Evaluating Risk in Construction–Schedule Model (ERIC–S): Construction Schedule Risk Model

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Abstract: Research was undertaken to develop a method to assist in the determination of the lower and upper activity duration values for schedule risk analysis by program evaluation and review technique analysis or Monte Carlo simulation. A belief network was the modeling environment used for this purpose, and the resulting model was named Evaluating Risk in Construction–Schedule Model. The development of the belief network model consisted of four steps. First, construction schedule risks were identified through a literature review, an expert review, and a group review by a team of experts. Second, cause effect relationships among these risks were identified through an expert survey. This led to the development of the structure of belief network model. Third, probabilities for various combinations of parents for each risk variable were obtained through an expert interview survey and incorporated into the model. Finally, sensitivity analysis was performed. The model was tested using 17 case studies with very good results.

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Introduction

"Probability is not about numbers. It is about the structure of reasoning."-Glenn Shafer CII (1989) defined risk as the probability that an unfavorable outcome will occur. Hertz and Thomas (1983) defined risk as uncertainty and the result of uncertainty. It refers to a lack of predictability about structure, outcomes, or consequences in a planning or decision situation. Risk analysis involves estimating the probabilities needed as input data for the evaluation of decision alternatives (Lifson and Shaifer 1982).

Construction projects are complex in nature and have many inherent uncertainties. These uncertainties are not only from the unique nature of the project but also from the diversity of resources and activities (CII 1989). In addition, external factors have a very significant effect on the outcome of a project. Broadly, these risks can affect the two basic factors against which the success of a project is usually measured—the schedule and the budget. This paper focuses on schedule risks.

Schedules are used to control engineering projects (CII 1986). Construction planning and scheduling is a logical analysis of a construction project together with a thorough knowledge of construction methods, materials, and practices (Fisk 1997). Most schedules are developed in a deterministic manner, i.e., activity durations are given as a single value, usually the most likely duration. There is an assumption that the duration is known with some certainty; however, the schedule often contains significant uncertainty, especially for nonroutine or risky projects. To address this issue, the program evaluation and review technique (PERT) was developed for the U.S. Navy in 1958 (Kerzner 2001).

For PERT, the estimator is required to define a statistical distribution for each activity that represents its possible durations in light of the uncertainty in the project. Any distribution can be defined; however, the beta or triangular distributions are often used, because sufficient data are rarely available for analysis to define a distribution with complex parameters. The beta and triangular distributions require the definition of three values for each activity—the lower or optimistic duration limit (L), the pessimistic or upper limit (U), and the most likely value (ML). The values are usually based on expert opinion taking into consideration the perceived risks associated with the expected project conditions. The mean and variance, shown in Eqs. (1) and (2), respectively are calculated for each activity from the three duration estimates

$$\text{Mean}_i=\frac{L_i+4ML_i+U_i}{6} \tag{1}$$

$$\text{Variance}_i=\left(\frac{U_i-L_i}{6}\right)^2 \tag{2}$$

Based on the central limit theorem (CLT), the mean duration of each path is the sum of the mean duration for each activity along the path. The critical path is the one with the maximum duration. The variance of the project duration is the sum of the variance for each activity along the critical path. The distribution of the critical path duration can be assumed to be normally distributed due to the CLT and is defined by its mean and variance. These values can then be used to evaluate various levels of confidence. For example, the mean value provides a 50% confidence that the project will be completed by that date or earlier.

PERT has three major limitations. First, it is based upon the central limit theorem that assumes all activities are independent. This may not be a reasonable assumption in construction scheduling. For example, all activities that require a specific trade may

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be similarly affected if there is a market shortage of that trade. Second, significantly more effort is required to estimate three duration values than just the most likely value generally used in deterministic scheduling. Third, there is no recognition that the critical path may change. Although the critical path is defined as the path with the maximum mean duration, another path with a slightly lower mean duration but greater variance may significantly affect the project.

Monte Carlo (MC) simulation is the next step in analysis complexity and comprehensiveness. Monte Carlo simulation uses probability distributions, primarily beta distributions, to represent the variable, in this case, activity duration. Beta distributions can be defined with three values for each input: (1) the most likely value; (2) the pessimistic; and (3) the optimistic. Random numbers are used to extract one duration estimate from each activity duration distribution resulting in one completed project run. The critical path calculations are performed for that run to determine the project duration. Multiple runs are made, and the project duration from each run is combined to define a probability distribution function for the project outcome. Output from the MC analysis can be summarized as probability statements about the outcome of the events (Bent and Humphreys 1996).

In MC simulation, there is no independence assumption. If MC is run assuming independence between activities, then the mean and variance of the outcome should be similar to that achieved through PERT, although PERT is generally optimistic. Methods have been developed to evaluate joint distribution tables in the case of correlated durations (Touran 1992). Even if independence of the activities is assumed, MC has two major advantages over PERT. First, the criticality index (CI) can be calculated for each activity. The CI shows the frequency with which an activity falls on the critical path. Second, the cost and duration can be determined for each run of the simulation, providing more comprehensive information about the possible events and the relationship between these two performance measures.

