Construction Project Network Evaluation with Correlated Schedule Risk Analysis Model

Önder Ökmen[1] and Ahmet Öztaş[2]

Abstract: Schedules are the means of determining project duration accurately, controlling project progress, and allocating resources efficiently in managing construction projects. It is not sufficient in today's conditions to evaluate the construction schedules that are affected widely by risks, uncertainties, unexpected situations, deviations, and surprises with well-known deterministic or probabilistic methods such as the critical path method, bar chart (Gantt chart), line of balance, or program evaluation and review technique. In this regard, this paper presents a new simulation-based model—the correlated schedule risk analysis model (CSRAM)—to evaluate construction activity networks under uncertainty when activity durations and risk factors are correlated. An example of a CSRAM application to a single-story house project is presented in the paper. The findings of this application show that CSRAM operates well and produces realistic results in capturing correlation indirectly between activity durations and risk factors regarding the extent of uncertainty inherent in the schedule.

DOI: 10.1061/(ASCE)0733-9364(2008)134:1(49)

CE Database subject headings: Construction management; Network analysis; Scheduling; Risk management; Correlation; Simulation models.

Introduction

The success of construction projects is evaluated based on such measures as production quality, scope sufficiency, social-environmental-technical functionality, safety requirements, planned completion time, and allocated budget. In order to realize these success criteria, various activities or tasks are performed throughout a project. Construction activities can be categorized as procurement, design, construction, and managerial, but cannot be standardized with typical norms because each construction project is uniquely associated with its specific conditions. If today's competitive and complex attributes of the construction sector are considered in addition to the uniqueness of each project, planning and scheduling become vital procedures for success, especially where target project time and budget are concerned.

Bar charts, line of balance (LOB), and the critical path method (CPM) have been the most popular methods of construction scheduling since the 1950s (Griffis and Farr 2000; Halphin and Woodhead 1998; Oberlender 2000). Although bar charts are frequently utilized for communication on-site at the worker level because of their simplicity, and LOB is used for scheduling repetitive project portions, CPM is accepted as the most suitable means of scheduling activity networks. This is due to its capabilities in showing the precedence relations between activities, exploring the critical activities, providing activity float times, and leading to optimized resource allocation. However, CPM is deterministic in nature because of the single crisp duration values assigned to activities during network analysis, as if these duration values are known certainly and are not changed by various risk factors. This limitation may lead to imprecise critical path identification and completion time measurement (Jaafari 1984).

Unfortunately, construction schedules are affected by uncertainties in weather, productivity, design, scope, site conditions, soil properties, material delivery time, equipment efficiency, etc. (Edwards 1995; Flanagan and Norman 1993). All risks in a construction project might be schedule risks because they are related to the schedule directly or indirectly. Moreover, all activities can be critical due to uncertainties, even those that are not critical according to deterministic CPM. In order to evaluate construction networks by considering risk factors, nondeterministic scheduling methods such as the program evaluation and review technique (PERT) (Dept. of the Navy 1958), the probabilistic network evaluation technique (PNET) (Ang et al. 1975), narrow reliability bounds (NRB) (Ditlevsen 1979), and Monte Carlo simulation (MCS) (Diaz and Hadipriono 1993) have been developed. None of these methods are independent from CPM, but rather can be considered as improved methods based on CPM. Furthermore, they can be considered as schedule risk analysis tools to be used within risk management systems.

Risk, in some manner, can be recognized as any result of uncertainty in any project-affecting factor, such as weather. This result may be a favorable or adverse variation in the affected project aspect, such as activity duration. In more clear terms, uncertainty in weather conditions may create the risk of variation in activity durations, whether in adverse or favorable direction; that is, the actual activity durations may be more or less than the expected durations. Risk management is defined as a systematic controlling procedure for predicted risks to be faced in an invest-

[1]Ph.D. Candidate, Civil Engineering Dept., Univ. of Gaziantep, Gaziantep, Turkey. E-mail: onderokmen@hotmail.com

[2]Assistant Professor, Civil Engineering Dept., Univ. of Gaziantep, Gaziantep, Turkey. E-mail: aoztas@gantep.edu.tr

Note. Discussion open until June 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 9, 2007; approved on June 21, 2007. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 134, No. 1, January 1, 2008. ©ASCE, ISSN 0733-9364/2008/1-49–63/$25.00.

ment or a project (Dikmen et al. 2004; Öztaş and Ökmen 2004). It is a stepwise procedure consisting of risk identification, risk classification, risk analysis, and risk response tasks (Flanagan and Norman 1993).

Schedule risk analysis methods such as PERT, MCS, and PNET are capable of taking uncertainties into account but become insufficient in identifying the sensitivity of activities or the whole schedule to risk factors. Furthermore, they ignore the correlation effect between activities (Wang and Demsetz 2000a,b). They only approach the problem within the context of taking the activity durations between some estimated bounds and trying to measure the variance of completion time. However, in case several activities are influenced by the same risk factor, their durations are correlated. If activities on a path are correlated, the variability of path duration will increase, and perhaps the project completion date will be highly uncertain (Wang and Demsetz 2000b).

So far, various schedule risk analysis models have been developed by researchers to provide risk factor-concerned sensitivity information, incorporate correlation effect into schedules, and support schedule risk management in risk response strategy development (Wang and Demsetz 2000b): model for uncertainty determination (MUD) (Carr 1979), project duration forecast (PRODUF) (Ahuja and Nandakumar 1985), PLATFORM (Levitt and Kunz 1985), conditional expected value model (CEV) (Ranasinghe and Russell 1992), exact simulation (Touran and Wiser 1992), factored simulation (Woolery and Crandall 1983), networks under correlated uncertainty (NETCOR) (Wang and Demsetz 2000b), and judgmental risk analysis process (JRAP) (Öztaş and Ökmen 2005; Ökmen and Öztaş 2006). All of these methods are risk factor based and capture the correlation, either directly by using correlation coefficients or indirectly by incorporating the risk factor effect activity by activity. While some of them consider both the favorable and adverse effect of factors, some consider only adverse effect. However, none considers the correlation between risk factors.

This paper presents a new simulation-based model—correlated schedule risk analysis model (CSRAM)—to evaluate construction activity networks under uncertainty when activity durations and risk factors are both correlated in between. CSRAM is introduced in the next section, after which a CSRAM application is presented for comparing the model with CPM, PERT, and MCS-based CPM (stochastic or nondeterministic CPM). Limitations, concluding remarks, and future work are presented last.

Correlated Schedule Risk Analysis Model

The correlated schedule risk analysis model (CSRAM) is a simulation-based risk analysis model that performs uncertainty evaluation on construction network schedules without neglecting the correlation effect between risk factors and between activities. Correlation is captured indirectly in two directions: one is between activities, and the other between risk factors. Input data complexity or the need for previous data is extremely lowered by utilizing qualitative estimates. For instance, correlation is not realized directly by requesting correlation coefficients (generally not available due to the lack of previous data) from the user; instead, it is captured indirectly by converting qualitative estimates to quantitative values through an iterative computation algorithm of the model. Another attribute of CSRAM is its capability of processing both the adverse and favorable effects of risk factors. For instance, "weather risk" might occur as worse than expected (adverse) or better than expected (favorable), and CSRAM takes this opposite-sided uncertainty effect into consideration for weather-sensitive activities. In this regard, the main features of CSRAM can be enumerated as follows:

- Simulation-based uncertainty evaluation algorithm.
- Elicitation of positive correlation indirectly between activity durations.
- Elicitation of positive correlation indirectly between risk factors.
- Simplification of required model input by utilizing qualitative and subjective data.
- Consideration of adverse and favorable effects of risk factors.
- Activity-, path-, and project-based risk factor sensitivity analysis.

CSRAM is designed as a construction schedule risk analysis method to be used within a project risk management system. It is not an alternative to CPM, but rather uses CPM's forward-backward network calculation algorithm when performing Monte Carlo simulation iterations. However, it is a factor- and simulation-based scheduling method and therefore follows an iterative procedure. In every iteration, it simulates the uncertainty in risk factors (thus in each iteration, each risk factor may occur as either better than expected, expected, or worse than expected) and reflects the adverse and favorable effects of this uncertainty on activity durations. The distinguishing side of the model is its capability of eliciting positive correlation between each risk factor pair and activity pair.

At the end of each CSRAM iteration, a different duration is produced for each activity (and subsequently different durations for the whole project, paths, and floats). The determination of whether a risk factor would occur that is better than expected, expected, or worse than expected in an iteration is carried out in a random fashion, but without neglecting correlation between risk factors. Moreover, activity durations are determined by considering the correlation between activities through utilizing qualitative data entered by the user to represent the degree of influence of each risk factor on each activity, with the following qualification terms: very effective, effective, or ineffective. Afterwards, these activity durations are used in forward-backward CPM calculation, and different duration values for the whole project, paths, and floats are produced.

When Monte Carlo simulation is completed, all these values are configured in statistical terms and charts, such as cumulative probability distributions, standard deviations, means, and so on. These resultant data show many project aspects, such as probability range of completing duration of the whole project, criticality degree of activities, path total float variations, path criticality degrees, path sensitivities to risk factors, and project sensitivities to risk factors. The manager can use these data in decision making, schedule controlling, risk response strategy development, resource allocation, and so on. For instance, by recognizing which risk factor is more effective on a particular path, a manager would be aware of what to control during the execution of the activities on this path. The position of CSRAM within a risk management system process and the flowchart that shows how it operates are illustrated in Figs. 1 and 2, respectively.

