RISK ASSESSMENT IN CONSTRUCTION SCHEDULES

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ABSTRACT: Construction projects are initiated in complex and dynamic environments resulting in circumstances of high uncertainty and risk, which are compounded by demanding time constraints. This paper describes a systematic way to consider and quantify uncertainty in construction schedules. The system incorporates knowledge and experience acquired from many experts, project-specific information, decision analysis techniques, and a mathematical model to estimate the amount of risk in a construction schedule at the initiation of a project. The model provides the means for sensitivity analyses for different outcomes wherein the effect of critical and significant risk factors can be evaluated. The paper focuses on lessons learned from past projects and describes a risk assessment process involving typical inputs and expected outputs. The paper also briefly reviews the information technology of HyperCard and Excel, which were used to develop the system.

INTRODUCTION

A 1992 worldwide survey reported that the majority of construction projects fail to achieve the objectives of the schedule (Cooper 1994). On many of these projects a schedule overrun did not seem probable at the beginning of the project. Sometimes schedule targets are missed because of unforeseen events that even experienced construction managers could not have anticipated. However, schedule target dates are more often missed because of events, such as design problems and industrial disputes, that were predictable but their likelihood and effects are difficult to predict with any precision because no two construction projects are the same (Thompson and Perry 1992).

A survey by Laufer and Stukhart (1992) of 40 U.S. construction managers and owners indicated that for scope and design objectives only 35% of the projects considered had low uncertainty and the remaining 65% had medium to very high uncertainty at the beginning of construction. The costs of the projects averaged $5,000,000. This finding was confirmed in a more recent report by Laufer and Howell (1993). They concluded that approximately 80% of projects at the beginning of construction possessed a high level of uncertainty.

The amount of uncertainty in the internal and external environments of a project is an important factor in determining whether there will be a schedule overrun. However, attempting to consider realistically the uncertainty in construction schedules poses three challenges. The first challenge is that systems are not endorsed professionally or available commercially, which can be used to structure project uncertainty and measure the effects on the project schedule. The second challenge is the lack of easily accessible information documenting the experience of the construction industry or the knowledge scattered within a corporation. The third challenge is the difficulty motivating the involvement of the senior project management team to address adequately schedule risks. Project teams generally are too preoccupied with solving current problems involved with getting work done and therefore have insufficient time to think about, much less carry out, a formal risk assessment program (Oglesby et al. 1989).

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The purpose of this paper is to discuss the development of a computer-based system for the assessment of construction schedule risk, which can increase the effectiveness of the traditional project scheduling processes. The system includes the following three key features:

1. A hypertext information system for schedule risk identification
2. A spreadsheet to describe and evaluate project uncertainty
3. Direct pictorial information to assist the decision makers in selecting a realistic yet acceptable project completion time.

Part of the development of the system utilized a Macintosh PC and commercially available application programs called HyperCard and Excel. In the system, the HyperCard application program provides an information module that can be used in identifying schedule risks. The Excel spreadsheet is the tool used for modeling the effects of the risks on the project performance time.

Part of the paper presents the findings of a literature review of articles dealing with problems in traditional scheduling processes. The problems are grouped into five primary classifications.

Four dimensions of construction schedule uncertainty then are presented; within each dimension, specific factors are identified that have lead historically to schedule risk. A computer-based system to model the effects of risks on the project schedule then is presented.

Then, explanations are given on how the risks are quantified and analyzed. The application and details of the computer system are described so that an example for modeling schedule risk can be shown. Before drawing some conclusions, the benefits of using the model are listed and the importance of the responsibility for schedule risk assessment and the timing of the assessment are emphasized.

PROBLEM STATEMENT

The complex characteristics of major construction projects have created the need for improved management support, techniques, and tools. Many companies have recognized this need and are drawing from their past experiences when developing project organizations, selecting management tools, deciding on contracting strategy, and developing project schedules. However, schedule overruns still frequently occur. Past experiences are not being analyzed, synthesized, and corrected sufficiently in order to prevent mistakes on past projects from being repeated.

There is a lack of an accepted method of risk assessment and management among professionals in the construction in-

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dustry compared with the financial and health professions. The construction industry also does not seem to recognize, nor accept, that risk should be addressed formally and given more serious attention. If a method of risk assessment and management were installed in the construction industry it should be extended into areas such as engineering design and analysis and life-cycle costs.