Whether PERT or MC are used, there is still the problem of defining the duration distribution for each activity.

Objectives

The primary objective of this research was to develop a comprehensive construction schedule risk model to provide suggestions for the upper and lower activity duration limits based on the project characteristics for the purpose of stochastic schedule analysis (PERT or MC simulation).

Supplemental objectives were to (1) identify construction schedule risks; (2) quantify and model the relationships between the risk variables; and (3) demonstrate that the model can be used in conjunction with Monte Carlo simulation to predict delay of a building construction project. The resulting model is referred to as the Evaluating Risk in Construction–Schedule Model (ERIC-S).

The scope of this research is to analyze risks for building construction schedules in Canadian urban and suburban areas with topography and other conditions similar to Southern Ontario. The model is intended for analysis of the owner's schedule early in the project when PERT or MC risk analysis would most likely be undertaken. The research includes development of a Bayesian belief network using the Microsoft Belief Network (MSBN) (Redmond, Wash.) Although not shown in this paper, a user interface for the belief network model was developed using Microsoft Visual Basic (Redmond, Wash.).

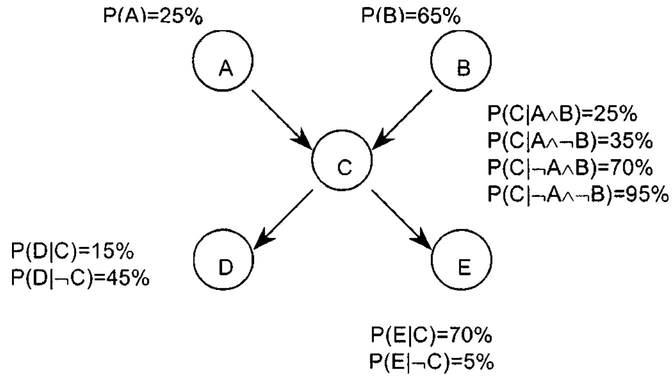

Fig. 1. Simple belief network

Belief Networks

A belief network is a graphical representation of conditional dependence among a group of variables. It presents a probabilistic approach to determine the likelihood of occurrence of certain variable conditions. Due to space constraints, the following discussion will only briefly describe this modeling environment. The interested reader may consult Pearl (1988) or Jensen (1996) for more detailed information.

A belief network, shown in Fig. 1, consists of nodes that represent variables and directional arcs (arrows) that represent conditional dependence relationships between those nodes in such a way that the node at the tail of the arrow (the parent node, Node *A*) affects the node to which the arrow points (the child node, Node *C*). Note, although the interpretation of causation is not entirely accurate (causation is unidirectional, but Bayes' theorem is symmetric and bidirectional), the terms cause and effect are used in this paper to facilitate the discussion. A conditional probability is the likelihood of a state of a variable that is dependent on the state of another variable (McCabe et al. 1998; Jensen 1996). Bayes' theorem is used to revise the belief about the state of a node depending on the evidence introduced for another variable. In the example, $P(D|\neg C)$ means probability of D=true given (denoted with $|$) that C=false where the false state is denoted with $\neg$.

When a node has many parents, the number of conditional probabilities required becomes quite large. For n binary (two states) parents of a binary child, 2^n probabilities must be specified to assess the node (Heckerman and Wellman 1995). In, node C requires $2^2=4$ conditional probabilities, D requires $2^1=2$ probabilities, and B requires $2^0=1$ probability.

Advantages of Belief Network Risk Model

The belief network modeling environment was used in this research for two important reasons. First, the belief network attempts to model the real world—not the expert. In a weighted scores or regression model, the weights reflect the variable's importance without explicit consideration of related factors or processes that connect the factors. The belief network model explicitly represents the relationships between the processes and events in the problem domain.

Second, risks are not always independent or additive. The effect of two events is not necessarily the sum of their individual effects. For example, heavy rain and a labor strike will individually and in combination have the same result—no work is done that day. Weighted score models sum the assigned scores as

