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Quantifying schedule risk in construction projects using Bayesian belief networks

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Abstract

Delays on construction projects cause financial losses for project stakeholders in developing countries. This paper describes how Bayesian belief network (BBN) is applied to quantify the probability of construction project delays in a developing country. Sixteen factors were identified through a questionnaire survey of 166 professionals. Eighteen cause-effect relationships among these factors were obtained through expert interview survey to develop a belief network model. The validity of the proposed model is tested using two realistic case studies. The findings of the study revealed that financial difficulties of owners and contractors, contractor's inadequate experience, and shortage of materials are the main causes of delay on construction projects in Vietnam. The results encourage practitioners to benefit from the BBNs. This approach is general and, as such, it may be applied to other construction projects with minor modifications.

Keywords: Bayesian belief networks; Construction projects; Risk management; Scheduling; Delays; Vietnam

1. Introduction

Schedules are essential to the successful execution of projects. Without a schedule, it is difficult to coordinate the diverse activities found in a construction project [1]. Most schedules are developed in a deterministic manner. However, schedules often contain significant uncertainty [15] because risk and uncertainty are inherent in all construction activities [2]. As a result, schedule delays are common in various construction projects and cause considerable losses to project parties. It is widely accepted that construction project schedule plays a key role in project management due to its influence on project success. Therefore, it is important to quantify probabilities of schedule delays when managing a construction project. To serve the need for proactive project management, the need has emerged for the development of facile methods to evaluate the probability of construction time-overruns.

Vietnam is highly regarded by many people as a promising economy, and there is much admiration for the growth of competitiveness and investment opportunities [3]. However the construction environment in Vietnam is risky due to poor infrastructure, underdeveloped management mechanisms, bureaucratic government, and little competition between state-own and private enterprises. As a result, delays in construction projects frequently cause financial losses for project stakeholders. As the saying goes, "a problem well identified is a problem half-solved". Therefore, predicting possible construction schedule delays is an effective step towards improving the chances for success on construction projects. There has been very little empirical work done on this subject in the Vietnam construction industry (VCI).

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The aim of this paper is to describe how BBN method can be used to predict schedule delay probability on construction projects in the VCI. Although the research is localized to the VCI, the approach being proposed can be applied in other construction industries. Therefore, the result should be useful, not only to practitioners in Vietnam but, also in other countries especially the developing economies.

2. Literature review

2.1. Significant factors causing delays on construction projects

The major factors causing delays on construction projects have been reviewed and critically appraised in many scientific journals and reports. Delay factors can be grouped under nine categories (Table 1) by adopting the classification in Assaf's work [18]. As shown in Table 1, owner-, contractor-, consultant-, and designer-related factors are factors caused by clients, contractors, consultants, and designers, respectively. Material-, workforce-, and equipment-related factors are input factors in the construction process relating to materials, workforce, and equipment, respectively. Environment-related factors are exogenous factors such as inclement weather, changes in government regulations and laws, traffic control and restriction at jobsite, and slow municipality permits. Project-related factors are factors deriving from the project characteristics and the project delivery system. Unrealistic contract duration, ineffective delay penalties, type of project bidding and award, and type of construction contract are typical factors in this category.

Moreover, there have been significant efforts devoted to identifying and evaluating the relative importance of the significant factors contributing to delay and cost overruns in construction projects [4–9,12,14–19], and to using artificial neural networks [10] as well as regression models [7,10,11,13,20] to predict time and cost performance of a variety of construction projects. Review of the extant literature shows that very little have been done on forecasting the probability of schedule delays in spite of its vital role in contributing to the success of construction projects. A Bayesian belief networks-based (BBN-based) model incorporating uncertainties through their conditional probabilities is an appropriate tool to provide proactive actions for stakeholders. A list of preliminary delay factors were derived from the aforementioned studies in order to ascertain the significant delay factors impacting construction projects in Vietnam.

2.2. Bayesian belief network method

Bayesian belief networks (BBNs), referred to as belief networks, were first developed at Stanford University in the 1970s [21]. BBNs describe cause-effect relationships among variables through graphical models. Belief networks consist of nodes, representing variables of the domain, and arcs, representing dependence relationships between the nodes [21]. Fig. 1 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. The cause-effect relationship between the *parent node* and the *child node* is often represented by an arrow or an arc referred to as edge. Child nodes are conditionally dependent upon their parent nodes.

BBNs are based on conditional probability theory which was developed in the late 1700s by Thomas Bayes. He discovered a basic law of probability which was then called Bayes' theorem [36]. Bayes' rule may be simply expressed as follows:

$$P(B/A) = \frac{P(A/B) * P(B)}{P(A)}$$

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

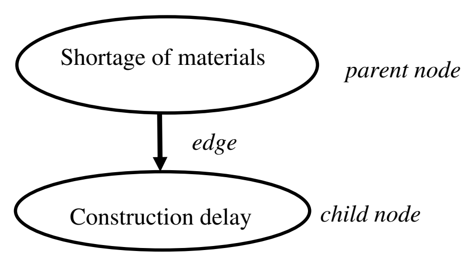


Fig. 1. A simple belief network in the construction delay.