As previously emphasized, crude procedures such as CPM (which produces deterministic results without giving any information about risk sensitivity) and stochastic CPM (which produces stochastic results without eliciting a correlation effect between schedule variables) are unrealistic techniques for representing the uncertain construction project environments. If more than one activity is a candidate to be influenced by the same risk factors, the duration of these activities would be correlated. For example, if

J. Constr. Eng. Manage., 2008, 134(1): 49-63

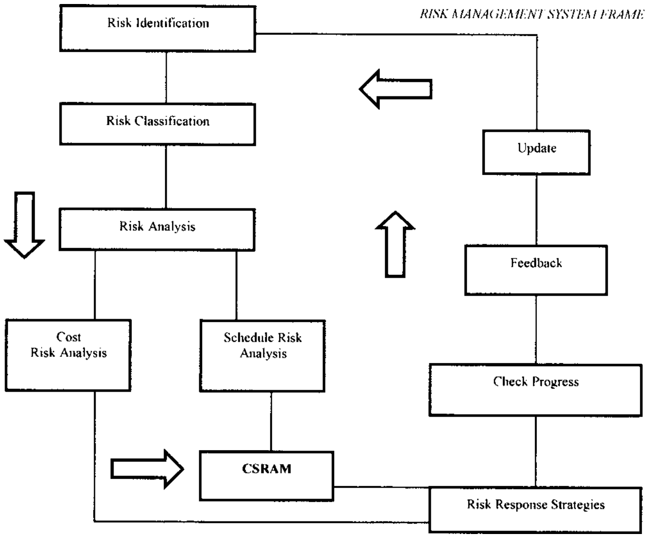

Fig. 1. Position of CSRAM in risk management process

the duration of one of the two correlated activities occurred as more than expected due to risk factors during an iteration, the duration of the other activity should also be taken as more than expected during this iteration. Unless such correlation effects are not incorporated into a scheduling model, unrealistic results will have been obtained. Therefore, the main argument and target of CSRAM is to model the uncertain construction conditions more realistically from the scheduling point of view.

Features of CSRAM

This section presents detailed information about the operation of the CSRAM process under different headings that disclose its different features.

Simplified Input Data

CSRAM is designed such that required input data are extremely easy to obtain. In other words, data that should be entered into CSRAM are mainly subjective, qualitative, depending on past experience, and therefore flexible for adaptation to specific conditions. However, the scope of the required input data for CSRAM is obviously wider when compared with PERT or stochastic CPM because CSRAM is a schedule risk analysis method and tries to explore the risk sensitivity of the project schedule to various uncertainties while incorporating a correlation between the model variables.

The input data that CSRAM requires are enumerated and described below:

- Network data: Work breakdown structure, predecessor relationships between activities (finish to start, start to start, start to finish, or finish to finish), and lag/lead times, which all are the data already needed for a simple CPM application.
- Minimum-most likely-maximum activity durations: Nothing more than classical PERT needs. No probability distributions, no dependence on previous sample data for statistical analysis, as in the case of stochastic CPM.
- Most important risk factors that are expected to affect the schedule: This information comes from the risk identification stage of a general risk management system execution (Fig. 1).

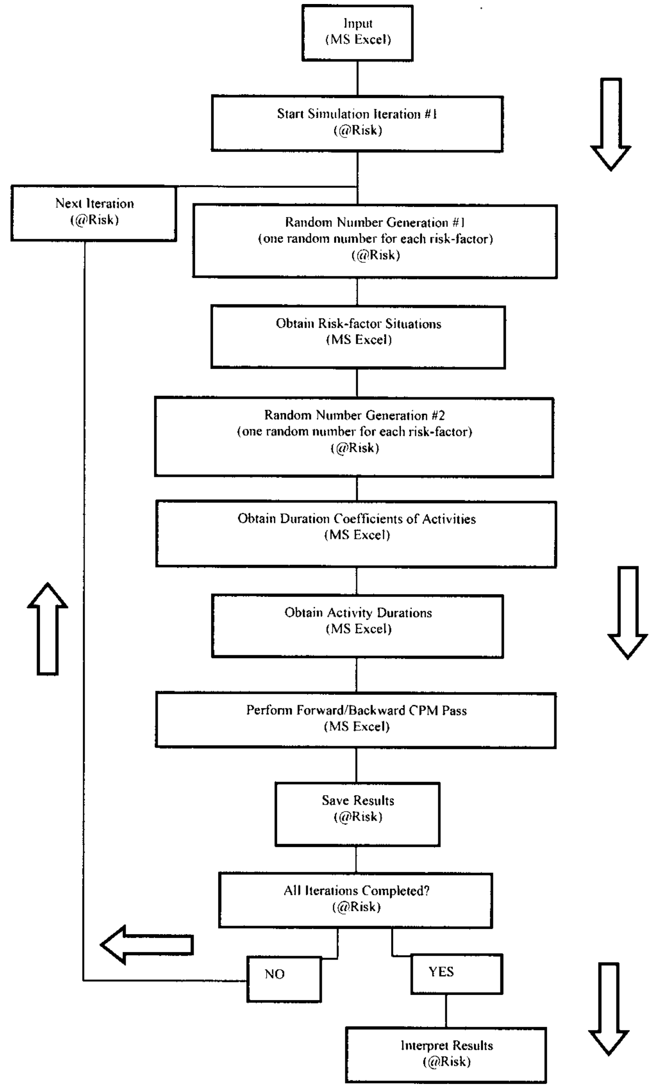

Fig. 2. Flowchart of CSRAM operation

- Activity–risk factor influence degrees: These are represented in qualitative terms such as very effective, effective, or ineffective. The user selects the appropriate qualification for each "activity–risk factor" pair. These data show the relative degree of how much a particular risk factor creates uncertainty on a particular activity's duration.
- Risk factor situation probability boundaries: Risk factors may occur as better than expected, expected, or worse than expected in real life. In each situation, they create favorable, neutral, or adverse uncertainty about activity durations, respectively. CSRAM needs to know the probability boundaries of risk factors' different situations to decide which situation will occur for a particular simulation step, so that the total effect of risk factors on activity durations are determined by the utilization of "activity–risk factor influence degrees" in conjunction with risk factor situations. "Risk factor situation probability boundaries" are judgmentally determined by the help of past experience and entered as numerical values between 0 and 1. For instance, when the user estimates that labor productivity risk is very probable to occur as worse than expected, less probable to occur as expected, and least probable to occur as better than expected, the user may enter 0.10–0.40–1.00 values, respectively, to represent better than expected, expected,

J. Constr. Eng. Manage., 2008, 134(1): 49-63

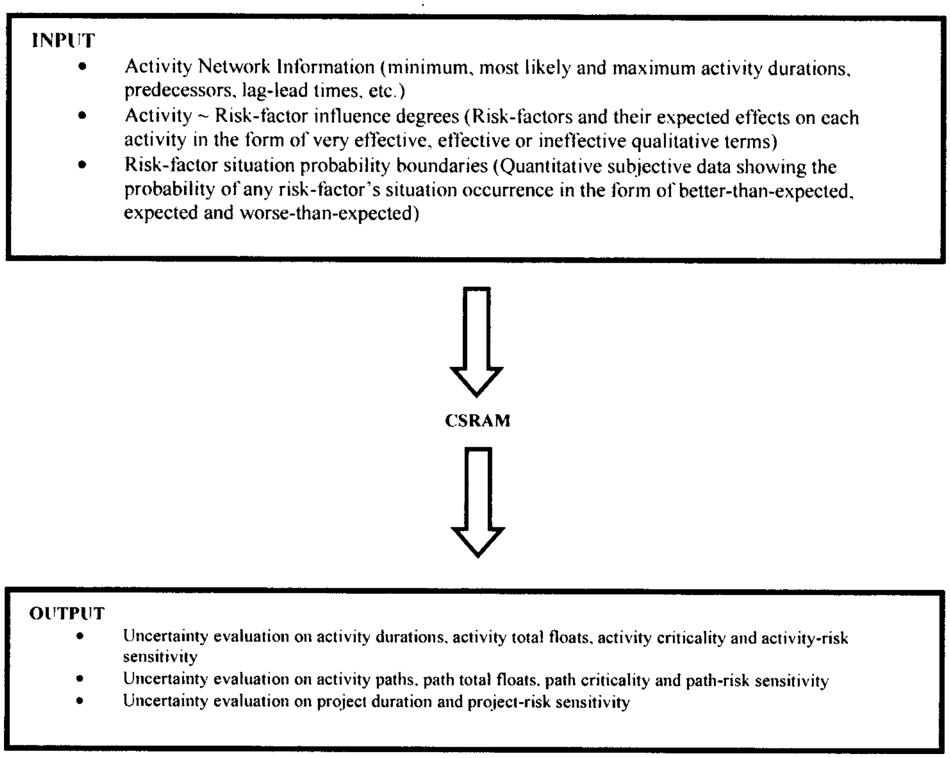

Fig. 3. Input-output chain of CSRAM

and worse than expected risk factor situation probability boundaries of this risk factor. In such a case, the probability of occurrence of better than expected, expected, and worse than expected in any CSRAM iteration becomes 0.10 (0.10–0.00), 0.30 (0.40–0.10), and 0.60 (1.00–0.40), respectively. Once more, it should be emphasized that these values are judgmental and their extents may change from user to user. However, risk identification techniques such as brainstorming and interviews with experienced personnel would provide more realistic and objective values.