J. Constr. Eng. Manage., 2003, 129(5): 518-527

Table 1. Risk Variables

Risk variables	Definition	States
Environmental		
Earthquake	Area history of an earthquake causing damage	Low/high risk
Seasons	Season that may affect the schedule	Spring and Fall/Summer/Winter
Precipitation	History of precipitation	Generally light/heavy
Humidity	Effect of humidity on the progress of work	Low/high
Geotechnical		
Archeological survey done	Was archeological survey done (historical buildings etc.)?	No/yes
Local geotechnical history	Geotechnical history of the area	Favorable/unfavorable
Geotechnical consultant	Experience of consultants in similar area and project scale	Experienced/inexperienced
Unexpected subsurface conditions	Unknown conditions that may result in delay	Low/high risk
Labor		
Labor union	The labor to be entirely union or a mix	Open/closed shop
Labor dispute/strike	The risk of labor disputes	Low/high risk
Labor availability	Are all labor abundantly available in the area?	Yes/no
Labor wage scales	Local prevalent wages of skilled and unskilled labor	High/moderate/low
Labor skill level	Competency level of labor	High/moderate/low
Potential for adverse activities	Risk that labor may actively delay progress	Low/high risk
Labor injuries	Risk to injury, local activity, and regard to site safety	Low/high risk
Labor productivity	General output of labor	High/moderate/low
Owner		
Owner type	Type of owner	Private/public/nonProfit
Owner financial stability	Financial stability of owner with respect to project	Sound/risky
Decision making	Efficiency of decision making by the owner	Efficient/inefficient
Progress payment	Progress payments at time specified in contract	On Time/delayed
Design		
Fast track schedule	Is design and construction running concurrently?	Yes/no
Design team	Experience of design group in type and size of project	Experienced/inexperienced
Multifunctional building	A multifunctional building may be more complex	Yes/no
Project definition	The degree to which the project scope is defined	Complete/incomplete
Innovative complex design	Design requiring unique details for various components	Yes/no
Design specifications	Degree of design specification completeness	Complete/incomplete
Design quality	Design quality in terms of design reviews or rework	High/low quality
Design changes	Risk that design changes will affect work progress	Low/high risk
Area condition		
Construction area	Site location	Outside/inside metro
Reconstruction project	Significant demolition, rehabilitation, in operating facility	No/yes
External site activity	Other site activity outside of construction	Yes/no
Traffic conditions	Traffic may affect movement of people, materials to site	Efficient/slow
On−site congestion	Is movement of equip, people, materials affected?	Open/congested
Traffic permits and approvals	Permits and approvals including traffic diversions	Few/excessive
Intense security	Is intense security required in the area?	Not required/required
Working hour restriction	Are work time restrictions in place	No/yes
Political		
Community attitude	Standpoint of the local residents toward the project	Friendly/hostile
Strong dissenting group	Is a strong influential group against the project?	No/yes
Relevant public inquiries	Any current public inquiries related to project?	None/going on
Potential of delay by others	The chance of delay by parties outside the contract	Low/high risk
Project stopped abandoned	Chance of project stopped or abandoned entirely	Low/high risk
Contractor		
Contractor prequalified	Will the contractors be prequalified?	Yes/no
Contractor ability and experience	Contractor's experience and ability including staff profiles	High/average/low
New technology	Will new construction methods be used?	Yes/no
Defective work	Risk of defects that necessitate rework	Low/high risk
Rework	The chance of frequent reworks needed	Low/high risk
Short breaks	Risk of many short breaks affecting productivity	Low/high risk

J. Constr. Eng. Manage., 2003, 129(5): 518-527

Table 1. (*Continued*)

Risk variables	Definition	States
Contractor non-labor resources		
Vendor bondability	Is vendor bonded to supply items for a specified time?	Yes/no
Critical items import	Are critical equipment or materials being imported?	On time/delayed
Equipment quality	Condition of contractor's equipment	Good/poor
Theft of equipment and tools	Chances of theft of equipment and tools affecting work	Low/high risk
Damage to equipment	Risk of damage to equipment by mishandling, low skill	Low/high risk
Equipment failure	The chance of equipment failure	Low/high risk
Equipment shortage	The chance of nonavailability of equipment	Low/high risk
Material		
Reliance on JIT material delivery	Level of reliance on just in time material delivery	High/low
Secure material yards	Is material yard secured to avoid sabotage or theft?	Yes/no
Material theft/fire	Chance of sabotage of material by anyone	Low/high risk
Material procurement	Status of fabricated or raw material procurement?	On schedule/delayed
Material shortage	The chance of nonavailability of material	Low/high risk

though they were additive. A more general discussion of the advantages of using belief networks can be found in McCabe et al. (1998)

Developing ERIC-S Model

Development of a belief network model consists of four basic steps: (1) identification of the variables; (2) identification of the relationships; (3) quantification of the relationships; and (4) model validation. Some information was available from the literature, but for the most part, expert knowledge was used. All of the experts had 15 or more years of experience in the construction industry.

Identification of Variables

These variables were identified from many sources, including the published literature, procedure manuals, questionnaire surveys, interviews, and brainstorming sessions of experts/practitioners. The variables reflect the scope of the problem and the level of detail to which the developers wish to work. There are two types of variables in this model: (1) the schedule risk variables; and (2) the activity variables. Risk variables are input nodes where evidence may describe the project conditions. Activity nodes are output nodes that represent activity duration values to be fed into the MC simulation.