Table 1
Summary of previous papers used to review and identify the major factors causing delays on construction projects

No.	Groups of delay factors	Authors
1	Project-related factors	[4,5,7,9–12,16,15,17–20,41,42,44,48,53,57,59,60,69,70,75–77]
2	Owner-related factors	[5–10,12,14–16,18,19,29,38,42,45,57,64,65,75,77]
3	Contractor-related factors	[4–10,12,14–19,29,37–39,44,47,52–54,56,57,64,69,70,72,74,77]
4	Consultant-related factors	[18,6,12,8,9,15,16,19,29,38,45,57,64,65,77]
5	Design-related factors	[4–7,11,15,17–20,38,42,44,47,52,54,57–59,64–66,71–75,77]
6	Material-related factors	[4,6,8,9,11,12,14–18,41,55,57,62,65,69,72,74,70,75,77]
7	Workforce-related factors	[4–9,12,15,16,18,39,41,43,46,47,49,50,54,56,57,61,65,68,72,74,77]
8	Equipment-related factors	[4,7,6,8,11,12,14–16,18,42,55,57,65,69,70,74]
9	Environment-related factors	[4–10,12,14–16,18,19,40,51,54,57,59,62,63,65,67,69,70,72,74,75,77]

The use of BBNs in construction has focused mainly on the improvement of construction operations [21], diagnosing upsets in an anaerobic wastewater treatment system [22], estimating the false-work erection productivity [23], making inferences in highway construction costs [24], estimating the pessimistic and optimistic values of activity durations based on project characteristics [15], and analyzing risk in construction contracts [25]. A review of aforementioned studies indicates that a quantitative evaluation of the factors influencing time performance in construction projects in Vietnam has yet to be performed.

3. Research methodology

3.1. Conceptual research framework

The study considered BBNs as the tool for predicting the probability of schedule delay because BBNs have the following principal advantages: (1) belief networks provide great flexibility in their capacity for accepting input and providing output [21]; (2) belief networks have the ability to allow the value of a variable to be entered as a known input or to evaluate the likelihood of a variable as an output of the system [21]; (3) BBNs can readily calculate the probability of events before and after the introduction of evidence and update its diagnosis or prediction [22]; (4) belief networks may be developed using expert opinion instead of requiring historical data [21]; (5) belief networks also allows variables to be added or removed without significantly affecting the remainder of the network because modifications to the network may be isolated [21]; and (6) BBNs gain insight into relationships among variables of the process due to its graphical display. However, the Bayesian method also has disadvantages that have been elaborated by Adams [25].

In order to develop a well-designed BBN research framework, the paper adopts, adjusts and breakdowns steps of a belief network model from McCabe et al. [21] which is considered to be suitable for the conditions of the VCI. Fig. 2 presents the step-by-step conceptual

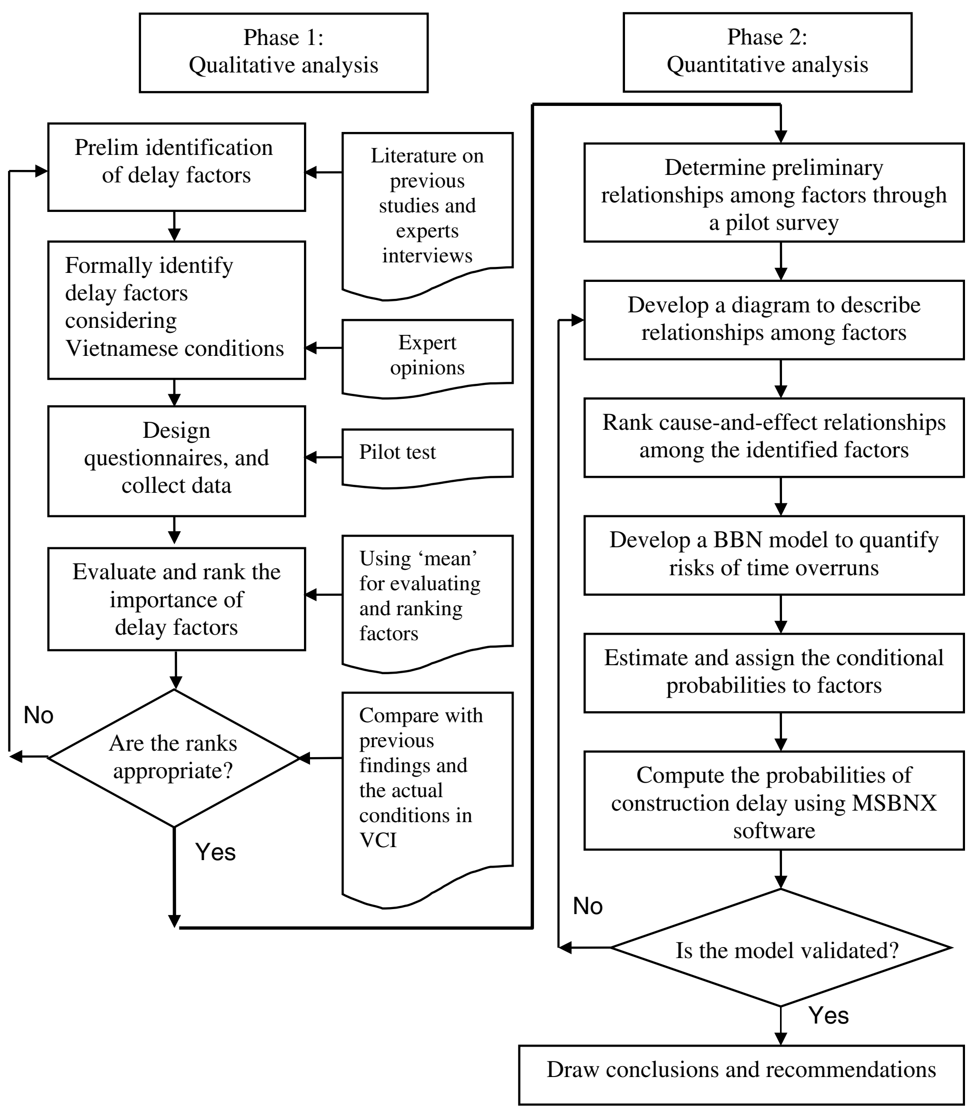


Fig. 2. Conceptual research framework.

research framework consisting of two phases: a qualitative phase and a quantitative phase.