- Correlation between risk factors: CSRAM requires information about which risk factors are correlated. For instance, if the user estimates that as weather becomes worse than expected, labor productivity will be worse than expected, or as weather becomes better than expected, labor productivity will be worse than expected, one may enter the information in the model that these two risk factors are correlated. Eventually, CSRAM's computation algorithm behaves accordingly.
- Simulation properties: The user should also enter characteristic preferences for a Monte Carlo simulation. The main preferences are iteration number and seed value. Generally, an iteration number equal to or greater than 1,000 is sufficient. Selection of the same seed value provides the selection of the same random variables for different simulations and is useful for comparison of the results of different simulations under the same randomly generated conditions.

The input-output chain of the model is illustrated briefly in Fig. 3.

Elicitation of Correlation between Activity Durations

CSRAM is eligible for eliciting correlation between activity durations indirectly. The user is not required to enter the correlation coefficients directly. Instead, correlation is supplied by activity–risk factor influence degrees entered by the user in the form of very effective-effective-ineffective qualitative terms. Correlation between activity durations is captured by entering the same or close qualitative estimates (very effective-very effective or very effective-effective) for any two activities thought to be sensitive to a particular risk factor. For the sake of comprehension of CSRAM's correlation capturing mechanism, consider the 10-activity-path project shown in Fig. 4. All the data assumed in this project are presented in Table 1.

All risk factors are assumed to be uncorrelated for the sake of

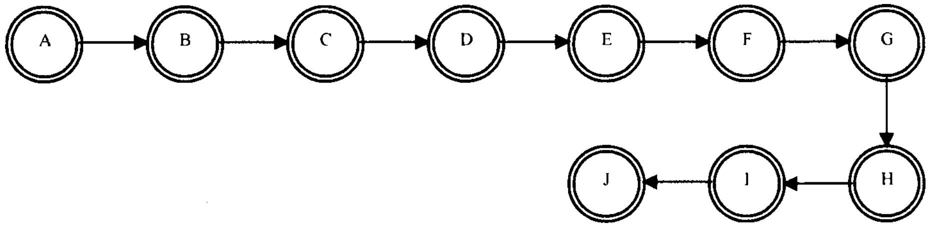

Fig. 4. Network diagram of the 10-activity path

J. Constr. Eng. Manage., 2008, 134(1): 49-63

Table 1. Input Data of 10-Activity Path

Activity–risk factor influence matrix															
				Risk factors		Risk factor 1	Risk factor 2	Risk factor 3	Risk factor 4	Risk factor 5	Risk factor 6	Risk factor 7	Risk factor 8	Risk factor 9	Risk factor 10
Simulation type=Monte Carlo Simulation Iteration number=1000 Seed value=100 Correlated risk factors=—				Risk factor situation probability boundaries	Better than expected	0.30	0.30	0.10	0.30	0.40	0.30	0.30	0.20	0.30	0.20
					Expected	0.60	0.60	0.50	0.70	0.70	0.60	0.70	0.60	0.70	0.60
					Worse than expected	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Activity label	Minimum expected activity duration	Most likely activity duration	Maximum expected activity duration	Predecessor activity	Network relation	Activity–risk factor influence degrees									
A	6	10	18	—	—	Very effective	Very effective	Ineffective	Effective	Effective	Effective	Very effective	Ineffective	Effective	Very effective
B	6	10	18	A	FS	Very effective	Effective	Effective	Very effective	Ineffective	Effective	Very effective	Effective	Very effective	Effective
C	6	10	18	B	FS	Very effective	Effective	Very effective	Ineffective	Effective	Effective	Ineffective	Very effective	Ineffective	Very effective
D	6	10	18	C	FS	Effective	Very effective	Very effective	Very effective	Ineffective	Effective	Ineffective	Ineffective	Effective	Ineffective
E	6	10	18	D	FS	Effective	Very effective	Effective	Effective	Ineffective	Very effective	Effective	Very effective	Effective	Ineffective
F	6	10	18	E	FS	Effective	Very effective	Ineffective	Effective	Very effective	Effective	Very effective	Effective	Effective	Ineffective
G	6	10	18	F	FS	Very effective	Effective	Ineffective	Effective	Very effective	Very effective	Effective	Ineffective	Effective	Effective
H	6	10	18	G	FS	Ineffective	Very effective	Very effective	Very effective	Effective	Very effective	Effective	Effective	Very effective	Effective
I	6	10	18	H	FS	Ineffective	Effective	Effective	Very effective	Very effective	Effective	Very effective	Very effective	Very effective	Very effective
J	6	10	18	I	FS	Very effective	Very effective	Ineffective	Effective	Effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective

J. Constr. Eng. Manage., 2008, 134(1): 49-63

simplicity. As shown in Table 1, the first two activities are strongly correlated when risk factor 1 is considered because the risk factor–activity degrees of influence of both activities are qualified by the very effective term. When risk factor 2 is considered, these two activities are assumed to be correlated again by the very effective–effective pair, but weaker with respect to risk factor 1. When risk factor 8 is considered, they are not correlated because risk factor 8 is not effective for both activities, so the ineffective term is used for risk factor 8's influence. Now consider iteration #1. Assume that CSRAM produced the random numbers 0.84, 0.92, 0.23, 0.42, 0.76, 0.06, 0.18, 0.27, 0.32, and 0.68 for risk factor i $(i=1 \rightarrow 10)$, respectively, in order to determine the risk factor situations for this particular iteration. CSRAM conducts this operation as follows (refer to Table 1):

- Iteration #1-rnd.no.#1 $= 0.84 > 0.60 \Rightarrow$ worse-than-expected (risk-factor-1).
- Iteration #1-rnd.no.#2 $= 0.92 > 0.60 \Rightarrow$ worse-than-expected (risk-factor-2).
- Iteration #1-rnd.no.#3 $= 0.10 < 0.23 < 0.50 \Rightarrow$ expected (risk-factor-3).
- Iteration #1-rnd.no.#4 $= 0.30 < 0.42 < 0.70 \Rightarrow$ expected (risk-factor-4).
- Iteration #1-rnd.no.#5 $= 0.76 > 0.70 \Rightarrow$ worse-than-expected (risk-factor-5).
- Iteration #1-rnd.no.#6 $= 0.06 < 0.30 \Rightarrow$ better-than-expected (risk-factor-6).
- Iteration #1-rnd.no.#7 $= 0.18 < 0.30 \Rightarrow$ better-than-expected (risk-factor-7).
- Iteration #1-rnd.no.#8 $= 0.20 < 0.27 < 0.60 \Rightarrow$ expected (risk-factor-8).
- Iteration #1-rnd.no.#9 $= 0.30 < 0.32 < 0.70 \Rightarrow$ expected (risk-factor-9).
- Iteration #1-rnd.no.#10 $= 0.68 > 0.60 \Rightarrow$ worse-than-expected (risk-factor-10).

After the risk factor situations are determined as above, CSRAM generates second random numbers (equal to the number of risk factors) to compute the activity durations to be used in a CPM forward-backward pass in iteration #1. Assume that second random numbers generated are 0.52, 0.47, 0.31, 0.92, 0.09, 0.99, 0.87, 0.27, 0.61, and 0.42 for risk factor i $(i=1 \rightarrow 10)$, respectively. Now consider activity A. The duration of this activity is computed as follows:

1. If activity duration coefficient of activity A
$$> 0 \Rightarrow \text{Activity duration} = [\text{most likely duration} + (\text{maximum duration} - \text{most likely duration}) \times \text{activity duration coefficient}]$$
2. If activity duration coefficient of activity A
$$< 0 \Rightarrow \text{Activity duration} = [\text{most likely duration} + (\text{most likely duration} - \text{minimum duration}) \times \text{activity duration coeff.}]$$

where

$$\text{Activity Duration Coefficient of Activity A} = \sum_{i=1}^{10} [(\text{random no.})_i \times (\text{activity/risk-factor influence degree value})_i]$$

such that

If $(\text{Risk-Factor Situation})_i$ is better-than-expected
$$\Rightarrow (\text{Activity/risk-factor influence degree value})_i < 0$$

If $(\text{Risk-Factor Situation})_i$ is worse-than-expected
$$\Rightarrow (\text{Activity/risk-factor influence degree value})_i > 0$$

$$\text{If } (\text{Risk-Factor Situation})_i \text{ is expected} \Rightarrow (\text{Activity/risk-factor influence degree value})_i = 0$$

where

If $(\text{Activity/risk-factor influence degree})_i$ is "very effective"
$$\Rightarrow (\text{Activity/risk-factor influence degree value})_i = \frac{0.70}{(\text{number of ``very effective'' terms assigned to Activity A})}$$

If $(\text{Activity/risk-factor influence degree})_i$ is "effective"
$$\Rightarrow (\text{Activity/risk-factor influence degree value})_i = \frac{0.30}{(\text{number of ``effective'' terms assigned to Activity A})}$$

CSRAM accepts the 0.70 scale value default for the total effect of "very effective" qualifications and 0.30 scale value default for the total effect of "effective" qualifications for a particular activity. Why these scale values are selected and the verification of such an acceptance will be discussed in the next CSRAM application section. Now for our current 10-activity-path example in Table 1, consider Activity A, which has 4 very effective, 4 effective, and 2 ineffective qualifications. Therefore, CSRAM divides 0.70 by 4 and assigns 0.175 as the activity–risk factor influence degree value to the very effective terms; and in a similar way it divides 0.30 by 4 and assigns 0.075 value to the effective terms. It assigns zero to the ineffective terms because they have no effect on Activity A's duration. It can be recognized that the summation of 4 0.175, 4 0.075, and 2 zeros is equal to 1.0, which means that the risk factors entered to CSRAM are assumed to be responsible for the total deviation of any activity's duration from the expected most likely value.