There are various ways to categorize construction risks. Based on the literature and a review by a group of experts, 10 categories specific to building construction schedules were developed. The categories are environment, geotechnical, labor, owner, design, area conditions, political, contractor, contractor nonlabor resources, and material. There were few papers that provided a direct study of schedule risks. But the main support from literature came from indirect links to delay factors. A discussion of each risk group is as follows:

1. *Environment*. Weather effects are one of the major sources of schedule risks (Mulholland and Christian 1999; AbouRizk and Wales 1997; Ruff et al. 1996; Laufer and Cohenca 1990; Bennett 1985). The construction work is affected by weather events such as snow, cold temperature, humidity, and rainfall (Thomas et al. 1999; Yates 1993; Ng et al. 1998). Weather conditions affect labor productivity either directly or indirectly (Smith and Bohn 1999; Sonmez and Rowings 1998; Thomas et al. 1992; Thomas and Napolitan 1995).
2. *Geotechnical*. One of the sources of construction schedule risks is differing site conditions (Mulholland and Christian 1999; Ruff et al. 1996; Russell 1993). Ng et al. (1998) reviewed a building construction project in Singapore and observed that soil type affects the time required for excavation.
3. *Labor*. Labor productivity has a major effect on construction progress (Thomas et al. 1999; Mulholland and Christian 1999; Finke 1998; Thomas 1992). There are several factors that effect labor productivity such as labor strikes, idle workers (Burleson et al. 1998; Smith and Bohn 1999; Yates 1993), and labor injuries (Everett 1999; Abdelhamid and Everett 1999a; Hinze et al. 1998; Hinze and Russell 1995). Unskilled labor and poor wage scales not only affect productivity but may also result in labor injuries (Anson and Wang 1998; Koehn and Kothari 1995). Labor unions play an important role in providing skilled labor, maintaining better labor wages (Fisk 1997; Rowings et al. 1996; Wong and Logcher 1986; Maloney and McFillen 1986a). Laufer and Cohence (1990) discussed the effects of labor scarcity and surplus on schedules. Labor disputes are another reason for delay of projects (Maloney and McFillen 1986b; Kangarl 1995).
4. *Owner*. Poor communication (Dozzi et al. 1996; Luiten and Tolman 1997; Thomas et al. 1998; Franks 1990), slow decision making (Bennett 1985; Tenah 1986; Smith and Bohn 1999), inexperienced management, inadequate supervision (Sanvido et al. 1992; Mulholland and Christian 1999; Arditi and Gunaydin 1998), financial problems, and late payments (Songer and Molenaar 1997; Bell and Stukhart 1986; Okpala and Aniekwu 1988) are schedule risks that come into play directly or indirectly through the owner.
5. *Design*. Design changes are a major risk to construction projects (Thomas et al. 1999; Finke 1998; Ng et al. 1998; Yates 1993; Hester and Kuprenas 1987). Experience of the design team with similar projects can also affect the project (Daoud 1997; Kartam 1996; Williams 1995; Sanvido et al. 1992; Kagan et al. 1986). Incomplete drawings, inaccurate design, and incomplete specifications are other sources of risks (Smith and Bohn 1999; Mulholland and Christian 1999; Arditi and Gunaydin 1998; Yates 1993; Laufer and Cohenca 1990; Vlatas 1986). Innovative design (Nam and

J. Constr. Eng. Manage., 2003, 129(5): 518-527

Tatum 1992), undefined scope, and frequent changes in scope affect some projects (Songer and Molenaar 1997; Wong and Logcher 1986). Diekmann et al. (1987) identified work grouping and preplanning as important factors affecting a project. Fast-track projects have their own set of inherent risks that may affect materials management or design quality (Thomas and Raynar 1997; Bell and Stukhart 1986; Vlatas 1986).