3.2. Phase 1: qualitative analysis

The purpose of this phase was to identify significant delay factors being applicable to the context of construction projects in Vietnam. A set of factors was initially identified from the published literature and brainstorming sessions with experts. Unstructured interviews were conducted with an expert group comprising ten construction practitioners and four academicians to identify the delay factors experienced in the VCI. This process yielded 42 factors, indicating the typical causes of delays on construction projects in Vietnam. Since lack of clarity in defining delay can lead to misleading conclusions [12], the definition of delay was explained clearly to the interviewees. Respondents were told that delay means time-overrun beyond the completion date specified in the contract for a construction project [18]. The study comprises three types of questionnaires (all in Vietnamese): (1) questionnaire 1 for evaluating the influence level of factors on the construction schedule; (2) questionnaire 2 for identifying cause-effect relationships among the causes of delays; and (3) questionnaire 3 for determining the conditional probabilities of the BBN-based model developed using data from two real projects.

A questionnaire (type 1) incorporating 42 factors was then carefully designed to evaluate the relative importance of delay factors. To facilitate the answers, a five-point Likert-type scale (from 1 = "no effect" to 5 = "strong effect") was adopted for rating by the respondents. Two hundred and eighty copies of the questionnaire were distributed to a random sample of construction personnel involved in construction projects in Ho Chi Minh city. Responses were received from 166 professionals. A response rate of 59% is adequate to analyze surveys in the construction industry [4,13]. To elicit the relative importance of factors, the study adopted the mean and Cronbach's alpha values for each of the factors. Sixteen factors (Table 2), which have the mean and Cronbach's alpha values higher than 3.5 and 0.7, respectively, were considered to be important factors contributing to construction delay. These values of Cronbach's alpha are adequate to proceed to the next steps as per the assertion by Mohamed [26]. Consequently, the sixteen factors were grouped into five categories as risk variables for the conceptual BBN-based model. The categories are materials, consultants, contractors, owners and construction environment.

3.3. Phase 2: quantitative analysis

The purposes of this phase are to determine the cause-and-effect relationships among factors identified in the qualitative phase, to develop the BBN-based model, and to estimate the probability of delays in construction. Firstly, the study used questionnaire 2 to determine the cause-effect relationships among the 16 identified factors. The questionnaire consists of two subtypes. The first-subtype questionnaire was designed in matrix form, in which the left column presented 16 identified factors as causes and the top row presented those factors as effects. Participants were asked to rate the factors using the following number values: 'very strong relationship' – 4, 'strong relationship' – 3, 'somewhat relationship' – 2, 'weak relationship' – 1, 'no relationship' – 0. One hundred and seventy participants were selected and the fist-subtype questionnaire was mailed to them. Eighty-eight responses were received, representing a response rate of 52%. The answers were statistically analyzed to elicit the implications behind

Table 2
Sixteen significant causes of construction delay in Vietnam construction industry (VCI)

Causes of delay	Overall		Owners		Site supervisors		Designers		Contractors	
	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
Owners' financial difficulties (x_1)	4.23	1	4.26	4	4.19	2	4.25	1	4.23	1
Inadequate contractors' experience (x_2)	4.13	2	4.29	3	4.27	1	3.82	4	4.14	2
Shortage of materials (x_3)	4.07	3	4.35	1	3.92	3	3.89	3	4.07	3
Contractors' financial difficulties (x_4)	3.98	4	4.35	1	3.85	4	3.79	5	3.94	7
Slow site handover (x_5)	3.94	5	3.87	7	3.81	5	3.96	2	4.00	5
Delays in progress payments by owners (x_6)	3.80	6	3.48	15	3.69	9	3.46	13	4.07	3
Low awarded bid prices (x_7)	3.73	7	3.52	14	3.27	14	3.75	6	3.96	6
Inappropriate construction methods (x_8)	3.70	8	3.81	10	3.54	12	3.61	7	3.74	9
Defective works and reworks (x_9)	3.67	9	3.87	7	3.58	10	3.54	8	3.68	11
Material price fluctuations (x_{10})	3.66	10	3.87	7	3.15	16	3.50	11	3.79	8
Lack of capable and responsible site supervisors (x_{11})	3.64	11	4.00	5	3.42	13	3.29	14	3.70	10
Inclement weather (x_{12})	3.63	12	3.61	13	3.81	5	3.54	8	3.62	13
Owners' site clearance difficulties (x_{13})	3.57	13	3.39	16	3.73	7	3.54	8	3.59	14
Lack of capable owners/project managers (x_{14})	3.56	14	3.71	11	3.58	10	3.50	11	3.52	16
Designers' inadequate experience and capability (x_{15})	3.55	15	3.97	6	3.23	15	3.11	15	3.64	12
Shortage of equipment (x_{16})	3.52	16	3.68	12	3.73	7	3.11	15	3.53	15

Note: x_i = encoding of the factor i.

Table 3
Eighteen cause-and-effect relationships among variables

Rank	Cause-effect relationships	Model variables	Mean	SD
1	$x_{13}-x_5$	$X_{13\text{–}5}$	3.27	0.854
2	x_5-y	$X_{5\text{–}y}$	3.23	1.003
3	x_3-y	$X_{3\text{–}y}$	3.20	0.860
4	x_4-x_3	$X_{4\text{–}3}$	3.14	0.899
5	x_1-x_6	$X_{1\text{–}6}$	3.08	1.127
6	x_2-x_8	$X_{2\text{–}8}$	3.03	0.877
7	x_6-x_4	$X_{6\text{–}4}$	2.85	0.824
8	x_9-y	$X_{9\text{–}y}$	2.83	1.031
9	x_8-x_9	$X_{8\text{–}9}$	2.67	0.956
10	$x_{14}-x_6$	$X_{14\text{–}6}$	2.63	0.835
11	x_1-x_{13}	$X_{1\text{–}13}$	2.51	1.213
12	$x_{10}-x_3$	$X_{10\text{–}3}$	2.38	1.138
13	$x_{15}-x_9$	$X_{15\text{–}9}$	2.28	0.909
14	$x_{11}-x_8$	$X_{11\text{–}8}$	2.23	0.867
15	x_4-x_{16}	$X_{4\text{–}16}$	2.17	0.746
16	$x_{16}-x_8$	$X_{16\text{–}8}$	2.07	1.070
17	x_7-x_4	$X_{7\text{–}4}$	2.05	1.209
18	$x_{12}-y$	$X_{12\text{–}y}$	2.02	0.994

Note: SD = standard deviation.

the respondents' evaluation. Table 3 shows the average scores and the standard deviations of 18 significant pairs.