By this scale-dependent computation, qualitative terms are converted to numerical values to be used in activity duration calculation in iteration #1 and in other iterations as well. Notice that the same random number group is used for the computation of all activities' duration computation in a particular iteration. Following the above procedure, Activity A's duration in iteration #1 is computed as follows:

$$\begin{aligned}\text{Activity Duration Coefficient of Activity A} &= 1 \times (0.52 \times 0.175) + 1 \times (0.47 \times 0.175) + 0 \times (0.31 \times 0) \\ &+ 0 \times (0.92 \times 0.075) + 1 \times (0.09 \times 0.075) + (-1) \\ &\times (0.99 \times 0.075) + (-1) \times (0.87 \times 0.175) \\ &+ 0 \times (0.27 \times 0) + 0 \times (0.61 \times 0.075) + 1 \\ &\times (0.42 \times 0.175) = 0.027 > 0 \Rightarrow\end{aligned}$$

$$\begin{aligned}\text{Activity duration of Activity A} &= [\text{most likely duration} \\ &+ (\text{maximum duration–most likely duration}) \\ &\times \text{activity duration coefficient}]\end{aligned}$$

J. Constr. Eng. Manage., 2008, 134(1): 49-63

$$\text{Activity duration of Activity A} = [10 + (18 - 10) \times 0.027] = 10.216 \text{ days}$$

CSRAM computes the durations of other activities during the simulation iterations in the same manner. It can be recognized that if the duration coefficient of an activity was found less than zero in an iteration, the activity duration would be computed between most likely and minimum activity durations. In the example above, since the activity duration coefficient of activity A was computed to be greater than zero, the activity duration of activity A has been computed to lie between the most likely and maximum activity durations.

Elicitation of Correlation between Risk Factors

Another distinguishing feature of CSRAM is its capability of modeling correlation between risk factors. The indirect elicitation method is followed just as it was for the correlation elicitation between activities. In other words, correlation coefficients between risk factors are not required, which would be already meaningless. Risk factors are not represented with probability distributions in CSRAM; accordingly, correlation coefficient values are not necessary, but instead are represented by risk factor situation probability boundaries. These input data are requested from the user in quantitative terms between 0 and 1, based on engineering judgment, experience, and previous data. It should be mentioned that such information can be explored during the risk identification stage of a risk management system (Fig. 1).

CSRAM provides the correlation between risk factors through two steps: first, it equates the risk factor situation probability boundaries of the risk factors that the user entered in the model as correlated, and second, it generates the same random numbers for the correlated risk factors to determine their risk factor situations and to compute the durations of the activities that are affected from them. The activity duration computation procedure is the same as shown in the previous section.

Simulation-Based Uncertainty Evaluation Algorithm

CSRAM evaluates the uncertainty in a construction schedule network by executing the Monte Carlo simulation technique. Scheduling is a complex problem, and a model produced for analyzing a schedule cannot be solved analytically. Simulation techniques are utilizable in such cases. Each iteration represents a different story for the whole project in different random conditions created in accordance with the input data. The forward-backward computation algorithm of CPM produces different project durations, float values, and critical paths in each iteration. All these values are saved by CSRAM, and the uncertainty and risk sensitivity are measured by integrating these data into statistical charts or values such as probability distributions, means, or variances.

The distinguishing schedule evaluation feature of CSRAM lies in the way it computes the activity durations with incorporating a positive correlation between activity durations and between risk factors indirectly. CSRAM's simulation and risk-based correlation elicitation algorithm produces more realistic results for managing schedule uncertainty. It simulates a schedule several times and helps the engineer to observe how the real system might behave in reality.

Random numbers are utilized in CSRAM. The probability of getting a value between 0 and 1 during a random number generation is equal when uniform probability distribution is used. The equal chance of getting any value between 0 and 1 represents the real system more realistically. For example, consider two risk factors that are not correlated. Since they are uncorrelated, the random numbers generated for determining their situations are produced independently in any iteration. However, if these two activities were introduced as correlated with the model, the same random numbers would be generated for determining their situations. In a particular iteration, if these two risk factors are uncorrelated, their situation might occur as better than expected–better than expected, better than expected–worse than expected, worse than expected–better than expected, or worse than expected–worse than expected, respectively. In real life, this is also the case; for instance, the soil conditions or weather situation may occur randomly. Random numbers generated through uniform probability distribution by CSRAM are utilized for modeling a kind of randomness like that experienced in real life.

CSRAM determines the risk factor situations during iterations by selecting the situation of a risk factor through a comparison of the randomly generated numbers against the "risk factor situation probability boundaries" entered by the user. For instance, if it is expected that soil conditions will occur as worse than expected with a dominant probability, the risk factor situation probability boundaries for soil conditions are entered accordingly, and so the probability of getting a worse than expected situation for soil conditions is increased in any iteration, despite the chance of getting any value between 0 and 1 that is used in the determination of a risk-factor situation being equal.

Activity-, Path-, and Project-Based Risk Factor Sensitivity Analysis

CSRAM provides useful information to a manager or decision maker about the uncertainty inherent in a construction project. The information provided is three sided: activity, path, and project based. Main provisions are the variation in total float and in critically of any activity, the sensitivity of any activity to any risk factor, the variation in total float and the variation in criticality of any path, the sensitivity of any path to any risk factor, the variation in total project duration, and the sensitivity of the whole project to any risk factor. Such information is invaluable for a manager to know in advance the sensitivity of the schedule variables to various risk factors, develop risk response strategies, and take precautions for the success of the project. For instance, if the manager is aware that a particular path is highly sensitive to a particular risk factor, and this path is a candidate to become a critical path with a high probability, then it is possible to develop strategies for lowering the effect of that particular risk factor on the activities of that path. If it is not possible to know this in advance, the risk of a schedule overrun will increase due to the risk of an increase in that path's duration and the chance of that path's becoming a critical path. CSRAM helps the manager to recognize how and what to manage in a construction schedule. In some way, the manager becomes aware of the extent of uncertainty and its effect on the schedule.

CSRAM Application

In this section, CSRAM is evaluated on a single-story house project. CSRAM input data for the project are given in Table 2. Ten risk factors are assumed to influence the schedule, and risk factors 1 and 2, 7 and 9, and 8 and 10 are assumed to correlate. Three different analyses are conducted as follows:

