, is presented in Fig. 3, which is used in a construction project. This technique is suitable to elaborate risk assessment of engineering construction projects. Through the Bayesian belief network process shown in Fig. 3, the cost related risk were identified at a glance through literature review, and risk reductions were easily measured by risk control activities.

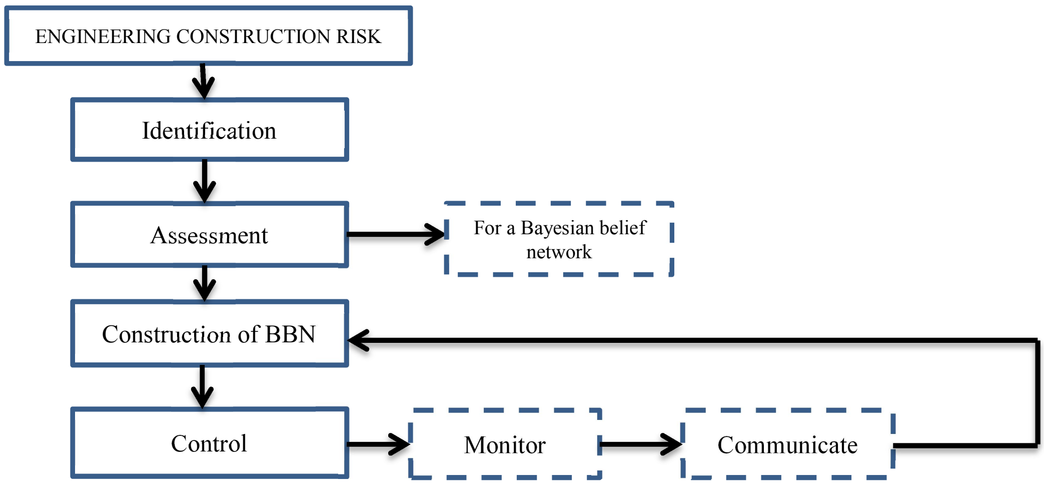


Fig. 3. Proposed risk assessment methodology for engineering construction projects using Bayesian belief network.

4. APPLICATION OF BBN IN ENGINEERING CONSTRUCTION PROJECTS

4.1. RISK IDENTIFICATION

The process of risk management begins with risk identification which develops the basis for the next steps of assessment, analysis and control, and if this is done correctly it ensures risk management effectiveness. The source of risks affecting construction projects includes but is not limited to; financial risk, technological risk, social risk, political risk and environmental risk. Since cost is one of the factors that is essential to the successful execution of a construction project, the study therefore identifies ten risk factors that can cause cost overruns in engineering construction projects as selected through literature review; they are listed in table 1;

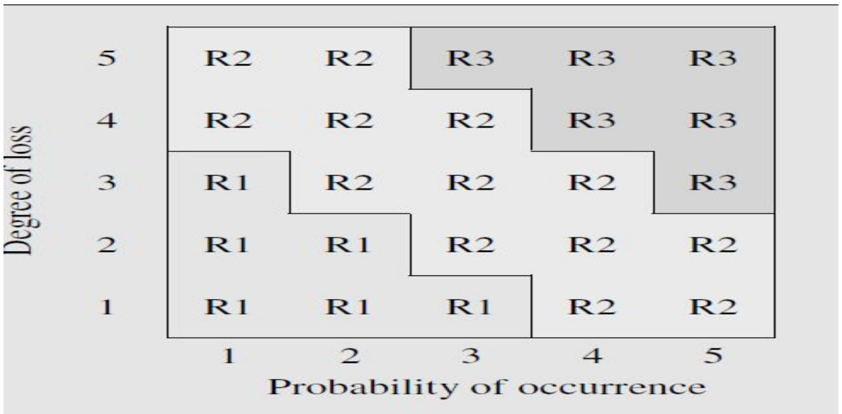
Table 1. The 10 major cost related risk factors affecting construction projects.