CLASSIFICATION AND SOURCES OF PROBLEMS IN TRADITIONAL SCHEDULING PROCESSES

The construction industry has been using quantitative network modeling techniques to simulate the construction process since the late 1950s. Network diagram techniques have helped in clarifying activity relationships and have assisted in the establishment of durations and coordination of construction projects. However, much has been written on the problems concerned with traditional scheduling processes (Birrell 1980). For example, one of the problems with traditional scheduling processes is that the critical-path method (CPM) approach is deterministic in nature; the process thereby ignores the effects of uncertainty by using a single value for the time estimate of each activity and even the entire construction of the project.

Five classifications summarizing problems that have been documented with traditional scheduling processes are shown in Table 1. The problems within each classification were categorized into the following three sources of constraints, which can limit effective use of traditional scheduling processes:

1. Technical problems involved with network concepts
2. Process problems in the application of network methodology
3. Problems involved with making the process work in construction.

One of the more serious problems with traditional scheduling processes is that they do not evaluate explicitly the uncertain and risky nature of the internal and external environment of a project. Thereby, in contradiction with reality, traditional project scheduling processes have treated uncertainty and risk as if they do not exist (Archibald and Lichtenberg 1994). Consequently, for projects with any amount of uncertainty, network-based planning processes have been proven inadequate for estimating a realistic project performance time (Laufer and Howell 1993).

TABLE 1. Traditional Project Scheduling Processes—Classification of Problems

Classification of problems (1)	Sources of Problems: Network theory (2)	Application of network methodology (3)	Realities of construction processes (4)
(a) Nature of Engineering and Construction Work			
Complex organization		x	
Activity dependencies	x		
Other techniques more appropriate		x	
Critical activities cost separation		x	
(b) Resource Allocation Process			
Networks inadequacy considering resources		x	
Equal importance to each activity in resource allocation		x	
Effect on resource program for each activity with single value time estimate	x		
Resource allocation algorithms use of priority rules	x		
Limited resource types in resource allocation program	x		
Resource allocation processes problem with project scope details			x
(c) Complexities of Project Operations and Scheduling Methods			
Schedules too complex for field			x
Choice of logic in network models	x		
Specialized scheduling operation team required			x
Interpretation of excessive computer output		x	
(d) Contractors Lack of Confidence in Network Scheduling Processes			
Credibility that construction process can be modeled			x
Many secondary business activities occur but not shown on schedule		x	
(e) Activity Time Estimating			
Lack of reliable and realistic time estimates for activities			x
Nature of activity duration requires experience			x
Time estimates only marginally address schedule risk		x	

SCHEDULE UNCERTAINTY

Uncertainty can affect the seemingly precise predictions of traditional scheduling processes. To provide a framework for a systematic and structured assessment of schedule uncertainty, four dimensions of schedule uncertainty were established. The following first three dimensions relate to the uncertainty in the project life-cycle phases: engineering design, procurement, and site construction. The uncertainty in each phase is driven by its own unique set of variables and is differentiated from the other phases by work content. The fourth dimension involves uncertainty in the effectiveness of the project management function in completing the project as scheduled (Diekmann et al. 1988) (Fig. 1).

In the engineering design phase, uncertainty problems are encountered that include designers with varying degrees of experience, the fragmentation of the engineering and construction processes, the trend to lump-sum bidding, economic and liability issues, constructability, and changes in design.

Sequential steps are involved in the procurement phase, and although simple in nature, the procurement process is more complex than it appears. There are a myriad of activities at various locations in which many widely dispersed personnel are required in the execution of the procurement process. High-risk factors in the procurement phase include vendor/contractor selection processes and delivery on time.

One of the critical factors for success during the construction phase is the need to develop an effective contracting strategy that fairly assigns risk and thereby encourages owner and contractor teamwork. One reason for failures in construction projects has been caused by the selection of a contracting format that did not fit the risk characteristics of the project. For example, the use of a lump-sum contract on a fast-track project can lead to many contract disputes and the diversion of management's attention from the critical fieldwork issues.

Poor management practices also create problems. The effectiveness of the project management function significantly

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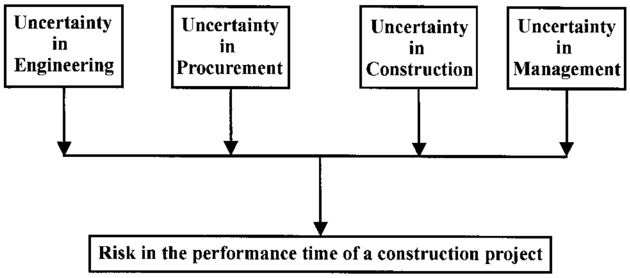

FIG. 1. Dimensions of Uncertainty in Schedule of Construction Project

TABLE 2. Characteristics of Successful and Unsuccessful Projects

Successful projects (1)	Unsuccessful projects (2)
Well-defined scope	Ill-defined scope
Early, extensive planning	Poor planning
Good leadership and supervision	Poor management and controls
Involved, positive owner relationships	Poor communication between disciplines
Good communications and relationships	Unrealistic schedules and budgets
Quick response to changes	Poor personnel quality
Engineering concerned with total project	Excessive changes

influences whether the planning project schedule duration will be achieved successfully. Table 2 shows some of the principal factors that influence the effectiveness of the project management function (The Business Roundtable ''Project'' 1986).