6. *Area Conditions*. Construction in a downtown area brings with it many risks (Russell 1993) including site congestion (Ng et al. 1998; Koehn and Kothari 1995; Thomas and Napolitan 1995; Thomas et al. 1992; Hester and Kuprenas 1987). Other important risks are traffic conditions near and around the site and the requirement for road permits and approvals to move equipment and materials around (Fisk 1997; Fisher and Rajan 1996). Sometimes access to the site is restricted, security is tight, or there is a restriction of working at the site (Bell and Stukhart 1986; Krizek et al. 1996; Anson and Wang 1998). Constructing at an operating facility has substantial risk, because complaint from users of the facility may cause work stoppages or require shifts to reduce disturbances created by the construction (Riley and Sanvido 1997; Daoud 1997; Mulholland and Christian 1999).
7. *Political*. Political risks can be an outcome of government instability (Okpala and Aniekwu 1988), changes in requirements of permits or approvals (Yates 1993; Mulholland and Christian 1999; Smith and Bohn 1999), and other institutions that can have an influence on a project (Jaselskis and Talukhaba 1998). Community attitude toward a construction project and related public inquiries may have a significant effect on the schedule (Randolph 1993).
8. *Contractor*. The contractor risks start with the prequalification process of the contractor and of the subcontractors (Mulholland and Christian 1999; Arditi and Gunaydin 1998; Daoud 1997; Krizek et al. 1996; Russell and Jaselskis 1992a). A (sub)contractor's experience and ability to meet project demands is the major risk factor (Amirkhanian and Baker 1992; Diekmann and Kim 1992; Russell and Jaselskis 1992b; Sanvido et al. 1992; Laufer and Cohenca 1990; Okpala and Anlekwu 1988; Maloney and McFillen 1986a).
   New technology or new methods of construction deployed by the contractor have the potential to affect the construction schedule (Abdelhamid and Everett 1999b). Construction errors are also sources of risks (Mulholland and Christian 1999; Abdelhamid and Everett 1999a) and may necessitate rework (Yates 1993; Friedrich et al. 1987; Thomas et al. 1992; Burati et al. 1992; Stacey 1991; Kartam 1996), and create unnecessary interruptions to work (Bennett 1985; Thomas and Napolitan 1995; Christian and Hachey 1995; Hester and Kuprenas 1987; Finke 1998; Thomas et al. 1999).
9. *Contractor Nonlabor Resources*. These risks include basic issues like availability of equipment (Mulholland and Christian 1999; Thomas and Napolitan 1995; Yates 1993; Smith and Bohn 1999; Thomas et al. 1992; Lemna et al. 1986) and quality of the equipment (Amirkhanian and Baker 1992; Koehn and Kothari 1995). Disruption of work due to malfunctioning equipment affects the schedule (Yates 1993). Evaluation and bonding of subcontractors and vendors are some of the methods to avoid risks (Bell and Stukhart 1986; Diekmann et al. 1987).
10. *Material*. Material risks include availability or shortage of materials (Mulholland and Christian 1999; Thomas and Napolitan 1995; Okpala and Aniekwu 1988; Teicholz 1987) and late delivery or procurement of materials (Smith and Bohn 1999; Thomas et al. 1999; Anson and Wang 1998; Ruff et al. 1996; Yates 1993; Thomas et al. 1992; Diekmann et al. 1987; Lemna et al. 1986).

Summary of Variables

The risks identified from the literature search were reviewed by checking the potential effect of each risk on the building construction schedule. The risk variables were ordered hierarchically based on the conditional dependence relationships as shown in Table 1. The objective was to arrange variables so that within each risk group, a variable could be a child of any variable above it in the list, and the same variable could only be a parent of those variables lower than it in the list.

Activity Variables

Analysis of the risk variables had to output information that could be incorporated into a MC simulation to establish the pessimistic and the optimistic duration values of each activity. These recommendations were to be obtained as the probabilities of states of activity variables.

Eight activity groups were identified to represent all the types of activities in a construction schedule. These groups are mobilization/demobilization, foundation/piling, labor intensive, equipment intensive, mechanical/electrical, roof/external, demolition, and commissioning. Two nodes are required for each group where one node represents the pessimistic value and the other gives the optimistic value. To define the states of activity nodes, it was quite important to model the effect of risks on activities. Because the most likely duration of activities was already there as a reference point, output could state a percent increase or decrease from the most likely duration to define the pessimistic and optimistic durations.

On the pessimistic side, the extreme state suggests at the most an increase of 100% in the duration, but on the optimistic side, the extreme case is 25% reduction in duration. The unbalanced highs and lows exist because there is a practical limit to the reduction that can be achieved for an activity, but there is practically no limit to the delay (Bulick 1993; Woodworth 1993).

The number of states for each pessimistic and optimistic node was controlled to prevent the number of probabilities from becoming exponentially large. The activity variables along with their states are shown in Table 2. It should be noted that associating a schedule activity with one of the activity variables is the responsibility of the scheduler.

Identification of Relationships

The second step is to develop conditional dependence relationships between the variables. A literature survey provided only 22 cause/effect links, increasing the importance of the expert survey. The amount of expert-solicited knowledge to be collected was significant so the questionnaire was used.

The questionnaire was prepared in a matrix form where the list of 69 risks in the left column represented the causes and the same 69 risks listed across the top represented the effects. If the experts were asked to review every combination pair of variables in the matrix, they would have had to review 4,761 relationships, which was impractical. Therefore, based on the literature survey, experience of writers, and the input of an expert, the relationships that were either impossible or extremely weak were shaded, indicating that the expert did not consider that combination. For example, the relationship between *Precipitation* as a cause and *earthquake* as an effect was shaded because precipitation is independent of

J. Constr. Eng. Manage., 2003, 129(5): 518-527

Table 2. Pessimistic Activity Variables and Their States

Variables	Pessimistic (P) increase duration by				Optimistic (O) decrease duration by		
	State 1 (%)	State 2 (%)	State 3 (%)	State 4 (%)	State 1 (%)	State 2 (%)	State 3 (%)
Mobilization, demobilization	20	60	100	—	5	10	15
Commissioning	20	60	100	—	5	10	15
Foundation, piling	25	50	75	100	5	15	25
Labor intensive	25	50	75	100	5	15	25
Demolition	25	50	75	100	5	10	15
Equipment intensive	25	50	75	100	5	10	15
Roof, external	25	50	75	100	5	10	20
Mechanical, electrical	25	50	75	100	5	10	20

earthquake, but the effect of *precipitation* on *labor productivity* space has been left open. This significantly reduced the number of values required to 408 variable pairs. The respondents were encouraged to mark any shaded box that they believed held some relationship. Each expert was asked to award scores to the relationships such that 0=no relationship; 1=weak relationship; 2=strong relationship; and 3=very strong relationship.