There are pairs of factors having either no relationship or weak relationship. For example, 'inclement weather' has no relationship with 'owner's financial difficulties' or 'contractor's financial difficulties'. Therefore, discussion between the authors and nine experts reduced the number of factor pairs significantly to 20. This resulted in the second-subtype questionnaire, which was a graphical representation of conditional dependence among the identified factors. To obtain conditional dependence relationships between those factors, the study adopted a procedure consisting of nine logical tests using two statistical values, namely the average and the skewness. Nine experts were involved in this procedure. Details of this procedure are available in Nasir et al. [15]. The procedure yielded 4 parent nodes, namely 'inclement weather', 'defective works and reworks', 'slow site handover' and 'shortage of materials'; and the child node, namely 'construction delay'. Discussion of cause-and-effect relationships is given in the next section.

Based on the 16 risk factors and the 18 cause-effect relationships among them, the free download computer program, MSBNX, was used to develop the BBN-based model. Finally, the developed model used two construction projects as case studies to validate the model. Details of this are available in the section on case studies.

4. Findings and analysis

4.1. Respondents profile

More than half (58%) of respondents in the first survey are functional and top managers (48% from top managements and 10% from functional managers). The large proportion of top and functional managers confirms the reliability of collected data for identifying factors affecting construction delay. The proportions of the respondents in terms of number of years involved in construction were: less than or equal to 5 years (29%), between 5 and 10 years (52%), and 10 years or more (19%). It would have been better if the proportion of respondents with 10 years or more could be increased. Moreover, the respondents have been involved in building projects (52%), industrial construction projects (30%), irrigation projects (3%) and others (15%). These implied that the study focuses mainly on building projects and industrial construction projects.

Among the respondents in the first survey, more than two-third confirmed that they often encountered construction delay whereas 4% rarely encountered delays and 24% always encountered delays. This implies that construction delay is 'a chronic disease' in the VCI. In addition, about 46% of respondents indicated that the average time-overrun is between 10% and 20% of the original construction duration while 24% of them confirmed that it is more than 20% of the agreed construction duration. Research in Saudi Arabia [18] showed that the average time-overrun is between 10% and 30% of the original duration.

4.2. Factors influencing construction delay

The collected data were statistically analyzed to determine the mean value of 42 delay factors. Table 2 shows the 16 most significant factors influencing construction delay. The results revealed that the top main causes of delay in construction of building projects and industrial construction projects included owner's financial difficulties, contractors' inadequate experience, shortage of materials, contractor's financial difficulties, slow site handover, inappropriate construction methods, defective works and reworks, and lack of capable owners/project managers. It is noticeable that contractors and consultants rated the factor "slow site handover" as very important, whereas the owners who take full responsibility for the site clearance only rated it as less significant.

Contractors and consultants ranked "owner's financial difficulties" as first priority whereas owners ranked it fourth. An acceptable explanation is that the complex procedure and bureaucracy in the local authorities are the main causes of this situation. Vietnam is typical among the less-developed economics in the ASEAN and East Asia [27]. Thus the Vietnamese government, the biggest customer of the VCI, empowered local authorities to undertake, as essential owners, medium and large projects. Though the domestic private sector has increased in recent years [28], this growth is trivial. As such, practitioners are still encountering this problem.

In Table 2, the second most highly rated cause of delay in construction projects is 'contractors' inadequate experience'. In Vietnam, there are no specialized construction management firms [29]; therefore, weak capacity of project management units (PMU) causes delays in the procurement process because most contracts entrust construction works to inexperienced contractors. It is interesting to note that contractors undertaking construction works themselves ranked ‘inadequate experience of contractors’ as a very important cause of delay.

Owners rated ‘shortage of materials’ and ‘contractor’s financial difficulties’ as the most important sources of delay, while contractors and consultants did not seem to agree. These imply that weak competence of project managers/owners in procurement planning and contract management, which seems very common in developing countries [17,18], resulted in project delay.

By contrast, the factor ‘designer’s inadequate experience and capability’ was ranked relatively low by all parties. Notably, owners rated this factor as important whereas contractors and consultants rated it unimportant. Since the VCI is still a labor-intensive industry [29], the least significant factor attributed to cause delay in construction projects in Vietnam is shortage of equipment.

4.3. Cause-effect relationship among variables

The data analysis shows that the relationship between ‘owner’s site clearance difficulties’ and ‘slow site handover’ has been ranked highest (Table 3) by 88 respondents in the second survey. Project site clearance usually faces many conflicts – internal and interface conflicts [30], between project teams and communities [29]. This is becoming more serious in Vietnam. Different from other countries, the Vietnamese Land Law separates the right of land use from the land property. The Government reserves for itself land ownership whereas people have only the right of land use. Before commencing construction and starting projects, owners have to negotiate with communities for compensation for the right of land use and then must meet with approval from the local government. As a result, the major causes of project delay are the bureaucracy in local government departments for the right of land use and the complex procedure for issuing land use certificates. The World Bank has expressed dissatisfaction with several projects in Vietnam for the same reasons [31].

Respondents indicated that inclement weather, defective works, slow site handover by owners, shortage of materials by contractors directly affect schedule delay (Table 3). This is a reasonable conclusion in Vietnamese conditions since the aforementioned factors have been widely reported to cause significant delays in project implementation [32–35]. It is worth noting that more than half (64.7%) of respondents who were contractors and owners rated contractor-related and owner-related relations as a very important causal relationship.

5. Case studies application of BBN-based model

5.1. Model description

Based on the identified factors causing delay on construction and the cause-and-effect relationships among factors, a preliminary model was developed and presented to functional managers on two case study building projects in Ho Chi Minh city. Brief information on the case studies is presented in the next section. At the first site visit late in April 2006, the functional managers were asked to verify which factors and relationships were appropriate for specific conditions in their project. The conceptual model was then finalized. The logic of sequence in the conceptual model (Fig. 3) is based on results of expert interviews and can be explained under the context of the VCI.

