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Abstract: Effective risk management is a central function in the successful planning and execution of large infrastructure projects. This paper explores how current knowledge-based approaches for risk management can be improved upon so that they are more responsive to the attributes of a project and the needs of system users. A review of existing knowledge-based systems for risk management provides a backdrop for a discussion on desirable characteristics of such an approach. The proposed methodology adopts a model-based technique in that explicit abstractions of project components and processes, and the physical, regulatory, political, social, financial, economic, contractual, and organizational environments in which they are located, are created to assist in the reasoning about possible risks. This contrasts with several current systems that use only implicit representations. The reasoning schema and models of the physical project and environment that are used for the reasoning process are described in the paper.

Key words: risk identification, project modeling, knowledge management, infrastructure projects.

Résumé : La gestion efficace des risques est une fonction clé pour réussir la planification et l'exécution de grands projets d'infrastructure. Cet article examine la manière dont les approches de gestion des risques basées sur les connaissances peuvent être améliorées afin qu'elles soient mieux adaptées aux attributs d'un projet et aux besoins des utilisateurs du système. Une revue des systèmes à base de connaissances pour la gestion des risques fournit la toile de fond d'une discussion sur les caractéristiques désirables d'une telle approche. La méthodologie proposée adopte une technique basée sur un modèle où les abstractions explicites de volets et de procédés du projet, ainsi que les environnements physiques, réglementaires, politiques, sociaux, financiers, économiques, contractuels et organisationnels dans lesquels ils sont situés, sont créées pour aider à déterminer les risques possibles. Cela contraste avec plusieurs systèmes actuels qui n'utilisent que des représentations implicites. Cet article décrit le schéma de raisonnement ainsi que les modèles du projet et de l'environnement physiques utilisés dans le processus de raisonnement.

Mots clés : identification des risques, modélisation de projets, gestion des connaissances, projets d'infrastructure.

[Traduit par la Rédaction]

Introduction

Economic risks are an unwelcome yet intrinsic part of all large infrastructure projects. The term economic risk is used in this paper to refer to any uncertain events that have the potential to impact cost or revenue items, either directly or indirectly, and that in turn affect economic measures such as rates of return and project cash flows and the ability to finance the project. The success or failure of a project, or even an organization, may very well depend on the approach that is adopted towards managing these risks. A systematic approach towards risk management can help in identifying and assessing the economic risks that are relevant to the project, in focusing on the major risks for the project, and in making informed decisions in controlling and mitigating these risks. A systematic risk management process (CIRIA 1996; Chapman and Ward 1997) is essentially made up of three main stages, namely risk identification, risk quantification, and risk response and control.

We regard risk identification as the most critical step of the risk management process. Unidentified risks can wreak havoc with the success of a project, as one is forced into a reactive mode as opposed to a proactive mode should the risks occur. The risks that need to be detected can be wide ranging and can be grouped under several categories such as financial, economic, environmental, technical, political, stakeholder, and organizational–contractual risks, and their consequences described in time, scope cost, quality, and safety metrics. Identification of most if not all of these risks for the project at hand can be a significant challenge and de-

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pends heavily on experience and knowledge gained from past projects. Presently, the methods available for identifying risks include brainstorming, the use of checklists and prompt lists, the use of surveys, questionnaires, and structured interviews, literature reviews, and knowledge-based systems (Akintoye et al. 2001).

Monte Carlo simulation, moment-based methods, numerical methods, and methods based on fuzzy logic are among the methods available for the quantification of the risks that are identified. These methodologies work at different levels of accuracy and detail and require varying types of input such as probabilistic parameters and linguistic input. Risk quantification provides a measure of the risk inherent in individual work packages or of the project as a whole and can assist in risk prioritization and in making decisions regarding risk response measures.

Responses to economic risks can be wide ranging. They include the transfer of risks among project parties through contractual agreements, the use of monetary, time, and design contingencies, the use of insurance, redesign of one or more aspects of the project, carrying out additional site investigations to minimize uncertainty, and so forth.