Nine experts participated. Responses for each causal relationship were counted as the number of experts scoring 0, 1, 2, and 3. Nine logical tests utilizing two statistical values, namely the average and the skewness, were developed to evaluate the data. The skewness statistic describes the weight of opinion where a positive skewness indicates the majority of experts gave a low score but a few gave a higher score and vice versa. The weak (W) parameter is the number of experts that scored the relationship as either a 0 or 1, and strong (S) is the number of experts that scored the relationship as 2 or 3. The difference between these two values, $|W\text{-}S|$, provides a measure of the weight of opinion of the experts.

Logical Tests F1 to F3 are rejection tests while Tests F4 to F7 are acceptance tests as shown in Table 3. A relationship that returned a false value for Tests F1 to F7 is subjected to Tests F8 and F9 simultaneously. These two tests are subjective tests based on the expert's opinions. Test F8 accepts the relationship if data seem to incline towards 3 and Test F9 rejects the relationship if data seem to incline toward 0.

Although a maximum limit of four parents for each variable was imposed to control the number of probabilities required, 22 parents were identified for *labor productivity*. This would require 2^{22} or 4,194,304 probabilities. The matter was resolved through discussion with the experts and the incorporation of a divorcing technique (Jensen 1996), which reduced to 64 the number of probabilities for the *labor productivity* node.

Activity Node Relationships

Activity nodes represent the eight activity types, which were identified earlier. The parents are shown in Table 4.

Relationship Quantification

Relationship quantification is often the most difficult step in belief-network (BN) development. In total, 366 probabilities for the risk nodes and 476 probabilities for the activity nodes were needed. As data were not available, and the literature yielded few probabilistic values, a survey of the experts was used to collect the data.

Collecting this large amount of data presented several challenges. First, the opinions were needed in numerical terms as a probability or they had to be easily transferable from qualitative to quantitative form. Megill (1984) and Edwards (1995) found that experts generally find it very difficult to provide opinions in quantified form. Second, if each expert had provided opinions for all the probabilities, significant time would have been required by the expert to complete the survey. This may not have been possible due to their busy schedule, and the strong possibility of an expert losing interest due to monotony of the questions. Third, the relationships to be reviewed by the experts to express their opinions were quite complex. There was only a slight change of relationship from one question to the next in a set of questions to specify probabilities for a variable. Thus, it was quite difficult to jump from one question to the next and maintain an understanding of the relationships.

The questionnaires, shown in part in Table 5, were prepared in sets to logically distribute the questions related to one variable. In this manner, an expert could take a break without losing the logic of the relationships. One writer was available while the experts

Table 3. Data Evaluation Tests

Test	Condition	If condition true	If condition false
1	Average <1.01	Reject relationship	Go to Test 2
2	Average <1.5 and $(W-S)>4$	Reject relationship	Go to Test 3
3	Average <1.5 and skewness=positive	Reject relationship	Go to Test 4
4	Average >2.49	Accept relationship	Go to Test 5
5	Average >1.99 and $(S-W)>4$	Accept relationship	Go to Test 6
6	Average >1.99 and skewness=negative	Accept relationship	Go to Test 7
7	No 0 scores, experts see some relationship	Accept relationship	Go to Tests 8 and 9
8	Scores are inclined toward 3	Accept relationship	Reject relationship
9	Scores are inclined toward 0	Reject relationship	Reject relationship

J. Constr. Eng. Manage., 2003, 129(5): 518-527

Table 4. Activity Node Parents

Activity node	Parents
Mobilization/demobilization	Permits and approvals; contractor ability and experience; site congestion
Foundation/piling	Unexpected subsurface conditions; contractor ability and experience; site congestion
Demolition	Reconstruction project; working hour restrictions; site congestion
Labor intensive	Labor productivity; contractor ability and experience; labor injuries
Equipment intensive	Equipment shortage; working hour restrictions; site congestion
Roof/external	Labor productivity; innovative complex design; seasons
Mechanical/electrical	Labor productivity; reliance on just in time material delivery; site congestion
Commissioning	Progress payment; contractor ability and experience; equipment quality

entered their responses. This semisupervised situation saved a lot of time since the queries of the experts were answered immediately.