J. Constr. Eng. Manage., 2008, 134(1): 49-63

Table 2. Input Data of Single-Story House Project

						Activity–risk factor influence matrix										
					Risk factors		Weather	Soil conditions	Material and equipment usage efficiency	Design sufficiency and design changes	Labor productivity	Subcontractor productivity	Material availability	Disputes with owner	Management quality	Activity complexity
					Risk factor situation probability boundaries	Better than expected	0.40	0.40	0.30	0.30	0.30	0.30	0.30	0.20	0.30	0.20
						Expected	0.70	0.70	0.60	0.70	0.70	0.60	0.70	0.50	0.70	0.50
						Worse than expected	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Activity label	Minimum expected activity duration (day)	Most likely activity duration (day)	Maximum expected activity duration (day)	Activity description	Predecessor activity		Activity–risk factor influence degrees									
A	4.00	6.00	8.00	Clear, excavate, and grade site	—		Very effective	Very effective	Effective	Ineffective	Effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
B	4.00	5.00	8.00	Excavate for foundation footings	A		Very effective	Very effective	Effective	Ineffective	Effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
C	2.00	3.00	5.00	Install electrical and other cable subground connections	B		Very effective	Very effective	Effective	Ineffective	Very effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
D	2.00	3.00	5.00	Install drinking water and sewage subground plumbing	B		Very effective	Very effective	Effective	Effective	Very effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
E	1.00	2.00	4.00	Pour foundation	C, D		Very effective	Effective	Effective	Ineffective	Effective	Very effective	Ineffective	Ineffective	Effective	Ineffective
F	15.00	20.00	30.00	Build external wooden frame	E(FS+2)		Very effective	Ineffective	Effective	Very effective	Very effective	Ineffective	Very effective	Ineffective	Effective	Very effective
G	8.00	10.00	14.00	Lay external brick walls	E		Very effective	Ineffective	Effective	Effective	Very effective	Ineffective	Very effective	Ineffective	Effective	Effective
H	3.00	4.00	6.00	Install interior drinking water and sewage plumbing	E		Ineffective	Ineffective	Effective	Effective	Very effective	Ineffective	Effective	Ineffective	Effective	Effective
I	4.00	6.00	8.00	Install electrical and other cable connections	E		Ineffective	Ineffective	Effective	Effective	Very effective	Ineffective	Effective	Ineffective	Effective	Effective
J	3.00	5.00	8.00	Install HVAC units	G, H, I		Ineffective	Ineffective	Effective	Effective	Very effective	Very effective	Effective	Ineffective	Effective	Effective
K	7.00	8.00	15.00	Build roof	G(SS+6), H		Very effective	Ineffective	Effective	Effective	Very effective	Ineffective	Effective	Ineffective	Effective	Effective
L	10.00	14.00	20.00	Lay internal walls and slab coverings	I, J		Ineffective	Ineffective	Effective	Effective	Very effective	Ineffective	Very effective	Ineffective	Effective	Effective
M	3.00	5.00	8.00	Initial painting	L(FF−5)		Effective	Ineffective	Effective	Effective	Very effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
N	8.00	10.00	15.00	Final carpentry work	L(FF−5)		Ineffective	Ineffective	Effective	Effective	Very effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
O	3.00	4.00	6.00	Final plumbing and other connections	M		Ineffective	Ineffective	Effective	Effective	Effective	Ineffective	Effective	Ineffective	Effective	Ineffective
P	4.00	5.00	7.00	Install exterior doors and windows	K		Effective	Ineffective	Effective	Effective	Very effective	Ineffective	Effective	Ineffective	Effective	Effective
Q	2.00	3.00	5.00	Install fixtures	L		Ineffective	Ineffective	Effective	Effective	Very effective	Ineffective	Effective	Ineffective	Effective	Effective
R	3.00	4.00	6.00	Install interior doors	N, Q		Ineffective	Ineffective	Effective	Effective	Very effective	Ineffective	Effective	Ineffective	Effective	Effective
S	5.00	6.00	8.00	Final painting	N, O, Q, R		Effective	Ineffective	Effective	Ineffective	Very effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
T	1.00	2.00	4.00	Final electrical work	S(FS−3)		Ineffective	Ineffective	Effective	Effective	Very effective	Ineffective	Effective	Ineffective	Effective	Effective
U	3.00	5.00	8.00	Grade site and prepare driveway	F		Very effective	Effective	Effective	Effective	Effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
V	4.00	5.00	7.00	Landscape and walkway work	U		Very effective	Effective	Effective	Effective	Effective	Ineffective	Ineffective	Ineffective	Effective	Ineffective
W	3.00	4.00	6.00	Final control and miscellaneous work	P, T, V		Effective	Ineffective	Effective	Effective	Effective	Ineffective	Ineffective	Very effective	Effective	Ineffective

- Application of CPM, PERT, stochastic CPM, and CSRAM to the project and comparison of the results.
- Application of CSRAM under different very effective scales to see the sensitivity of the model to this parameter.
- Conducting path and project-risk sensitivity analyses through CSRAM to observe which risk factors are more effective on the paths and the whole project, and to detect which noncritical paths are candidates to become critical due to the uncertainty in activity durations.

The major aim of this section is to show the applicability of CSRAM to a multipath real project and to show its capability of performing risk analysis on the schedule. The benefit of the results of the path- and project-based risk sensitivity analyses from the managerial point of view is also mentioned through some discussions within the section.

MS Excel and @Risk software programs have been used for the model's execution. First of all, CPM forward-backward pass calculation and total float-criticality exploration have been achieved by using MS Excel formulas on an MS Excel spreadsheet. This step is important because CSRAM is based on CPM calculations, as previously emphasized. Afterwards, CSRAM has been modeled on the same spreadsheet through designing the input cells first and setting up the model's algorithm with MS Excel formulas second. The last step of the model's execution on the multipath case project schedule has been conducting Monte Carlo simulation by using the commands of @Risk software program. In Fig. 2, this procedure has been clarified by noting the utilized software next to each item of the model's operation flowchart.

@Risk is indeed an add-in of MS Excel, to which it adds risk analysis and simulation capability. After any simulation, it reports the statistical results automatically in a regulated fashion. In this regard, the results of the CSRAM execution that are introduced through the next sections have been extracted from @Risk's reports and summarized. It should also be mentioned that the application of PERT has been carried out by utilizing MS Excel formulas, and the application of stochastic CPM has been performed by using both MS Excel formulas and @Risk.

Application of CPM, PERT, Stochastic CPM, and CSRAM on the Project

CPM, PERT, stochastic CPM, and CSRAM have been applied to the project data given in Table 2. The statistical results and the project duration cumulative probability distributions produced by PERT, stochastic CPM, and CSRAM are presented in Table 3 and Fig. 5, respectively. In the stochastic CPM application, the activity durations are assumed to follow triangle probability distributions; 1,000 iterations have been conducted in all simulations.

The results reveal that CSRAM produces a larger maximum-minimum project duration interval and greater standard deviation with respect to PERT and stochastic CPM. In other words, the uncertainty effect is larger than the PERT and stochastic CPM suppose. This is also clear in Fig. 5, where the cumulative probability distribution produced by CSRAM is wider than the other distributions. The uncertainty is obviously caused by the risk factors and the correlation effect between activities and between risk factors. When the correlation coefficients captured by CSRAM and stochastic CPM in Table 3 are compared, the correlation effect can be seen more clearly. Except from CSRAM, the applied methods have no capability of capturing correlation and exploring the actual uncertainty level.

Table 3. Results of CPM, PERT, Stochastic CPM, and CSRAM Application

Method	Minimum path duration (day)	Maximum path duration (day)	Mean path duration (day)	Variance of path duration	Standard deviation of path duration	Probability of corresponding CPM duration	Captured correlation coefficient between Activity A and Activity B	Captured correlation coefficient between Activity B and Activity C	Captured correlation coefficient between Activity C and Activity D	Captured correlation coefficient between Activity D and Activity E	Captured correlation coefficient between Activity E and Activity F	Captured correlation coefficient between Activity F and Activity G
CPM	—	—	61.00	—	—	—	—	—	—	—	—	—
PERT	56.45	70.21	63.33	7.11	2.67	19%	—	—	—	—	—	—
Stochastic CPM	56.32	77.96	66.00	10.47	3.24	6%	0.02	−0.03	−0.01	−0.04	−0.01	−0.02
CSRAM	50.42	82.78	62.71	28.88	5.37	42%	0.95	0.93	0.98	0.73	0.39	0.91

J. Constr. Eng. Manage., 2008, 134(1): 49-63

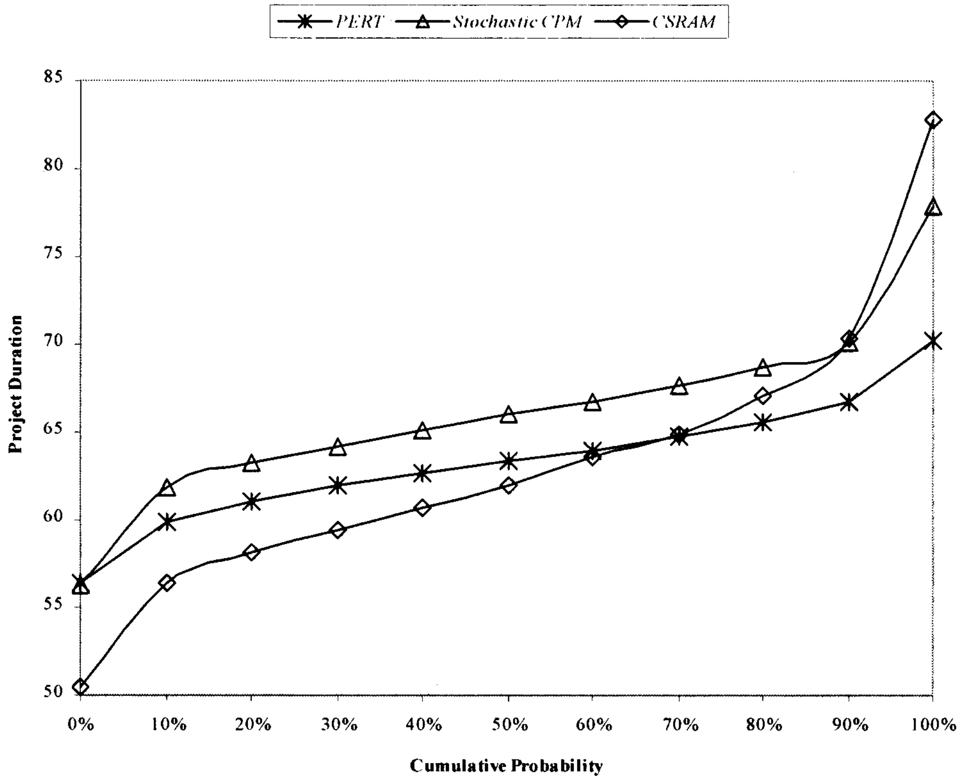

Fig. 5. Cumulative probability distributions of project duration in PERT, stochastic CPM, and CSRAM application