The foregoing brief introduction to the risk management process illustrates that project stakeholders face a challenging task in successfully identifying applicable risks, selecting suitable quantification methods, and subsequently identifying appropriate responses to the risks. Therefore, experience gained from past projects can be extremely useful in this process. The body of knowledge regarding project risk analysis and management is not coherent, however, and in its current state provides somewhat of a confusing picture (AbouRizk 2000). Our view, which is shared by others (e.g., Raftery and Ng 1993), is that knowledge-based methodologies that assist in capturing and organizing risk management knowledge gained on past projects and in reusing it in future projects hold considerable promise for developing a comprehensive yet practical approach for use by industry.

The goal of this paper is to set out an approach for a knowledge-based methodology for risk management, with the main focus being on the risk-identification component of the methodology. Although parts of the approach are still in their conceptual stages, some aspects have been implemented that have helped to demonstrate both the flexibility and practicality of the approach. In the following section, currently available knowledge-based approaches are summarized to provide a backdrop for the identification of desirable system requirements and lessons learned. Thereafter, means of representing the products, processes, and the environment of the project to assist with risk identification are discussed. These representations are done in a way that minimizes the users' burden for defining these dimensions by adopting knowledge management structures developed through experience on past projects and interaction with other experts. The paper concludes by identifying future work that needs to be carried out in developing the methodology.

State of the art

There is a vast literature on risk management (for example, see Williams (1995) for an excellent compilation and classification of the literature) and an emerging literature on the development of computer-based tools to assist in the risk management process. Of specific interest are computerized knowledge-based methodologies proposed by researchers that attempt to capture and reuse risk-related knowledge. The characteristics of several systems that are reflective of currently available knowledge-based approaches are summarized under five key themes in Table 1. An explanation of the headings in Table 1 is as follows:

(1) Implementation — This category details whether the system is a working prototype or a full working model. It also provides an assessment of the generality of the domain to which the system can be applied, i.e., whether the application of the system is restricted to certain types of projects, or whether it is broadly applicable.

(2) Input–output — This category describes the nature of the information required by the system from the user and the character of the output produced by the system.

(3) Model of product–processes–environment — This is a description of how the physical characteristics and processes of the project and the characteristics of the environment in which it is located are represented in the knowledge-based system. For example, in some systems project components are represented as arguments of production rules, whereas some other systems provide templates that explicitly set out the project components. The support provided by the systems for modeling defining attributes of the project at hand is also described.

(4) Nature of knowledge base — This category provides a description of the form and characteristics of the knowledge stored by the system (e.g., rules, cases, templates). The use of risk registers and checklists to accumulate and categorize information about risk events is also described. Furthermore, the application of approaches such as fuzzy logic to support qualitative input–output is highlighted.

(5) Risk management functions supported — The support the system provides for individual risk management functions (e.g., risk identification) is described in this category. Specific approaches taken towards risk quantification (e.g., use of Bayesian probabilities, fuzzy logic) are identified, where applicable.

Most knowledge-based risk management systems currently available are prototype systems, as illustrated by the implementation category of Table 1, and appear not to have been extended and implemented in day to day practice. Rigidity in input required (e.g., the same level of detail of information is required whether one is in the very preliminary stages of defining a project or after considerable development work has been carried out) seems to be a defining characteristic of many of these systems, which are also inflexible regarding the level of detail of the output. Some systems are an exception, providing a degree of flexibility to the user for tailoring the system and its output. For example, the human–computer cooperative system (Niwa 1989) allows specification of the type of user so that appropriate queries and output can be forwarded to the user. Technical risk identification and mitigation system (TRIMS) (Best Manufacturing Practices Center of Excellence 2001) allows the definition of new templates for different project types that the user might encounter. Amending or augmenting the

Table 1. Comparative analysis of knowledge-based systems for risk management.