Risk category	**Risk factors**
Cost related risk	• Tight project schedule • Design variation • Variation by the client • Unsuitable construction program planning • Occurrence of disputes • Price inflation of construction materials • Excessive approval procedures in administrative work • Incomplete approval and other documents • Incomplete or inaccurate cost estimates • Inadequate programme scheduling

4.2. RISK ASSESSMENT FOR A BAYESIAN BELIEF NETWORK

In adopting the Bayesian belief network for risk assessment, the risk level of each risk item identified in an engineering construction project is measured and the dataset is modified for a Bayesian belief network analysis where the severity of the risk is determined by Kuo [10] using the degree of loss and the probability of occurrence. The dataset is modified using the risk matrix shown in Fig. 4- to apply a Bayesian belief network.

$$\text{Risk} = (\text{the degree of loss}) \times (\text{the probability of occurrence}) \qquad (2)$$



Low risk level: R1, High risk level: R3

Fig. 4. Risk matrix for Bayesian belief network [3].

For this study, the probability of occurrence and the degree of loss is measured on a five-point likert scale (from very low to very high), for each risk. The risk level was simulated using a risk matrix for performing analysis of a Bayesian belief network.

4.3. A BAYESIAN BELIEF NETWORK CONSTRUCTION SIMULATION USING NETICA SOFTWARE

A Bayesian belief network is constructed by structural learning and used to examine the relationships among risk variables [3]. Consequently, a Bayesian belief network was constructed by structural learning and parameter using Netica (https://www.norsys.com/), which is a decision-support software. Fig. 5 shows a Bayesian belief networks for cost related risk based on the identified factors causing cost overruns on construction and the cause and effect relationships among factors, a conceptual model (Fig.5) is developed. As shown in Fig. 5, four risk factors directly causing cost overruns in construction projects are referred to as proximal factors. These proximal factors are Unsuitable construction program, incomplete approval, occurrence of disputes and incomplete estimates. The other factors indirectly causing cost overruns can be called distal factors. The distal factors from fig. 5 are tight project schedule, variation by client, price inflation of construction materials, inadequate programme scheduling, design variation and excessive approval procedure.

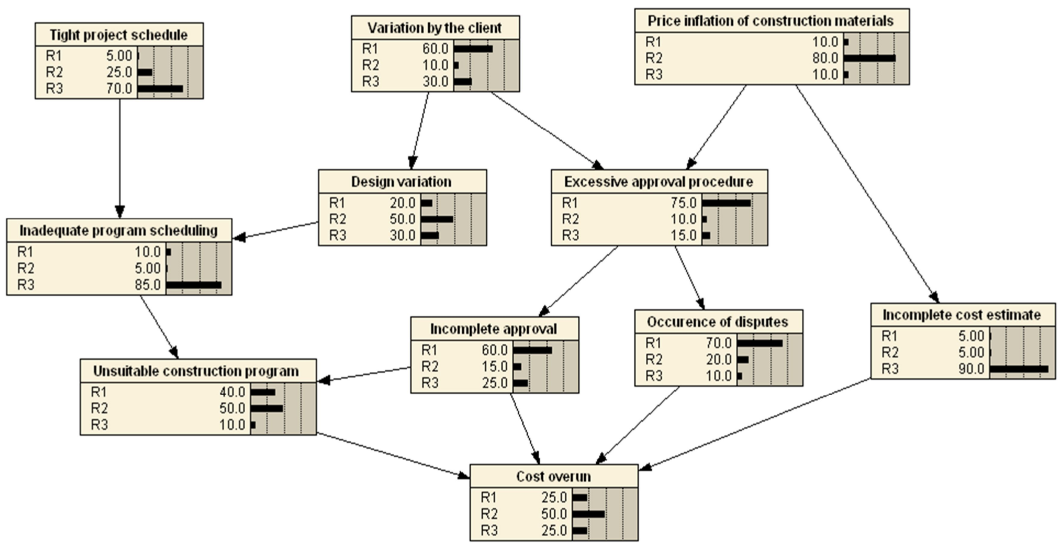


Fig. 5. A BBN for cost related risk in construction projects.

Table 2 shows the high probability risk factors of R3, which is the highest level of risk. The serious cost related risks were tight project schedule, inadequate program scheduling, design variation, inaccurate or incomplete cost estimates, unsuitable construction program and price inflation.