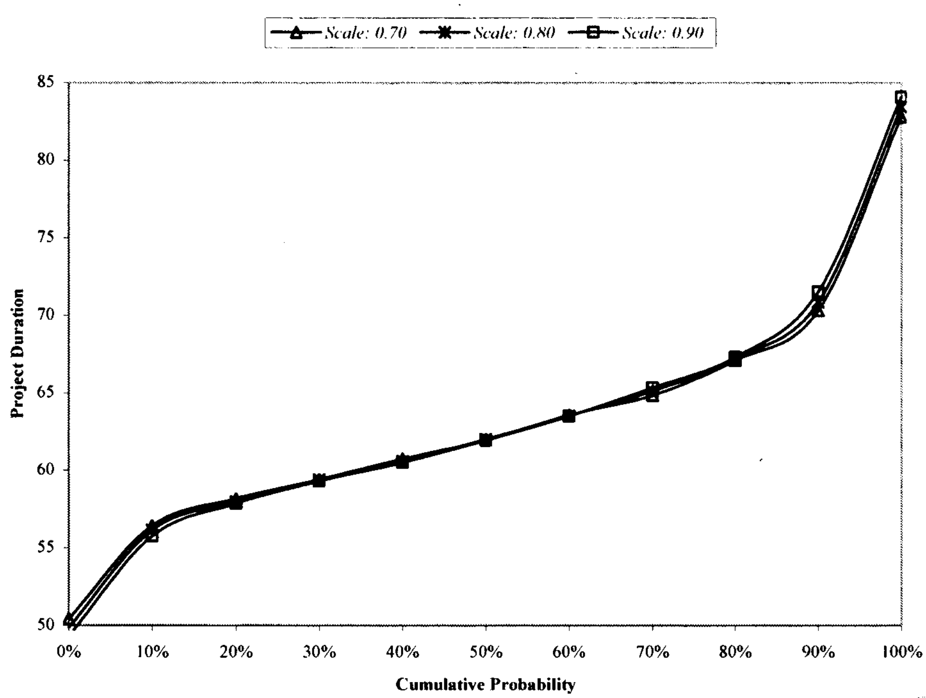

Fig. 6. Cumulative probability distributions of project duration under different very effective scales

J. Constr. Eng. Manage., 2008, 134(1): 49-63

Table 4. Results of Project Risk Sensitivity Analysis

Scenario	Minimum path duration (day)	Maximum path duration (day)	Mean path duration (day)	Variance of path duration	Standard deviation of path duration	Standard deviation mean ratio
All risk factors	50.42	82.78	62.71	28.88	5.37	0.09
Risk factors 1–2	57.38	67.53	61.24	6.10	2.47	0.04
Risk factor 3	59.62	63.56	61.31	0.94	0.97	0.02
Risk factor 4	60.19	62.61	61.12	0.31	0.56	0.01
Risk factor 5	54.98	71.88	61.67	16.00	4.00	0.06
Risk factor 6	59.95	62.75	61.19	0.47	0.68	0.01
Risk factors 7–9	57.48	67.13	61.42	4.97	2.23	0.04
Risk factors 8–10	59.57	63.69	61.49	1.06	1.03	0.02

Application of CSRAM under Different Very Effective Scales

CSRAM is applied to the same project by using different very effective scales in this section. The very effective scale values tested are 0.7, 0.8, and 0.9. The resultant project duration cumulative probability distributions are given in Fig. 6. The graph shows that the cumulative distributions are very close in each scale value preference. This means that risk analysis capability of CSRAM has not changed under different scale values. This is the desired result from CSRAM. In other words, CSRAM is not sensitive to scale values. Therefore, very effective scale was accepted as 0.7 default value in CSRAM, and accordingly the requirement of the scale parameter value entrance by the user was eliminated.

Conducting Path Risk Sensitivity Analysis and Project Risk Sensitivity Analysis

In this section, the risk sensitivity of the project and the paths was investigated. Knowledge of which risk factors are more effective for the project and the paths gives the manager the opportunity to manage the schedule better; knowing what to keep under control when managing the paths prevents overrunning the planned schedule time. Controlling only the activities on the critical paths is not sufficient for decreasing the risk of overrunning the schedule because the uncritical paths may also become critical due to the uncertainty in activity durations. For this reason, it is important to know what to control when managing both critical and uncritical paths. In this context, CSRAM has been designed with the capability of detecting which risk factors are more responsible for the uncertainty in the project and path durations.

Table 4 contains the results of the project risk sensitivity analysis. When the table is examined, it is observed that risk factor 5 (labor productivity) creates the greatest variance, standard deviation, and maximum-minimum duration interval. This means that risk factor 5 is the most responsible factor for the project duration variance, and in turn, is the factor most responsible for the schedule uncertainty. Furthermore, the other statistical values reveal that risk factors 1–2 (weather–soil conditions) and risk factors 7–9 (material availability–management quality), which are correlated in between, are the other most effective risks after risk factor 5. Thus it is important to focus on these risk factors during the management of the project in order to lower the uncertainty effect and in turn to lower the risk of overrunning the planned project completion time. However, the risk factors that are more effective (especially for the uncritical paths, which are candidates for turning to critical due to the uncertainty effect) should also be known in order to manage the paths properly and decrease the uncertainty effect.

CSRAM detects 34 paths in this house project. Table 5 contains a portion of the results of the path risk sensitivity analysis. It can be recognized that some of the paths show more variability with respect to their total float. CSRAM computes the total float of paths by subtracting the sum of durations of activities on a path from the project duration during simulation iterations. Then it finds the change in total floats of the paths throughout the whole simulation. Probable minimum and maximum float values are an indication of this variability. For instance, consider paths 4 and 11 in Table 5. Path 4 is an uncritical path according to CPM, but CSRAM finds that its total float may change from 0 to 21 days, which means that its criticality is highly uncertain. Path 11 is also an uncritical path according to CPM, but CSRAM finds that its total float may change from 2.52 to 5.82 days, which means that it is a near-critical path. Knowing which risk factors are more effective on such paths is important for a manager to take precautions in advance for preventing these paths' becoming critical. If such paths become critical or near critical, the risk of overrunning a schedule time increases. Besides the uncritical paths of CPM, critical paths are also important for focusing attention. Consider paths 1 and 2 in Table 5. They are critical paths according to CPM, and therefore have no opportunity to extend in duration. If they extend, the project duration would extend. At this point, it can be concluded that total floats of the paths are very useful for managing the uncertainty in a project. Since the critical paths have zero total floats, they are difficult to manage because any extension of such paths leads directly to extension of the project duration.

Tables 5 and 6 contain the information that CSRAM has produced about which paths are highly uncertain in criticality and which risk factors are mostly responsible for this uncertainty. CSRAM performs such an analysis in two steps: by running the risk factors all together first, and then running them separately. At the first step, the model finds the uncertainty in path floats and determines which paths are more uncertain in criticality and which are near critical (the results are shown in Table 5). At the second step, it runs the risk factors separately on the schedule to find the responsible risk factors on the uncertainty of such paths (the results in Table 6).

If the results in Table 6 are examined, it is clear that risk factor 5 (labor productivity) is the most responsible for the uncertainty in path durations; it stands in the first order of the most affecting risk factors for almost all the paths. Furthermore, risk factors 1–2 (weather–soil conditions) and 7–9 (material availability–management quality), which are correlated in between, are the other most-effective risks after risk factor 5. This is compatible with the result obtained in project risk sensitivity analysis. In

J. Constr. Eng. Manage., 2008, 134(1): 49-63

Table 5. Results of Path Risk Sensitivity Analysis (First Step—Risk Factors Together)