A list of other sources of risk that create schedule uncertainty can be found in Appendix I. For scheduling to be effective in an uncertain environment, knowledge gained from formal education, training, and substantial planning experience is required. However, the valuable knowledge and experience that is acquired during the construction of a facility often are not available for the construction of the next similar facility. A number of factors have contributed to the shortage in recording past project experiences. The following are four of the principal reasons:

1. The project team assumes each project is unique; therefore old records are often considered of little value, and the records are not maintained or are discarded (Sanvido and Medeiros 1990).
2. At the end of the project there is a lack of interest or funding to conduct postproject reviews.
3. A formal or convenient process does not exist to capture and transfer readily knowledge to subsequent projects (Ibbs 1986; Mohan 1990).
4. At the end of a project often there is not a similar project in progress to which the professional and trades personnel can be transferred.

SCHEDULE RISK ASSESSMENT APPROACH

The schedule risk system, presented in this paper, is based on experience gained with large power plant projects; however, the principles apply to any construction project. The development of the system also draws from recent research and advances in risk analysis. The following were the primary reference materials: (1) The successive principle (Lichtenberg 1988); (2) the concepts of conventional CPM/program evaluation and review technique (PERT) and management science techniques; (3) the research on risk management in capital projects at the University of Colorado at Boulder; (4) the report entitled ''Engineering Construction Risks,'' by Thompson and Perry (1992); and (5) the report, ''Confronting Uncertainty in Risk Management,'' by A. D. Finkel (1990) of the Center for Risk Management, Washington, D.C.

Classic risk analysis is undertaken in the following three iterative phases: (1) Risk identification; (2) risk measurement; and (3) risk management (Diekmann et al. 1988). The subject of this paper, risk assessment, is involved with the first two phases of risk analysis. Risk identification involves determining which variable are likely to affect the schedule. Risk measurement involves evaluating and quantifying the probability of the occurrence of a risk and the effects on the schedule (Fig. 2).

To demonstrate the ideas presented in this paper, an assessment of schedule risk is performed on a simulated megaproject in the following sections. The situation is one of a large-scale owner organization, having the predominate role in the engineering effort and in setting the master schedule for the entire project, while also acting in the role of construction manager. The design of the $1 billion facility will draw on resources from three prime engineering firms producing designs that result in 115 major supply contracts and 85 prime on-site construction contracts. Over the course of 5 years, approximately 11,000,000 h of engineering, manufacturing, on-site work, and management will be required to complete the project. During this period, an average of over 1,000 people will be working each month in widely dispersed geographic locations.

Suppose you were responsible for establishing the duration of this construction project; you have divided the project into four phases with the description and duration associated with each phase as follows: engineering design, procurement, construction, and commissioning estimated at 37, 35, 39, and 14 months, respectively. The schedule is to be of a fast-track nature with optimum overlapping of engineering design, procurement, construction, and commissioning activities, which means the preparation of the detailed civil engineering design will be started even before the design descriptions have been completed or equipment ordered and vendor shop drawings have been received.

Further, suppose that planning and design are early in the conceptual phase. Accordingly, the scope is not stabilized, all parties have not found consensus, implementation methods have not been decided yet, and parts of the project may even need further research and development. As a result, one of the biggest problems will be in establishing the interphase overlap and subsequent overall project duration.

The problem stems from the fact that quantities of work are somewhat influenced by variables only known with any degree of certainty as the job progresses. Indeed, one survey revealed that 70% of the respondents had experienced schedule changes related to ''differing site conditions'' that were either not