The risks factors that were directly related to cost overruns were unsuitable construction program planning, incomplete approval, occurrence of disputes and incomplete cost estimates.

Table 2. Major cost related risk for construction projects.

Risk factor	**R1**	**R2**	**R3**
Tight project schedule	5.0	25.0	70.0
Inadequate program scheduling	10.0	5.0	85.0
Design variation	20.0	10.0	30.0
Inaccurate cost estimate	5.0	5.0	90.0
Unsuitable construction program	40.0	50.0	10.0
Price Inflation	10.0	80.0	10.0

4.4. RISK CONTROL

After a Bayesian belief network is constructed, a sensitivity analysis is also carried out using the Netica software which efficiently measures the degree to which findings at any node can influence the beliefs at another node, given the findings currently entered [3]. The measures are in the form of mutual information (entropy reduction), or the expected reduction of real variance. Sensitivity is represented by entropy: a larger entropy between nodes produces a bigger influence [3].

Important cost related risk factors that should be controlled were selected as presented in table 3. Entropy reduction (mutual information) values were calculated for sensitivity analysis of risk factors related to project cost performance. Table 3 shows the results of the entropy reduction.

The important risk factors that directly affect cost performance are unsuitable construction program planning, incomplete approval, occurrence of disputes and incomplete cost estimates. The value of entropy reduction of unsuitable construction planning was larger than incomplete approval, occurrence of disputes and incomplete cost estimates. Since the risk factor that affected project performance are all cost related, risk reduction can be achieved through risk control efforts exerted by construction companies, and major controllable risk were listed from the sensitivity analysis.

Table 3. A summary of the sensitivity analysis for a construction project.

Project Performance	Risk Factor	Entropy Reduction
Cost overruns	Unsuitable construction planning	1.361
	Incomplete approval	1.353
	Occurrence of disputes	1.157
	Incomplete cost estimate	0.569

5. DISCUSSION

A properly implemented risk management process will enhance the successful completion of engineering construction projects and thereby making the project more profitable. In a construction project where cost really matters, executing a project within the specified budget is critical, therefore, predicting the likelihood of cost-overrun plays a key role toward project success.

Thus, risk assessment is a critical procedure for decision-making and projecting success. Its main purpose is to estimate risk by identifying the undesired events, the likelihood of occurrence of the unwanted event, and the consequence of such event. This involves measures, either conducted quantitatively or qualitatively, to estimate the significance level of the individual risk factors to the project, so as to estimate the risk to project success. Accordingly, with a better quantification measuring result, managers can recognize which risks are more important and then deploy more resources on it to eliminate or mitigate the expected consequences.

The important reasons why the Bayesian belief network is proposed for construction risk assessment in this study is that they allow inference based on observation and calculate conditional probabilities of risk factors that are the disadvantages of the influence diagram and cross impact method [3, 11]. Probabilistic inference, also called belief updating, is simply the task of computing the posterior probability distribution of the Bayesian belief network given the evidence, i.e. given the observed value of some variables in the network [11]. Inference with Bayesian belief network can be both predictive (i.e. reasoning from observations of causes to new belief about the effects) and diagnostic (i.e. reasoning from observed effects to updated belief about causes [12].

6. CONCLUSION

This study presented a methodology for engineering construction risk assessment using a Bayesian belief network. For this, we identified ten cost-related risk factors from literature review that affects a construction project cost performance. The top main cost related risks were tight project schedule, inadequate program scheduling, design variation, inaccurate or incomplete cost estimates, unsuitable construction program and price inflation of construction materials.

These risk factors were simulated using a risk matrix for performing analysis of a Bayesian belief network. Based on the variable and identified cause and effect relationships, the Bayesian belief network based model was developed for a construction project situation.

The change of project cost performance risk was measured by the risk reduction activities (entropy reduction) for unsuitable construction program planning, incomplete approval, occurrence of disputes and incomplete cost estimates.

This methodology is robust and can be applied to a variety of decision-making and sensitivity analysis in the engineering construction challenges. Bayesian belief network are more flexible to use more than other statistical methods and modelling tools.

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