Since the majority of Vietnamese real estate developers are medium-sized companies, owner’s financial difficulties are common in Vietnam and are sources of financial shortages for land use compensation and for monthly payments to contractors. In addition, incapable project managers, who are deficient in necessary skills for monitoring and controlling project performance, may also cause late payments to contractors because of late approval of completed works. Next are low tenders due to competition between bidders, owner’s acceptance of the lowest tender, and delays in payment by owners can lead to financial difficulties for contractors which may, in turn, cause late delivery of materials, equipment shortages. Subsequently, equipment shortages, contractors’ inadequate experience, and incapable site supervisors may cause inappropriate construction methods which can result in defective works and reworks. Since designers are responsible for impractical designs and are not involved throughout the project’s life, incapable designers may cause defective works and reworks. Contracts are often awarded to incapable designers, consultants and contractors due to unfair and “unsound” (i.e., bid shopping) bidding processes in Vietnam [29]. Besides, owners must completely compensate for land use right before site clearance in conformance to the Land Law. Therefore, owner’s difficulties in site clearance, such as funding deficiencies and complex procedures of compensation for land use, may cause slow site handover and subsequently result in delays to the construction phase. Eventually, slow site handover deriving from slow permits by local government officials and conflicts with neighbors, shortage of construction materials resulting from fluctuations of material prices, defective works and reworks, and inclement weather may directly cause significant delays in the construction phase.

As shown in Fig. 3, four factors causing delay in construction schedule are referred to as proximal factors. Other factors indirectly causing project delay can be called distal factors. Quantitative risk evaluations of construction schedule delay in the two case studies are established based on the conceptual models that were developed.

5.2. Description of the case studies

Two case studies were used to validate the BBN-based model. Table 4 presents brief information on both projects. The two projects were funded by private owners and were high-rise buildings in Ho Chi Minh city. Project A was

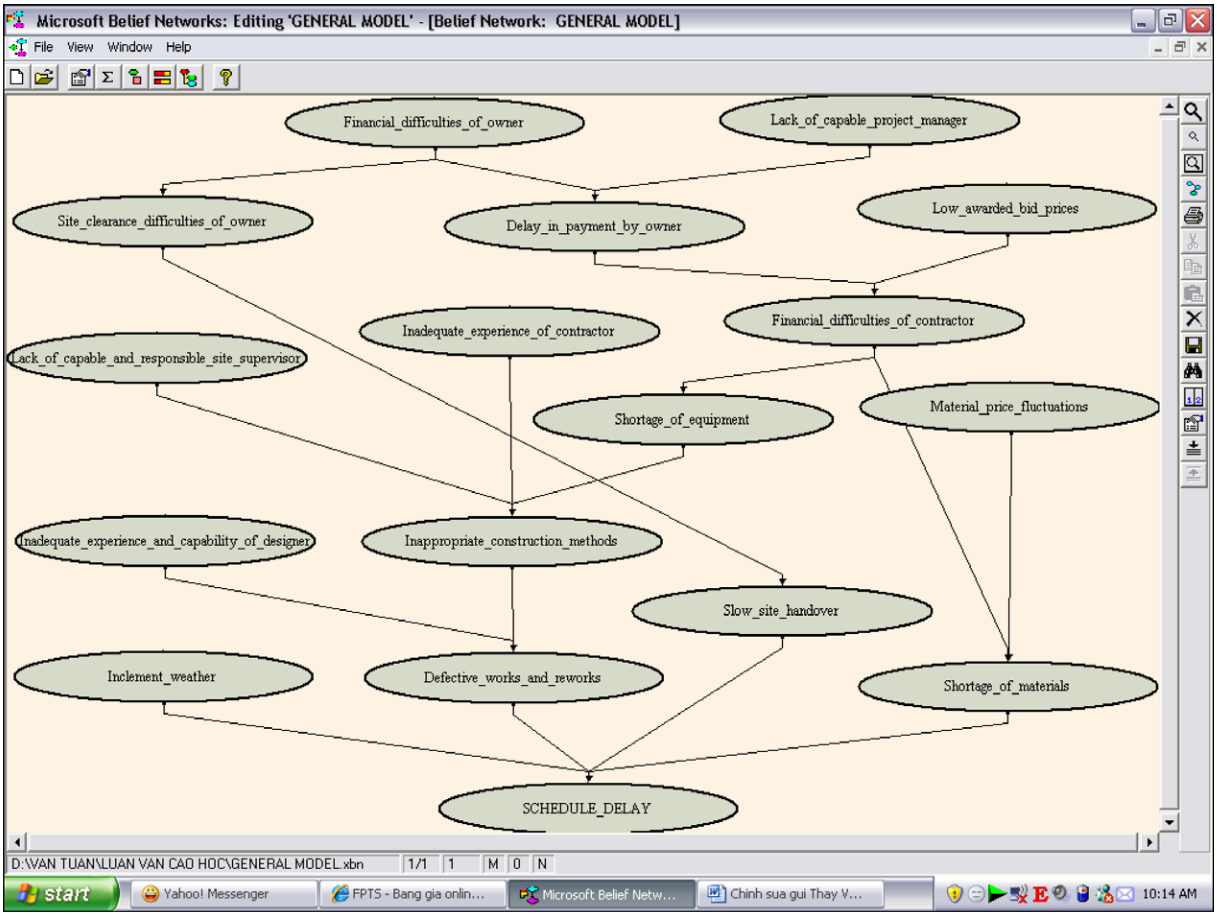


Fig. 3. The conceptual BBN-based model for predicting the probability of construction delay.

under construction while project B was completed at the time of study.

5.3. Verifying variables and cause-and-effect relationships

Before applying the BBN-based model, the verification of variables and cause-and-effect relationships are indispensable for the model's validation. Therefore, the model was insightfully verified and applied into the construction phase of the two case studies. The following work was conducted to present the model validation and to demonstrate its application.