Path number	Activities	CSRAM-Risk factors together: Minimum path float	Maximum path float	Mean path duration	Standard deviation of path duration	Criticality
1	A,B,C,E,G,J,L,Q,R,S,T,W	0.00	0.28	62.68	5.37	Critical
2	A,B,D,E,J,G,L,Q,R,S,T,W	0.00	0.33	62.68	5.36	Critical
3	A,B,C,E,I,J,L,M,O,S,T,W	11.19	15.17	50.37	4.72	Uncritical
4	A,B,C,E,F,U,V,W	0.09	21.68	53.25	4.69	Uncertain criticality—highly variable path float
5	A,B,C,E,G,J,L,M,O,S,T,W	6.60	10.80	54.54	4.83	Uncritical
6	A,B,C,E,H,J,L,M,O,S,T,W	12.68	17.17	48.49	4.60	Uncritical
7	A,B,C,E,I,L,M,O,S,T,W	15.27	22.00	45.21	4.31	Uncritical
8	A,B,C,E,I,J,L,N,R,S,T,W	11.14	14.84	50.39	4.88	Uncritical
9	A,B,C,E,I,J,L,N,S,T,W	14.67	20.42	46.26	4.45	Uncritical
10	A,B,C,E,I,J,L,Q,S,T,W	7.14	10.84	54.39	4.88	Uncritical
11	A,B,C,E,I,J,L,Q,R,S,T,W	2.52	5.87	58.52	5.32	Near critical
12	A,B,C,E,G,J,L,N,S,T,W	10.28	15.28	50.43	4.56	Uncritical
13	A,B,C,E,G,J,L,N,R,S,T,W	7.15	9.73	54.55	4.96	Uncritical
14	A,B,C,E,H,J,L,N,S,T,W	16.04	22.42	44.38	4.34	Uncritical
15	A,B,C,E,H,J,L,N,R,S,T,W	12.67	16.84	48.51	4.76	Uncritical
16	A,B,C,E,H,J,L,Q,R,S,T,W	4.52	7.87	56.64	5.20	Near critical
17	A,B,C,E,H,K,P,W	17,47	33.52	38.37	3.67	Uncritical—highly variable path float
18	A,B,C,E,G,K,P,W	15.53	31.99	40.42	3.95	Uncritical—highly variable path float
19	A,B,D,E,I,J,L,M,O,S,T,W	11.18	15.33	50.37	4.71	Uncritical
20	A,B,D,E,F,U,V,W	0.00	21.66	53.25	4.68	Uncertain criticality—highly variable path float
21	A,B,D,E,G,K,P,W	6.61	10.73	54.53	4.82	Uncritical
22	A,B,D,E,I,H,J,L,M,O,S,T,W	12.64	17.33	48.49	4.59	Uncritical
23	A,B,D,E,I,L,M,O,S,T,W	15.23	22.25	45.21	4.30	Uncritical
24	A,B,D,E,I,J,L,N,R,S,T,W	11.06	15.01	50.39	4.87	Uncritical
25	A,B,D,E,I,J,L,N,S,T,W	14.66	20.59	46.26	4.45	Uncritical
26	A,B,D,E,I,J,L,Q,S,T,W	7.06	11.01	54.39	4.87	Uncritical
27	A,B,D,E,I,J,L,Q,R,S,T,W	2.48	5.98	58.51	5.32	Near critical
28	A,B,D,E,G,J,L,N,S,T,W	10.26	15.42	50.42	4.55	Uncritical
29	A,B,D,E,J,L,N,R,S,T,W	7.13	9.84	54.55	4.95	Uncritical
30	A,B,D,E,H,J,L,N,S,T,W	16.10	22.59	44.38	4.33	Uncritical
31	A,B,D,E,H,J,L,N,R,S,T,W	12.66	17.01	48.50	4.75	Uncritical
32	A,B,D,E,H,J,L,Q,R,S,T,W	4.48	7.98	56.63	5.19	Near critical
33	A,B,D,E,H,K,P,W	17.44	33.50	38.37	3.67	Uncritical—highly variable path float
34	A,B,D,E,G,K,P,W	15.51	31.97	40.41	3.95	Uncritical—highly variable path float

other words, these three risk factors are the most effective factors not only for path duration uncertainty but also for project duration uncertainty.

Paths 1, 2, 4, 11, 16, 17, 18, 20, 27, 32, 33, 34 are those on which the managerial attention should be focused first for the sake of schedule success of the project because they are either critical, near critical, uncertain critical, or uncritical with highly variable floats. The risk factors substantially influencing these paths are as follows (extracted from Table 6):

- Paths 1, 2—critical; labor productivity, weather–soil conditions, material availability–management quality.
- Paths 11, 16, 27, 32—near critical; labor productivity, weather–soil conditions, material availability–management quality.
- Paths 4, 20—uncertain critical with highly variable path float; weather–soil conditions, material availability–management quality.
- Paths 17, 33—uncritical with highly variable path float; weather–soil conditions, labor productivity.
- Paths 18, 34—uncritical with highly variable path float; labor productivity, weather–soil conditions, material availability–management quality.

Some activities may be common for several paths in a construction schedule, and the risk factors that substantially affect these paths may differ. In such cases, these common activities should be managed by taking into account all the risk factors that affect the paths to which these common activities belong.

Limitations of CSRAM

The limitations of CSRAM can be described as follows:

- Dependence on realistic input data: In order to get realistic results from CSRAM, the data entered in the model should be realistic. First of all, work breakdown structure and network relationships between activities should cover the schedule requirements. Next, minimum-most likely-maximum activity

J. Constr. Eng. Manage., 2008, 134(1): 49-63

Table 6. Results of Path Risk Sensitivity Analysis (Second Step—Risk Factors Separately)

	Risk factors 1–2			Risk factor 3			Risk factor 4			Risk factor 5		
Path number	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio
1	61.24	2.47	0.04	61.30	0.98	0.02	61.09	0.51	0.01	61.67	4.00	0.06
2	61.24	2.47	0.04	61.29	0.94	0.02	61.11	0.57	0.01	61.67	4.00	0.06
3	49.19	2.13	0.04	49.29	0.98	0.02	49.08	0.51	0.01	49.43	3.45	0.07
4	52.35	4.04	0.08	52.35	1.08	0.02	52.13	0.63	0.01	52.19	1.06	0.02
5	53.24	2.47	0.05	53.32	1.04	0.02	53.10	0.56	0.01	53.51	3.15	0.06
6	47.19	2.13	0.05	47.30	0.97	0.02	47.09	0.50	0.01	47.54	3.31	0.07
7	44.19	2.13	0.05	44.27	0.91	0.02	44.07	0.44	0.01	44.38	3.04	0.07
8	49.19	2.13	0.04	49.25	0.88	0.02	49.06	0.41	0.01	49.50	3.81	0.08
9	45.19	2.13	0.05	45.24	0.83	0.02	45.05	0.37	0.01	45.40	3.31	0.07
10	53.19	2.13	0.04	53.25	0.88	0.02	53.06	0.41	0.01	53.50	3.81	0.07
11	57.19	2.13	0.04	57.27	0.92	0.02	57.07	0.46	0.01	57.60	4.30	0.07
12	49.24	2.47	0.05	49.27	0.89	0.02	49.07	0.42	0.01	49.48	3.00	0.06
13	53.24	2.47	0.05	53.28	0.93	0.02	53.08	0.46	0.01	53.58	3.50	0.07
14	43.19	2.13	0.05	43.25	0.82	0.02	43.06	0.36	0.01	43.51	3.17	0.07
15	47.19	2.13	0.05	47.26	0.87	0.02	47.07	0.40	0.01	47.61	3.67	0.08
16	55.19	2.13	0.04	55.28	0.91	0.02	55.08	0.44	0.01	55.71	4.17	0.07
17	37.49	2.80	0.07	37.23	0.62	0.02	37.08	0.24	0.01	37.59	2.17	0.06
18	39.53	3.14	0.08	39.25	0.68	0.02	39.09	0.30	0.01	39.55	2.00	0.05
19	49.19	2.13	0.04	49.28	0.94	0.02	49.10	0.58	0.01	49.43	3.45	0.07
20	52.35	4.04	0.08	52.34	1.04	0.02	52.15	0.70	0.01	52.19	1.06	0.02
21	53.24	2.47	0.05	53.31	1.00	0.02	53.12	0.63	0.01	53.51	3.15	0.06
22	47.19	2.13	0.05	47.28	0.93	0.02	47.10	0.57	0.01	47.54	3.31	0.07
23	44.19	2.13	0.05	44.26	0.87	0.02	44.09	0.51	0.01	44.38	3.04	0.07
24	49.19	2.13	0.04	49.24	0.84	0.02	49.07	0.48	0.01	49.50	3.81	0.08
25	45.19	2.13	0.05	45.23	0.80	0.02	45.07	0.44	0.01	45.40	3.31	0.07
26	53.19	2.13	0.04	53.24	0.84	0.02	53.07	0.48	0.01	53.50	3.81	0.07
27	57.19	2.13	0.04	57.26	0.89	0.02	57.08	0.52	0.01	57.60	4.30	0.07
28	49.24	2.47	0.05	49.26	0.85	0.02	49.09	0.49	0.01	49.48	3.00	0.06
29	53.24	2.47	0.05	53.27	0.90	0.02	53.10	0.53	0.01	53.58	3.50	0.07
30	43.19	2.13	0.05	43.23	0.79	0.02	43.07	0.43	0.01	43.51	3.17	0.07
31	47.19	2.13	0.05	47.25	0.83	0.02	47.08	0.47	0.01	47.61	3.67	0.08
32	55.19	2.13	0.04	55.26	0.87	0.02	55.09	0.51	0.01	55.71	4.17	0.07
33	37.49	2.80	0.07	37.22	0.58	0.02	37.09	0.31	0.01	37.59	2.17	0.06
34	39.53	3.14	0.08	39.24	0.65	0.02	39.11	0.37	0.01	39.55	2.00	0.05

	Risk factor 6			Risk factors 7–9			Risk factors 8–10			
Path number	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Most effective risk factors (in descending order)
1	61.19	0.68	0.01	61.41	2.24	0.04	61.49	1.03	0.02	5, 1–2, 7–9
2	61.19	0.68	0.01	61.40	2.20	0.04	61.49	1.03	0.02	5, 1–2, 7–9
3	49.19	0.68	0.01	49.34	2.03	0.04	49.40	0.88	0.02	5, 1–2, 7–9
4	52.09	0.26	0.00	52.33	1.50	0.03	52.52	1.06	0.02	1–2, 7–9
5	53.19	0.68	0.01	53.44	2.35	0.04	53.44	0.94	0.02	5, 1–2, 7–9
6	47.19	0.68	0.01	47.36	2.00	0.04	47.41	0.87	0.02	5, 1–2, 7–9
7	44.09	0.26	0.01	44.32	1.89	0.04	44.37	0.81	0.02	5, 1–2, 7–9
8	49.19	0.68	0.01	49.29	1.83	0.04	49.43	0.93	0.02	5, 1–2, 7–9
9	45.19	0.68	0.02	45.27	1.75	0.04	45.40	0.88	0.02	5, 1–2, 7–9
10	53.19	0.68	0.01	53.29	1.83	0.03	53.43	0.93	0.02	5, 1–2, 7–9
11	57.19	0.68	0.01	57.31	1.92	0.03	57.45	0.97	0.02	5, 1–2, 7–9