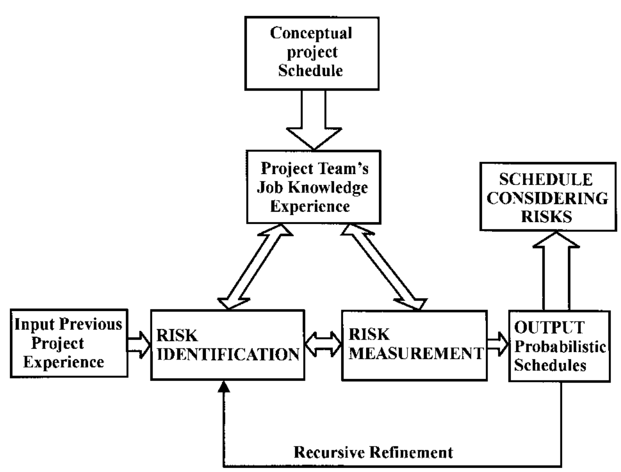

FIG. 2. Assessment of Schedule Risk System

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known or not anticipated at the start of the project (Halligan et al. 1987). For the project under consideration, the level of sophistication used to develop each deterministic activity time estimate ranged from the project management team's experience to historical data. Therefore, because the actual execution of the project will occur over a span of many years, the reliability of activity time estimates is questionable.

Ultimately, more engineering design will resolve some of the uncertainties surrounding the design effort and construction quantities, but at this point in time, an estimate of the overall project duration must be produced based on this uncertain data. To model the effects of uncertainty on the project schedule, the execution of the following three recursive steps is required: (1) Identify schedule risks; (2) evaluate their effects and the probability of occurrence; and (3) within the proposed project schedule framework, model the risks and their effects to obtain the project's schedule risk profile. For the project under consideration, the results from the analysis indicated that the expected project duration of 59.6 months is 3% greater than the originally predicted deterministic duration of 58 months.

IDENTIFICATION OF SCHEDULE RISKS

During the planning of a project, it is not possible to measure directly the time required for the various phases or observe directly how these phases interrelate. Thus, at the conceptual stage of a project a base case schedule model is developed to predict the performance time of the project. However, uncertainty surrounds all facets of most projects and can confound any attempts to predict precisely the performance time of a project with confidence. Therefore, at this stage, a good schedule analysis would demand explicit identification of the risks to the project schedule.

The HyperCard system (discussed later) can provide the basis for risk identification by presenting most known schedule risks. The database provided by the HyperCard system should act as a stimulus for follow-up brainstorming sessions with the key members of the project team. The output from the review of the HyperCard database and the brainstorming process should produce a comprehensive list of potential schedule risks, which then can be rewritten and reordered into the relevant risks for each dimension of schedule uncertainty. Refer to a sample of a database of engineering design risks in Table 3.

QUANTIFYING SCHEDULE RISK

The guidelines for quantifying uncertainty, developed at the Center for Risk Management (Washington, D.C.), were used for modeling the effects of schedule risks on the performance time of a project. For the purposes of the modeling process, the variance of the performance time distribution of a project was used to measure schedule risk. Variance implies uncertainty; it can be used as an objective measure of the ability to predict a reliable performance time for a project. The larger the variance the greater the risk associated with the performance time of the project. Indeed, variance often has been used by the financial community to measure the riskiness of investment options (Keller et al. 1994).

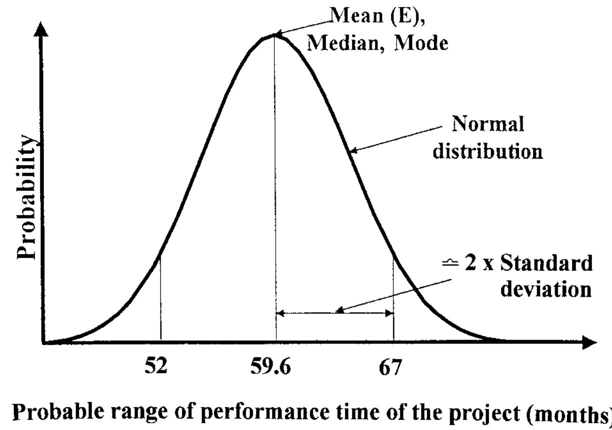

FIG. 3. Probability Density Function: Performance Time of Project

The PERT technique was used to develop a project performance time distribution and as a basis to compute the probability that a project will be completed on or before a scheduled time, without the need to take other than normal measures to expedite the activities of the project. The information from the PERT calculation is summarized in Fig. 3. The probability density function shown in Fig. 3 has the following two structural characteristics: (1) A normal distribution (bell-shaped curve); and (2) symmetry about the mean, i.e., the expected project performance time E. The variance V_T of the distribution answers the question as to how typical is the expected project performance time E of all values in the data set.