The conceptual model was then refined by professionals in the two projects. Cause-and-effect relationships among variables were also reviewed and re-defined by line and functional managers involved in each project. In order to ensure that the model is suitable for each case study, managers were encouraged to add new factors or to remove others from the conceptual model.

After reviewing, the BBN-based model for project A (Fig. 4) differed from the conceptual model in 'site clearance difficulties of owners'. As per the Vietnamese Land Law, owners must completely compensate for land use on a new project before starting site clearance. Depending on the conditions of each project, the local government will then permit clearing the whole or partial project area in order to mitigate adverse impacts to the local community. Thus, slow site handover of the remaining area may cause critical delays. In this paper, 'site clearance difficulties of owners' are problems deriving from compensating for land use while 'slow site handover' not only concerns problems caused by site clearance difficulties of owners but also by slow government permits and conflicts with neighbors.

Table 4
Brief information about two projects

Description	Project A	Project B
Project type	Building project	Building project
Owner	Private sector	Private sector
Project scope	22 floors including one basement	10 floor including one basement
Commencement date	April 2004	March 2005
Completion date based on construction contract	June 2006	November 2005
Original duration based on contract	26 months	8 months
Actual completion date	August 2006	December 2005
Time-overrun duration	02 months	01 month
Percentage of time-overrun	7.7%	12.5%

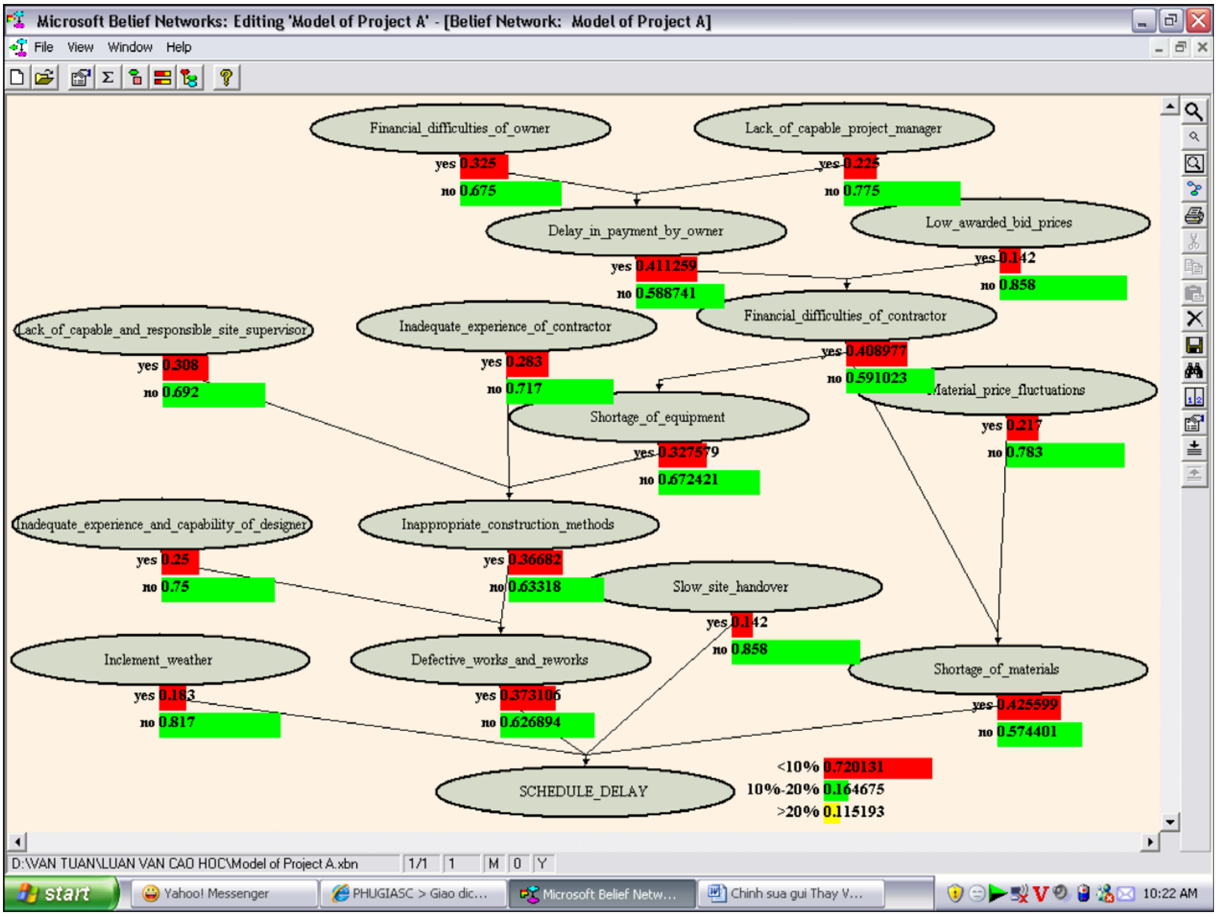


Fig. 4. The BBN-based model and base-run probabilities for variable's states (project A).

For project A, a new project, although compensating for land use was fully completed, the local government only allowed 60% of the site area to be cleared. Therefore, although 'site clearance difficulty of the owner' was absent from model A, 'slow site handover' was still cited perhaps due to slow granting of permits by the municipality for clearance and possible problems with neighbors.