The response options were both qualitative and quantitative. The experts were asked to circle one probability or two adjacent probabilities with the help of the subjective guideline (Edwards 1995)—1 to 25% was labeled as strongly disagree; 25 to 45% as somewhat disagree; 45 to 65% as in between; 65 to 85% as somewhat agree; and over 85% as strongly agree. Note that the probabilities do not extend to 100 and 0%.

Seven experts participated in this survey. Each expert generally required more than one session with each session lasting 40 min. on average. For each relationship, three or more opinions were sought. The values were combined as an average for input to the model. Where the maximum and minimum opinions differed by more than 30%, the experts were asked to review their responses. The limit of 30% was determined rather arbitrarily, because it represented a reasonable difference of opinion. The next step involved testing, verification, and review of the model.

Table 5. Section of the Questionnaire for Collecting Probabilities

Factors	Will result in	Likelihood (use guideline)
Metro city Generally heavy precipitation Summer season	Efficient traffic flow	—
Metro city Generally light precipitation Winter season	Efficient traffic flow	—
Metro city Generally light precipitation Spring/Fall season	Efficient traffic flow	—

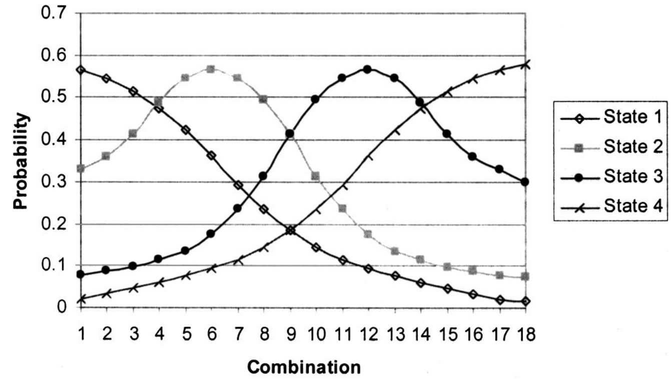

Fig. 2. Probability distribution for 18 combinations of parents for 4 states of child

Activity Node Probabilities

As mentioned, 476 probabilities for activity nodes were needed. An expert survey for this purpose presented two disadvantages. First, distribution of unity among three or four states of an activity node over several combinations is extremely difficult when the decision is based only on experience. Second, the distribution had to maintain a predictable and consistent progression from an ideal condition to worst condition among all the combinations of parent states.

An expert-supported method was developed to address this problem. An expert reviewed the cause/effect relationships and provided a guideline to rank the cases from best to worst. The guideline provided a weight to parents of an activity variable based on their effect on the child. With the help of these weights, the combinations of states of parents were ranked. The parent with the highest weight influenced the ranking of combinations the most.

Graphs were developed to distribute probabilities among combinations of parent states (8, 12, or 18) and states of the child-activity variable (3 or 4) so that there is a logical flow of probabilities from best to worst cases. The number of distributions in a graph equals the number of states of the child for that case. Thus, for 18 parent state combinations and 4 child states, four distributions are needed as shown in Fig. 2. As the probability of a state decreases, the probability of another state increases.

ERIC-S Model Verification

Sensitivity analysis is used to determine the effect of changes in the value of each variable that is considered to be a potentially serious risk to the project (Thompson and Perry 1992). Six risk nodes were selected at random, and the results for all the combinations of their states were compared. The test was repeated several times by selecting other combinations of risk variables. A detailed review of all such analyses showed that the activity nodes are not overly sensitive, because they do not show abrupt changes in their result with a slight change of project conditions.

A test was performed to compare the effectiveness and efficiency of the ERIC-S model versus the traditional method for range estimating by project personnel. In this case, a facility owner wanted to know the risk associated with completing a large fast-tracked construction project by the target date, which was 20 months from the start. MC was the chosen method for evaluating the schedule. The schedule contained about 2,100 activities, so the activities were divided among the participants according to their knowledge of the project conditions. It took 6 weeks to