ANALYSIS OF SCHEDULE RISK

The information from the PERT calculation can be used to determine the lower (5%) and upper (95%) confidence limits of the performance time distribution of a project and thereby provide the variables for a schedule probability statement. The probability statement is defined as follows: the largest proba-

TABLE 3. Sample of Database of Engineering/Design Risks

Risk number (1)	Risk source (2)	Importance (3)	Confidence level (4)	Independent (I) or dependent (D) risks (5)	Description (6)
30	Productivity	High	Medium	I	Actual engineering hours greater than planned
31	Engineering centers	Medium	Medium	D	Geographic location of engineering staff
32	Engineering resource pool	Medium	High	D	Depth and qualifications of engineering replacement resources
33	Engineering estimate	High	High	D	Accuracy of engineering estimate
34	Material substitution	High	Medium	D	Redesign due to material substitution
35	Qualified staff	Medium	Medium	D	Capability to perform work in allowable time frame
60	Design errors	High	Low	I	
90	Design criteria	High	Medium	I	Availability of well-documented design standards
91	Code changes	Medium	High	D	Changes to codes that affect project design criteria
92	Site investigation	High	Low	D	Problems or engineering changes due to insufficient site investigation
93	Design standards	Medium	Medium	D	Availability of well-documented design standards
94	Technology	High	Medium	D	Degree of uncertainty in technology

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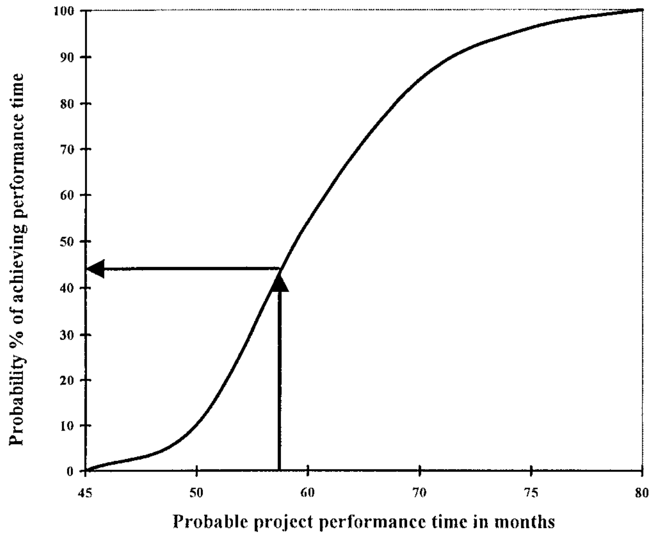

FIG. 4. CDF: Performance Time of Project

bility exists that the project will be finished during month 59 (Fig. 3), the expected performance time E; however, if things go badly, with a probability of 1 in 20, the project may not finish until month 67, the upper confidence level. Similarly, if things go well, again with a proability of 1 in 20, the project could finish as early as month 52, the lower confidence limit (Cowie and Carr 1984).

An alternative to a probability statement and a more descriptive tool for conveying the uncertainty in project performance time is the cumulative density function (CDF). The CDF displays the same information contained in the probability statement. However, the CDF enables the direct calculation of a range of confidence and the direct comparison of uncertainty in alternative project scenarios. Refer to Fig. 4, which shows the CDF resulting from the assessment of schedule risk, for the project under consideration, which has a planned duration of 58 months.

The more variance a critical-path activity contains, compared with other critical-path activities, the more important it is in determining the amount of direct risk to the performance time of a project. Therefore, the variance of each critical-path activity V_t can be used to determine the amount that an activity contributes to the total project performance time risk V_T. Thus, to reduce the project performance time risk V_T, it would be necessary to reduce the variance V_t of the critical-path activities.

The standard deviation $V_t^{1/2}$ and expected performance time t_e of the critical-path activities can be used to measure the relative risk between activities. The activity with the highest relative risk is subject to a larger proportional change in duration and therefore is considered at higher risk than other critical-path activities. The proportionate measure of variability of an activity is determined by calculating its coefficient of variation, which is equal to its standard deviation divided by its expected performance time.

APPLICATION OF COMPUTERS

The computer-based system for the assessment of schedule risk consists of a HyperCard risk factor identification module, which contains information acquired from many experts and previous construction projects and then uses statistical techniques embedded in an Excel spreadsheet. The output of the system includes the schedule confidence limits and the risk profiles of the critical-path activities.

The HyperCard knowledge base consists of four risk dimensions, namely, engineering design, procurement, construction, and project management and risk factors for each dimension. The Excel spreadsheet used for modeling schedule risk requires as inputs the optimistic, likely, and pessimistic activity times; the relative importance of risks; and calculates the expected performance time and the variance in the performance time distribution, as well as other information and statistical data.

HYPERCARD INFORMATION SYSTEM FOR RISK IDENTIFICATION

A Hypertext system is used to store and give access to information concerning previously experienced schedule risks. The system is composed of schedule risk information (facts, data, and heuristics) linked together using hypertext tools. The information can be in the form of text, graphics, or pictures. Thereby, typical project risks can be documented and made available to assist new project teams in becoming aware of general risk information and the possible inferences for a specific project.