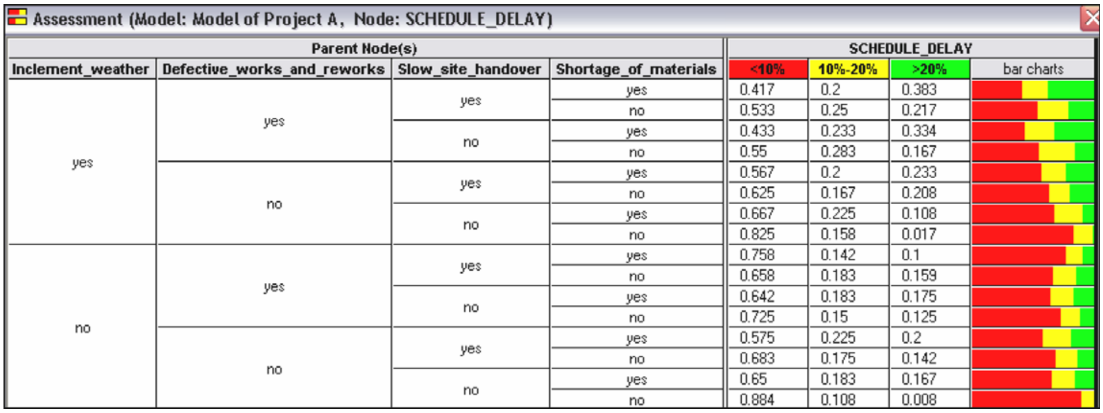
The BBN-based model for project B differed from the conceptual model in 'site clearance difficulties of owners', 'lack of capable project managers', and 'slow site handover'. It should be noted that project B is concerned with the re-construction of a very old building. Thus, there were very few problems of site clearance. In addition, the owner of project B employed a professional firm of project management consultants. As a result, 'lack of capable project managers' did not feature in the model for project B.

5.4. Computerized model building

Based on the variables and cause-and-effect relationships identified by line and functional managers, the BBN-based model was built using the free download software MSNBX from Microsoft Inc. In a BBN, each variable has four characteristics as follows: (1) the variable name; (2) the variable status; (3) its relationships (parent node) with other variables (child nodes); (4) its data table (table of condition probabilities). Since the determination of a variable's state is important for computerized applications, each variable is assigned its appropriate status to reflect its conditions in regard to the risk during the construction phase. For example, the variable 'schedule delay' is assigned three states, namely '<10%', '10–20%', and '>20%' whereas the remaining variables have two opposite states: 'YES' and 'NO'. The assignments '<10%', '10–20%', and '>20%' are defined as time-overrun durations which are less than 10%, between 10% and 20%, and greater than 20% compared to the original duration stipulated in the construction contract, respectively. It should be noted that the assigned states for each variable was advised by project managers who were directly in charge of the construction tasks in both projects. Data tables for the variable 'schedule delay' (Fig. 5) and the other variables (Fig. 6, for example) are inputs from the judgments of line and functional managers in the cases. This technique is referred to as Bayesian belief networks or belief networks because of the aforementioned manner of data input.

5.5. Computerized model input

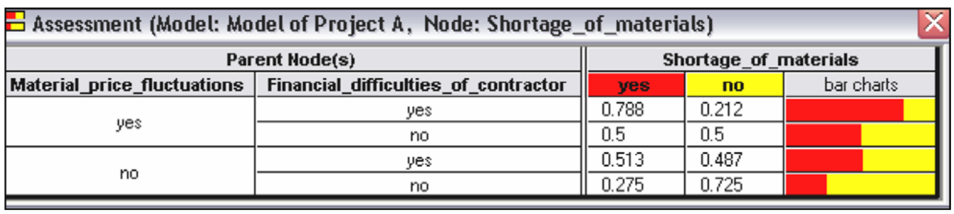
After the computerized model was built in the MSBNX environment and verified by managers, questionnaire 3,



Assessment (Model: Model of Project A, Node: SCHEDULE_DELAY)

Parent Node(s)				SCHEDULE_DELAY			
Inclement_weather	Defective_works_and_reworks	Slow_site_handover	Shortage_of_materials	<10%	10%-20%	>20%	bar charts
yes	yes	yes	yes	0.417	0.2	0.383	
			no	0.533	0.25	0.217	
		no	yes	0.433	0.233	0.334	
			no	0.55	0.283	0.167	
	no	yes	yes	0.567	0.2	0.233	
			no	0.625	0.167	0.208	
		no	yes	0.667	0.225	0.108	
			no	0.825	0.158	0.017	
no	yes	yes	yes	0.758	0.142	0.1	
			no	0.658	0.183	0.159	
		no	yes	0.642	0.183	0.175	
			no	0.725	0.15	0.125	
	no	yes	yes	0.575	0.225	0.2	
			no	0.683	0.175	0.142	
		no	yes	0.65	0.183	0.167	
			no	0.884	0.108	0.008	

Fig. 5. Full data table for the output variable ‘schedule delay’.



Assessment (Model: Model of Project A, Node: Shortage_of_materials)

Parent Node(s)		Shortage_of_materials		
Material_price_fluctuations	Financial_difficulties_of_contractor	yes	no	bar charts
yes	yes	0.788	0.212	
	no	0.5	0.5	
no	yes	0.513	0.487	
	no	0.275	0.725	

Fig. 6. Full data table for variable ‘non-available materials on time’.

shown in part in Table 5, was developed to obtain the conditional probabilities for each variable from line and functional managers. Eight experts participated in the survey. Generally, experts were asked to judge frequencies of a variable's states based on certain states of other variables that have cause-and-effect relationships with that variable. For example, given that: (1) ‘inclement weather’ and ‘defective works and reworks’ are NO; (2) ‘slow site handover’ and ‘shortage of materials’ are YES, the frequencies of ‘<10%’, ‘10–20%’ and ‘>20%’ states of ‘schedule delay’ were judged as 57.5%, 22.5% and 20%, respectively (Fig. 5). These frequencies were facilitated in practice by a built-in function of MSBNX. Based on expert's judgment, a similar procedure is applied to each state of this variable – ‘schedule delay’ – in other conditions and to the other variables.

Table 5
A part of questionnaire 3 to quantify the conditional probabilities for each variable

Parent nodes If		Child node Defective works and reworks	
Inappropriate construction methods	Designer's inadequate experience and capability	Yes	No
Yes	Yes		
	No		
No	Yes		
	No		

5.6. Model output and evaluation

After the data input facilitated by MSBNX, the model could be used to identify and evaluate the probabilities of each variable's states. Table 6 illustrates the model outputs for projects A and B.