J. Constr. Eng. Manage., 2003, 129(5): 518-527

Table 6. Summary of Case Study Analysis

Project	Project completion dates (dd-mm-yy)		Monte Carlo dates (dd-mm-yy)			P (actual) (%)
	Target	Actual	Earliest	Expected	Latest	
1A	01-Dec-88	15-Feb-89	20-Dec-88	26-Jan-89	22-Mar-89	88
1B	28-Nov-88	15-Feb-89	13-Dec-88	07-Feb-89	08-May-89	60
2	07-Oct-88	03-Nov-89	01-Nov-88	08-May-89	29-Nov-89	97
3A	15-Aug-91	20-Oct-91	19-Aug-91	12-Sep-91	22-Oct-91	99
3B	12-Aug-91	10-Oct-91	27-Aug-91	13-Sep-91	14-Oct-91	99
4A	03-Aug-98	17-Sep-98	10-Aug-98	25-Aug-98	21-Sep-98	99
4B	21-Oct-98	02-Nov-98	26-Oct-98	02-Nov-98	12-Nov-98	28
4C	04-Dec-98	11-Dec-98	07-Dec-98	16-Dec-98	30-Dec-98	12
5	03-Dec-91	22-Apr-92	12-Dec-91	26-Mar-92	24-Jul-92	72
6	29-Apr-93	07-Sep-93	29-Jun-93	22-Nov-93	22-Apr-94	9
7	30-Sep-93	05-Jan-94	01-Oct-93	07-Dec-93	24-Feb-94	87
8	02-Jun-95	28-Jul-95	19-Jul-95	11-Aug-95	10-Oct-95	23
9	19-Nov-91	30-Jun-92	11-Nov-91	20-Feb-92	01-Jul-92	98
10	13-Nov-78	12-Nov-79	08-Jan-79	09-Jun-79	11-Dec-79	99
11	22-Oct-82	17-Mar-83	28-Dec-82	03-Jul-83	31-Jan-84	5
12	20-Jul-83	23-Sep-83	29-Jul-83	26-Aug-83	28-Sep-83	98
13	31-Jan-88	01-Dec-88	01-Feb-88	01-Nov-88	01-Jun-89	46

collect the data due to the busy schedule of the participants. In 79% of the activities, the original duration was considered appropriate as the most likely value. It was found that the experts were not comfortable providing extreme values for the pessimistic durations, in part because pessimism with the project was counterproductive. As a result, 66% of the activity duration ranges fell within ±15% of the most likely value; however, there was a clear skewness to the right within these distributions with the most extreme optimistic values ranging to −50% of the most likely, and the most extreme pessimistic values extending to +300%. Based on the MC simulation, the expected project completion, i.e., the mean or 50% confidence completion date, was 7 weeks later than the target date identified in the CPM schedule. This was verified using PERT.

To test ERIC-S, the state of the project was entered as evidence into the model. The output suggestions for the optimistic and pessimistic durations were entered into the schedule and MC was run. The total time to evaluate the project conditions, enter it into the ERIC-S model, and run the analysis was about 3 h. The expected duration for the ERIC-S model was 2 weeks later than the expert analysis and 9 weeks later than the target. In the two cases, the earliest date was the same, but the ERIC-S model was slightly more pessimistic with the latest date extending 4 weeks with a cumulative probability of only 5% in those 4 weeks.

This example has shown that the model is performing very well relative to the experts. Although the resulting project completion date extended beyond the expert analysis slightly, the participants found the results very satisfactory and wished that ERIC-S had been used instead of the effort that was required of them to evaluate the duration ranges.

Case Studies

The predictive quality of ERIC-S was tested next. Seventeen cases from 13 projects were analyzed. Table 6 shows a summary of the results. Column 2 is the target date originally defined in the project schedule, and Column 3 shows the actual completion date. Each project report was reviewed to determine the project conditions (evidence) related to that project, and the schedule activities were associated with the activity variables. The belief network was instantiated with the evidence, and the results were extracted and entered to the schedule as pessimistic and optimistic durations, using the original duration as the most likely value. After running 100 iterations of the MC simulation, the earliest, expected, and latest completion dates (shown in Columns 4, 5, and 6, respectively) were extracted. From this distribution, the probability of the actual delay defined by the MC distribution, shown in Column 7, was determined. In all cases, the actual completion date fell within the predicted distribution. In other words, the ERIC-S model simulation was able to predict the completion date within the range.

Conclusions

Research was undertaken to develop a comprehensive schedule-risk model to estimate the pessimistic and optimistic values of an activity duration based on project characteristics. The resulting model is referred to as ERIC-S. This is the first construction schedule-risks model known to the writers that quantifies the relationships between the variables.

The model was tested on a large project in which the target completion date was under scrutiny. The results were almost identical to those coming from the project participants except that the data from the experts took 6 weeks, whereas entering project characteristics into the ERIC-S model took only 2 h, showing that the model is both effective and efficient.

The model, limited to building construction projects in Canadian urban areas with conditions similar to Southern Ontario, is intended for use at the early stages of project development. A total of 69 risks to a building construction schedule were identified. The risks were categorized as environmental, geotechnical, labor, owner, design, area conditions, political, contractor, contractor nonlabor resources, and material. The relationships among the variables were qualified and quantified within the belief network environment. The model was validated with historical data from 17 case studies with very good results.

J. Constr. Eng. Manage., 2003, 129(5): 518-527

It was found that the belief network provided a very flexible modeling environment. Due to the lack of historical data and information in the literature, the majority of the information came from experts. The modeling environment allowed seamless integration of all information types.

Minor modifications to the model may adapt it sufficiently to be applied to a different environment successfully. It should be tested with data from specific types of major, complex building projects such as institutional buildings or transportation terminals to determine its applicability to these projects.

It is hoped that this model will provide decision support to project owners, consultants, and researchers as a project delay-prediction tool.

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