The HyperCard shell program was used to develop the risk identification module. It is an object-oriented program and is based on the concept of a series of cards making up stacks, with information and linking devices located on each card. The HyperCard program can be used to create page formats containing objects with information and buttons, which can be used for linking and browsing through information in the database. Once developed, the system protocol requires little additional programming to add information to the database. Another feature offered by HyperCard is that the system enables the user to backtrack. This is achieved by a screen display of minimaps giving a survey of documents visited. The structure of the HyperCard knowledge base is shown in Fig. 5.

The system's links provide the means to access the documents within the database. The links, which guide the user through the database, can be divided into two types: organizational and navigational. Organizational links connect the structure of the system. These links appear as buttons along the bottom of every screen. Clicking the buttons executes the links and thus allows the user to move between the various documents in the database.

In the database the basic elements of information are contained in objects. Once an object has been defined, it is possible to define navigational links that lead to other documents in the database. These navigational links were used to provide features such as importance factor criteria and confidence level definitions.

MODELING UNCERTAINTY

Following an interactive session with the HyperCard information system, the effects of the risks identified in the four dimensions of schedule uncertainty can be evaluated. For each dimension of schedule uncertainty (engineering design, procurement, construction, and project management) it is likely that some combination of risks will be encountered. To illustrate the computational basis and the implementation of the approach, a small sample of the EXCEL database used for modeling uncertainty in the engineering design phase is shown in Table 3, and a portion of the EXCEL spreadsheet for modeling the total project schedule risk is shown in Tables 4 and 5. The information contained in the table can be displayed pictorially on the computer screen using the graphical functions of the EXCEL program.

The EXCEL spreadsheet model also provides the means for sensitivity analyses for different outcomes. Sensitivity analyses can be performed by varying one uncertain element at a time and examining the effect of the change in that element on the total project performance time. Sometimes changes in an element will not significantly affect the project schedule. On the

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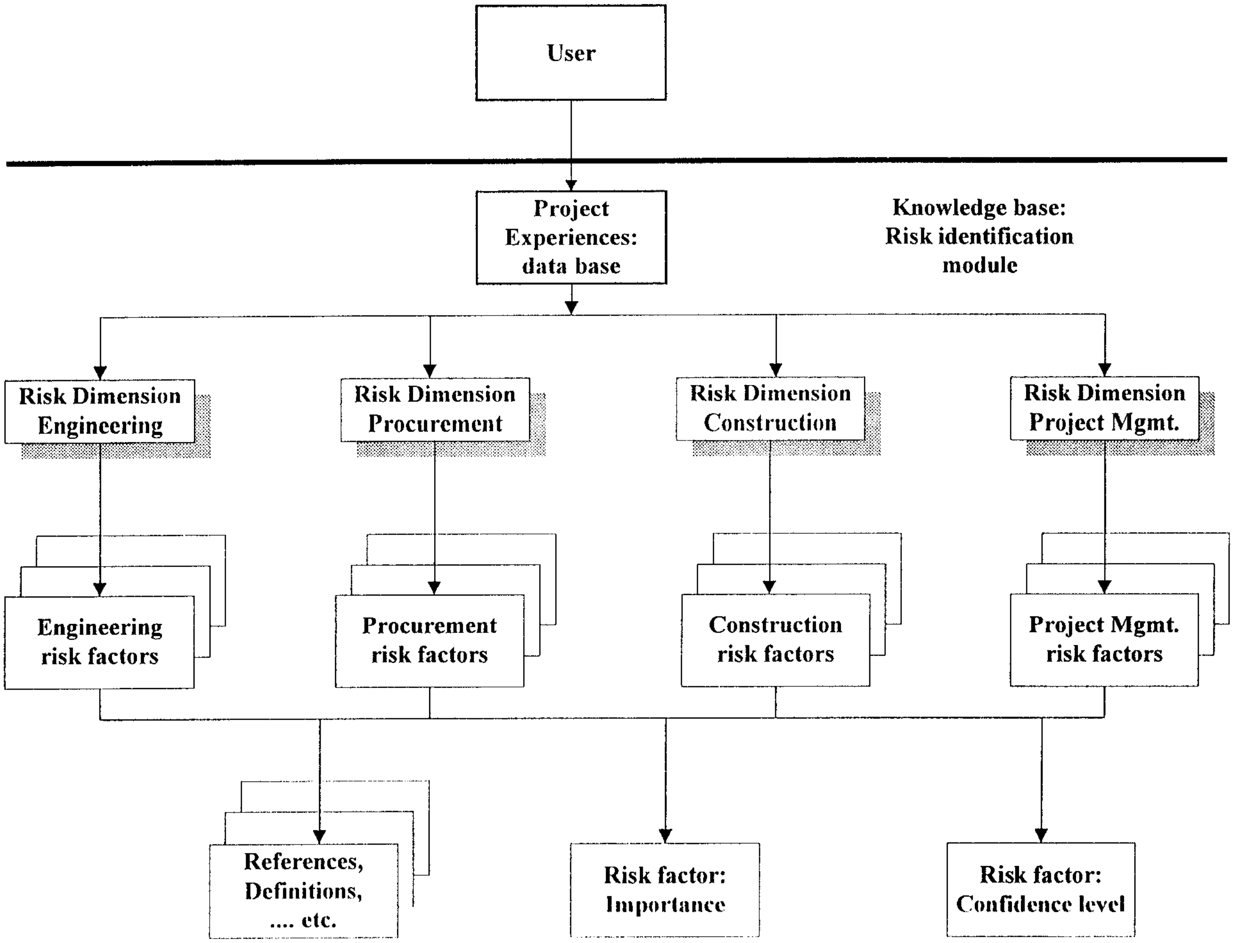