It is estimated that the likelihood of construction delay in project A is approximately 72% for the state of “<10%”, whereas it is 16% for the state of “10–20%” and 12% for the state of “>20%”. Consequently, the construction duration of project A tends to extend with time-overrun duration less than 10% of the original duration. Regarding project B, the likelihood of construction delay is approximately 67% for the state of “10–20%” whereas it is 20% for the state of “<10%” and 13% for the state of “>20%”. Consequently, the construction duration of project B tends to extend with time-overrun duration between 10% and 20% of the original duration.

In reality, there was a two-month delay by the contractor on project A completed in August 2006. The delay on project A is 7.7% of the original duration (26

Table 6
The BBN-based model outputs for project A and B

The states of construction time-overrun (compared with original duration based on contract)	The probabilities of time- overrun (%)	
	Project A	Project B
“<10%”	72	20
“10–20%”	16	67
“>20%”	12	13

months). Interestingly, the model predicted that the probability of construction delay in project A is nearly 72% with time-overrun less than 10% of the project's original duration. This implied that the BBN-based model gave very good prediction for construction delay in project A. For project B, there is a 1-month delay, which is approximately 12% of the project's original duration. The BBN-based model for project B forecasted that the probability of construction delay is approximately 67% with the time-overrun between 10% and 20% of the original duration. In summary, the BBN-based model provided a good prediction for quantifying construction delay in both case study projects.

Moreover, each project stakeholder can identify its capability to eliminate the possibility of time-overrun. For example, on project A, contractors should understand their responsibility to provide materials on time and should be well-prepared for their finance to avoid time-overrun since the probability of "shortage of materials" and "financial difficulties by contractors" are 43% and 41%, respectively (Fig. 4). Owners should recognize their duty in monthly payment on timely basis to contractors as an effective solution to eliminate time-overrun.

The model can be used to evaluate the effects of each variable's state on the distribution of the other variables. This technique is called sensitivity analysis which can help project managers to make right decisions in order to avoid construction delay. For example, regarding project A, when "shortage of materials" is NO (probability of NO state is 1), the probability of time-overrun being less than 10%, between 10% and 20%, and >20% is 79%, 14% and 7%, respectively (Table 7). Conversely, the probabilities of '10–20%' and '>20%' increases to 19% and 18%, respectively when "shortage of materials" is YES (probability of YES state is 1). It can be said that the probable time-overrun of project A is very sensitive to the "shortage of materials". Most other factors are insensitive in the case study A. Similarly, the results of sensitive analysis indicated that the probability of project B's time-overrun is very sensitive to the "shortage of materials". Therefore, the probable time-overrun is very sensitive to the 'shortage of materials'. It is recommended that all project parties should focus on eliminating shortage of materials in order to avoid time-overrun.

Table 7
The probability distributions of construction time-overrun under different scenarios (project A)

Scenarios of "non-available materials on time"	Probability distribution (%) of construction time-overrun		
	"<10%"	"10–20%"	">20%"
YES	63	19	18
Base-run	72	16	12
NO	79	14	7

6. Conclusions

In a construction project where time truly equals money, the management of time is critical [1], thus predicting the likelihood of time-overrun may play a key role towards project success. As the saying goes, "we cannot manage what we cannot measure". Project managers should know the probability of time-overrun in order to take the necessary corrective actions. Therefore, a distinct need has emerged to develop facilitated methods for evaluating the probability of construction time-overruns. The major objective of this paper is to quantify the probability of delays in construction projects in Vietnam using Bayesian belief networks. The main results of the study are as follows:

- Sixteen significant factors causing delays in construction projects in Vietnam were identified as the result of a comprehensive literature survey (survey 1) and ratings by construction professionals in Vietnam. Following this, 18 cause-and-effect relationships among the 16 factors were established based on expert survey.
- The top main causes of delay in building and industrial construction projects included owner's financial difficulties, inadequate experience and financial difficulties of contractors, shortage of materials, slow site handover, inappropriate construction methods, defective works and reworks, and lack management capacity by owners/project managers.
- Based on the variables and identified cause-and-effect relationships, the BBN-based model was developed and applied to two case study building projects in Ho Chi Minh city in order to validate the model. The model performed well in predicting the probability of construction delay in both case studies.
- The model developed may be used to evaluate the effects of each variable's state on the distribution of other variables. The result of sensitivity analysis using the BBN-based model indicated that construction delay is extremely sensitive to the factors 'shortage of materials', 'defective construction work' and 'slow site handover'.

It is recommended that contractors should clearly understand their responsibility to provide materials on time and be well-prepared for this financial responsibility in order to avoid time-overrun. Owners need to focus on their responsibility for monthly timely payment to contractors as an effective solution to eliminate delay in construction projects. Moreover, it should be noted that all project parties should focus on the shortage of materials as a way of preventing time-overrun. In summary, the risk assessment model for construction delay in building projects using BBNs has been developed and the potential demonstrated in this study. The results proved that belief networks are very useful when historical data are insufficient. In such cases, the experts' judgment plays a vital role. Belief networks are an expressive graphical language for representing uncertain knowledge about causal and associational relations among [24] construction schedule variables.

Although extensive efforts have gone into this study, limitations are unavoidable. The research team reviewed more than fifty papers to identify preliminary factors causing delays on construction. However literature review can never be exhaustive. It should be possible to extend the BBN-based model by adding more variables and cause-and-effect relationships in order to accurately quantify probable delay on other construction projects. Moreover, each variable can be assigned more than the two states (YES and NO) used in the present model. This research used two case studies to validate the proposed framework and model. Thus, generalization for the other similar projects may be too bold. Future research could use the BBN-based model in other construction projects in order to explore its utility. However, the approach in this research is still general, and as such, it may be applied to other construction projects with minor modifications. The results encourage practitioners to benefit from the power of BBNs.

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