J. Constr. Eng. Manage., 2008, 134(1): 49-63

Table 6. (*Continued.*)

Path number	Risk factor 6			Risk factors 7–9			Risk factors 8–10			Most effective risk factors (in descending order)
	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	Mean path duration	Standard deviation of path duration	Standard deviation/mean ratio	
12	49.19	0.68	0.01	49.37	2.07	0.04	49.44	0.94	0.02	5, 1–2, 7–9
13	53.19	0.68	0.01	53.39	2.16	0.04	53.47	0.99	0.02	5, 1–2, 7–9
14	43.19	0.68	0.02	43.29	1.73	0.04	43.41	0.87	0.02	5, 1–2, 7–9
15	47.19	0.68	0.01	47.31	1.81	0.04	47.43	0.92	0.02	5, 1–2, 7–9
16	55.19	0.68	0.01	55.33	1.89	0.03	55.45	0.96	0.02	5, 1–2, 7–9
17	37.09	0.26	0.01	37.23	0.78	0.02	37.39	0.75	0.02	1–2, 5
18	39.09	0.26	0.01	39.31	1.12	0.03	39.43	0.82	0.02	1–2, 5, 7–9
19	49.19	0.68	0.01	49.33	1.99	0.04	49.40	0.88	0.02	5, 1–2, 7–9
20	52.09	0.26	0.00	52.32	1.47	0.03	52.52	1.06	0.02	1–2, 7–9
21	53.19	0.68	0.01	53.43	2.32	0.04	53.44	0.94	0.02	5, 1–2, 7–9
22	47.19	0.68	0.01	47.35	1.97	0.04	47.41	0.87	0.02	5, 1–2, 7–9
23	44.09	0.26	0.01	44.31	1.86	0.04	44.37	0.81	0.02	5, 1–2, 7–9
24	49.19	0.68	0.01	49.29	1.80	0.04	49.43	0.93	0.02	5, 1–2, 7–9
25	45.19	0.68	0.02	45.27	1.71	0.04	45.40	0.88	0.02	5, 1–2, 7–9
26	53.19	0.68	0.01	53.29	1.80	0.03	53.43	0.93	0.02	5, 1–2, 7–9
27	57.19	0.68	0.01	57.30	1.88	0.03	57.45	0.97	0.02	5, 1–2, 7–9
28	49.19	0.68	0.01	49.36	2.04	0.04	49.44	0.94	0.02	5, 1–2, 7–9
29	53.19	0.68	0.01	53.38	2.12	0.04	53.47	0.99	0.02	5, 1–2, 7–9
30	43.19	0.68	0.02	43.28	1.69	0.04	43.41	0.87	0.02	5, 1–2, 7–9
31	47.19	0.68	0.01	47.30	1.77	0.04	47.43	0.92	0.02	5, 1–2, 7–9
32	55.19	0.68	0.01	55.32	1.86	0.03	55.45	0.96	0.02	5, 1–2, 7–9
33	37.09	0.26	0.01	37.22	0.74	0.02	37.39	0.75	0.02	1–2, 5
34	39.09	0.26	0.01	39.30	1.09	0.03	39.43	0.82	0.02	1–2, 5, 7–9

durations should be determined realistically by taking the project conditions, resources, and constraints into consideration. Finally, all of the "risk factors," "activity–risk factor influence degrees," and "risk-factor situation probability boundaries" should be determined properly by using appropriate risk identification techniques. Obviously, unrealistic or missing input data would produce unrealistic and wrong results.

- Default model parameters: Activity–risk factor influence degrees are entered, whether as very effective, effective, and ineffective qualitative terms. However, one may argue about very very or very very very effective terms. There is no limit for this, but the amount of input data would increase as the number of such terms is increased. A model, to claim practicality, should require simplified input data as much as possible.
- Ignorance of implication dates and locations of the activities: An activity that is affected extremely by a particular risk factor in certain periods of a year may not be affected by the same risk factor in different time periods. Or, an activity that is affected extremely by a particular risk factor in certain locations of a construction site may not be affected by the same risk factor in different locations of the same site. Weather sensitive activities may be a good example for the former date-dependent state. CSRAM is not capable of modeling such marginal situations.

Conclusions and Future Work

In this study, a new schedule risk analysis model called CSRAM has been introduced. CSRAM is a simulation-based model developed for the purpose of evaluating construction activity networks under uncertainty when activity durations and risk factors are correlated. The operational logic of the model and an example CSRAM application to a single-story house project are included into the paper. Furthermore, its limitations have been emphasized. The results of the CSRAM application show that CSRAM operates well and produces realistic results regarding the uncertainty extent inherent in the schedule. However, this conclusion cannot be generalized; CSRAM should be tested on several schedules for full evaluation. Further case studies are being carried out for this purpose; this paper comprises only the development of the model.

CSRAM can be computerized easily by utilizing table processor software and embedded macros and can be further designed in a user-friendly form. In this paper, MS Excel and @Risk software programs have been used for CSRAM's execution. Its full computerization can be proposed as a future work.

References

Ahuja, H. N., and Nandakumar, V. (1985). "Simulation model to forecast project completion time." *J. Constr. Eng. Manage.*, 111(4), 325–342.

Ang, A. H.-S., Chaher, A. A., and Abdelnour, J. (1975). "Analysis of activity networks under uncertainty." *J. Engrg. Mech. Div.*, 101(4), 373–387.

Carr, R. I. (1979). "Simulation of construction project duration." *J. Constr. Div.*, 105(2), 117–128.

Dept. of the Navy. (1958). "PERT, program evaluation research task." *Phase I Summary Rep.*, Special Projects Office, Bureau of Ordnance, Washington, D.C.

Diaz, C. F., and Hadipriono, F. C. (1993). "Nondeterministic networking

methods." *J. Constr. Eng. Manage.*, 119(1), 40–57.
Dikmen, I., Birgönül, M. T., and Arikan, A. E. (2004). "A critical review of risk management support tools." *Proc., ARCOM 2004, Association of Researchers in Construction Management*, Heriot Watt Univ., U.K., Vol. 2, 1145–1154.
Ditlevsen, O. (1979). "Narrow reliability bounds for structural systems." *J. Struct. Mech.*, 7(4), 453–472.
Edwards, L. (1995). *Practical risk management in the construction industry*, Thomas Telford, London.
Flanagan, R., and Norman, G. (1993). *Risk management and construction*, Backwell Scientific, Cambridge, U.K.
Griffis, F. H., and Farr, J. V. (2000). *Construction planning for engineers*, McGraw-Hill, Singapore.
Halphin, D. W., and Woodhead, R. W. (1998). *Construction management*, Wiley, New York.
Jaafari, A. (1984). "Criticism of CPM for project planning analysis." *J. Constr. Eng. Manage.*, 110(2), 222–223.
Levitt, R. E., and Kunz, J. C. (1985). "Using knowledge of construction and project management for automated schedule updating." *Proj. Manage. J.*, 16(5), 57–76.
Oberlender, G. D. (2000). *Project management for engineering and construction*, 2nd Ed., McGraw-Hill, Boston.
Ökmen, Ö., and Öztaş, A. (2006). "Application of stochastic CPM, PERT and judgmental risk analysis process (JRAP) adapted CPM: A comparative study." *4th Int. Engineering and Construction Conf.*, ASCE, Reston, Va.
Öztaş, A., and Ökmen, Ö. (2004). "Risk analysis in fixed-price design-build construction projects." *Build. Environ.*, 39, 229–37.
Öztaş, A., and Ökmen, Ö. (2005). "Judgmental risk analysis process development in construction projects." *Build. Environ.*, 40(9), 1244–1254.
Ranasinghe, M., and Russell, A. D. (1992). "Treatment of correlation for risk analysis of engineering projects." *Civ. Eng. Syst.*, 9, 17–39.
Touran, A., and Wiser, E. P. (1992). "Monte Carlo technique with correlated random variables." *J. Constr. Eng. Manage.*, 118(2), 258–272.
Wang, W.-C., and Demsetz, L. A. (2000a). "Application example for evaluating networks considering correlation." *J. Constr. Eng. Manage.*, 126(6), 467–474.
Wang, W.-C., and Demsetz, L. A. (2000b). "Model for evaluating networks under correlated uncertainty—NETCOR." *J. Constr. Eng. Manage.*, 126(6), 458–466.
Woolery, J. C., and Crandall, K. C. (1983). "Stochastic network model for planning scheduling." *J. Constr. Eng. Manage.*, 109(3), 342–354.

J. Constr. Eng. Manage., 2008, 134(1): 49-63