FIG. 5. Structure of HyperCard Knowledge Base

TABLE 4. Sample of EXCEL Spreadsheet Used for Modeling Schedule Risk Design Phase

Engineering risks (1)	Importance (2)	Confidence (3)	Activity Time Estimate (months) Optimistic (4)	Likely (5)	Pessimistic (6)	Expected (7)	Variance (8)	Relative importance (%) (9)
Productivity	High	Medium	33	37	45	37.7	14	20
Design errors	High	Low	36	37	40	37.3	1.6	5
Design criteria	High	Medium	35	37	41	37.3	3.5	12

Note: Expected performance time of the engineering design phase is 37.8 months.

TABLE 5. Sample of EXCEL Spreadsheet Used for Modeling Schedule Risk: Project Performance

(1)	Selected Project Duration (months) 40 (2)	45 (3)	50 (4)	55 (5)	60 (6)	65 (7)	70 (8)	75 (9)	80 (10)
Probability project duration (%)	0	0	1	12	54	91	96	99	100

Note: Expected project performance time is 59.6 months.

other hand, sometimes even small changes will have a disproportionately large effect.

BENEFITS OF USING MODEL

The scheduling of industrial construction projects can benefit greatly through the extension of traditional project scheduling processes to include an assessment of schedule risk process. The following are the significant benefits:

1. Use of the HyperCard information system provides a focus and common understanding and perception of the project risks and their potential consequences.
2. Modeling uncertainty in a project forces a reexamination of the assumptions and identifies which factors drive schedule performances.
3. The risk identification process using the HyperCard database can reduce pessimism and lead to the recognition of hidden assumptions.
4. The system attempts to achieve a balance between the precise choice of a project performance time and the imprecision in the available information.

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5. Risk assessment provides support for early planning decisions and can lead to choices giving more valuable prospects for the owner and project manager.
6. The process allows the owner and the project manager to act quickly and decisively when a risk event occurs.
7. The system provides a specific instrument and communication structure (i.e., the HyperCard database) for the transfer of learning experiences between projects.

RESPONSIBILITY AND TIMING OF ASSESSMENT OF SCHEDULE RISK

All risks have a price and risk taker; there are many risk takers involved with a major construction project: the owner, the financial agency, the project manager, the designer, the constructor, the manufacturers and suppliers, labor, the insurance agency, the legal advisor, and the public and regulatory agencies. However, by the time a project moves into the implementation phase, the risk takers are forced to manage within the strategies and tactics of the owner already in place. Therefore, it is only from the broad context of the owner's total project perspective that all of the risks associated with a project can be identified adequately and solutions proposed.

It is not acceptable to wait for risk to emerge before taking risk management action. A more proactive approach is required; it is in the owner's best interest to undertake a consideration of potential risks early in the project life cycle (Diekmann et al. 1988). Unless a project is founded on a realistic basis the long-term opportunity for the project to be profitable will be reduced greatly. Difficulties also will be revealed in the following three areas of project control: (1) Project coordination; (2) budget and time management; and (3) general administration and supervision.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Since 1960, the construction industry has used quantitative network–based modeling processes to schedule construction projects; the industry has acknowledged that the use of network scheduling processes has paid handsome results. Notwithstanding the successes traditional scheduling processes have enjoyed, on occasion they are deficient in meeting the demands of construction practice.

Traditional planning and scheduling methods such as CPM are limited by the assumption that each activity has only one possible outcome and will be completed successfully. In reality, there are multiple possible outcomes for an activity with different consequences; and this is something that a schedule risk analysis can model. Therefore, to produce an effective schedule, a more thorough scheduling process is required with a formal recognition and assessment of project uncertainty, principally, during the conceptual stage of the project.

The computer-based system discussed in this paper is involved with construction of a time-based model for the assessment of schedule risk. The system provides a structured approach to identify the sources of risk in a project and based on these risks determine the range of schedule outcomes. The system can assist in improving the effectiveness of the traditional project scheduling processes by (1) ensuring project participants formally evaluate uncertainty in the internal and external project environment, (2) opening channels of communications, (3) overcoming the deterministic limitations of traditional scheduling processes, and (4) providing an approach to document institutional knowledge and foster organizational learning. Thus, the use of the system should ensure that all projects are planned in a more realistic manner.

Microcomputer-based scheduling systems are evolving continuously. Extensions to network modeling concepts, such as the prototype system discussed in this paper, should enhance the effectiveness of scheduling processes. The following four recommendations are proposed, which could move the development process forward:

1. The assessment of schedule risk should be considered one of the owners responsibilities for the overall project.
2. The identification and measurement of risk should be included as an essential element of the conceptual planning process.
3. Some form of an electronic knowledge-based system should be developed and used within the construction industry to document and transfer project experience and institutional knowledge to new projects.
4. A formalized contingency approach should be used when establishing the performance time estimate for a project. A project's schedule contingency should provide a reasonable degree of confidence that the planned project performance time can be accomplished successfully.

Interest in risk assessment is growing. With an increasingly complex and rapidly changing business environment, owners and their contractors are being challenged to manage risk while maintaining control and improving performance. However, some owners are not familiar with the concepts of risk assessment. Therefore, the onus must fall on the construction industry to market the concepts of risk assessment so that all owners recognize that the analysis of schedule risk in not just a cost but rather an investment, in terms of actual money saved, when resources are used more efficiently and the consequence of a delay to the project can be avoided.

APPENDIX I. SOURCES OF RISKS AFFECTING SCHEDULE

1. Engineering design
   - Regulatory, code, and safety
   - Requirements
   - Drawing control process
   - Environment impact assessment
   - Location and number of engineering centers
   - Engineering resource qualifications and pool depth
   - Engineering estimate
   - Project scope definition
   - Early engineering deliverables
   - Technology
   - Design criteria
   - Engineering and procurement interfacing
   - Engineering productivity
   - Engineering resources requirements
   - Material substitution procedure
   - Site investigation
2. Procurement
   - Vendor bid greater than estimate
   - Long lead items equipment and bulk material
   - Identification of equipment and material
   - Management techniques and systems
   - Specification changes affecting manufacturing
   - Vendor quality control
   - Vendor drawing control
   - Warranties
   - Procurement document control process
   - Manufacturing process
   - Material management organization
   - Tender evaluation and purchase order cycle
   - Vendor performance
   - Transportation concerns
   - Vendor labor problems

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3. Site construction
    - Temporary facilities
    - Approved for construction drawings
    - Codes and standards
    - Standards of contract documents
    - Contractor selection process
    - Existing facilities
    - Government permits
    - Labor relations
    - Labor resource planning
    - Quality control
    - Safety
    - Site management process
    - Trades productivity
    - Construction turnover coordination
    - Design errors
    - Scope-related quantity increases
    - Percent complete of engineering at start site work
    - Design changes during construction
    - Constructability reviews
    - Contract strategy
    - Differing site conditions
    - Force mais, oui
    - Availability of equipment and material
    - Loss control program
    - Regulatory delays
    - Location
    - Site management staffing
    - Weather effects
    - Construction mistakes
    - Site stores management
    - Defective materials
    - Site access
4. Project management
    - Third-party overview
    - Start-up plan
    - Major equipment plan
    - Management experience
    - Project management budget
    - Project organizational model and implementation
    - Project control process
    - Project procedures
    - Definition of authority and responsibility
    - Scope definition and estimate
    - Financial/funding
    - External actions
    - Management resource pool
    - Owner quality assurance
    - Project complexity
    - Project duration
    - Project schedule
    - Committment to the schedule
    - Records management
    - Regulatory reporting
    - Change order control
    - Owner driven

APPENDIX II. REFERENCES

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APPENDIX III. NOTATION

The following symbols are used in this paper:

E = expected project performance time;
t_e = expected performance time of activity;
V_T = variance of project's performance time distribution;
V_t = variance of activity's performance time distribution; and
$V_t^{1/2}$ = standard deviation of performance time distribution of activity.

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