Implementation	Input–output	Model of product–process–environment	Nature of knowledge base	Risk management functions supported
Project risk management (PRIMA) system (Alquier and Tignol 2001)				
Currently implemented as a prototype; intended for use during the bidding phase of industrial product development	Input: list of elements such as subproducts, either selected from a repository or input directly; values for probability of risk causes and the gravity of the risks Output: a listing of risks associated with elements of the technical solution; risk causes, their effects, and mitigation actions are also listed; risk exposure levels are also calculated	Project elements such as subproducts, processes, and cost items are incorporated into what is termed a "technical solution"; the technical solution is organized as a list, with some elements arranged hierarchically (e.g., subproduct, processes, resources); although details of external environmental entities (e.g., customers) are stored within the system, they are not used directly in reasoning about project risks	Elements of technical solutions that are developed can be stored in a database, to be used recurrently; risks such as "failure of partner" can be attached to elements of the technical solution; these risks are incorporated automatically into a new technical solution that makes use of elements stored in the recurrent element database; the risks are organized into several categories; listings of risk causes, risk impacts, and mitigation actions are linked to each risk	Risk identification and quantification of risk exposure; probabilities relating to the occurrence of risk causes and the gravity of the risk impacts are used to calculate a value for risk exposure for each risk; summation of these values gives the overall risk exposure
Project risk knowledge management environment (PRIME) system (Tah and Carr 2001)				
Research prototype	Input: likelihood and severity of risk factors in linguistic form Output: risk effect on work tasks in linguistic form (e.g., possible change in earthwork cost is "medium")	Product, process, and environmental models are absent; output refers to impact on process components (work tasks)	Rule based; utilizes fuzzy logic in risk quantification; fuzzy associative maps set out the risk magnitude, given the likelihood and severity of the risk factors that are subjectively assigned by the user; the total effect of many factors is computed if necessary; risk factors that have been considered include weather, plant availability, site investigation, and plant suitability	Risk quantification; cost, schedule, safety, and quality risks are considered
Technical risk identification and mitigation system (TRIMS) (Best Manufacturing Practices Center of Excellence 2001)				
Full working system being used mainly by U.S. defense contractors; the current knowledge base is applicable to software-development projects, and typical military acquisition projects such as missile production	Input: minimal; restricted to project milestones, and answers to queries on whether specific actions have been carried out Output: risk level of project elements in terms of "high," "medium," and "low"; specific actions (or their non-implementation) that contribute to the risk level can be identified	Process based; fairly detailed, generic models of standard project types are part of the system	Knowledge about projects is captured in templates that set out typical activities of specific project types; actions that act as risk mitigators are attached to each element of the template; reasoning about the risk level is based on the level of compliance to each activity	Risk identification; risk quantification is also carried out through assignment of weights that signify the importance of risk-related actions; the risk level is obtained by summing up the weights of noncompliant activities and comparing the value with pre-defined thresholds

Table 1 (*continued*).

Implementation	Input–output	Model of product–process–environment	Nature of knowledge base	Risk management functions supported
Risk consultant (Eon Solutions Ltd. and C & A Systems Security Ltd. 2001)				
Working system commercially available; application domain is security and associated risk of information technology (IT) systems in business enterprises	Input: answers to a questionnaire that primarily checks compliance with risk avoidance–mitigation strategies Output: probable risks, relative importance of risks, implications of risks, and recommendations for risk avoidance	System can be customized based on the organizational environment; product, process, and environmental models are not present	Knowledge about possible risks is captured using rules that link risk avoidance–generating actions to risk events; rules are also used in encoding knowledge on relative impact to organization by certain risks and the type of implication for the organization (financial, customer loss, etc.)	Risk identification; risk quantification through the evaluation of the relative importance of threats and vulnerabilities; risk response by generating appropriate recommendations and solutions
Fuzzy case based reasoning system for predictive project risk assessment and risk classification (Cox 1999)				
Working system currently being applied to software-development projects	Input: project activity network; values of attributes such as project type, visibility of project within organization, and resource scarcity Output: project outcome in terms of possible values of critical parameters (e.g., cost and duration)	Projects and organizational environment are characterized by attributes such as project type, resource scarcity, and visibility; project processes in terms of a network diagram are used in expressing project size–complexity	Utilizes case-based reasoning; details of past cases are held in a relational database; a fuzzy clustering technique that organizes the case base into similar categories and a feature extraction methodology that performs compact rule induction are used	Risk quantification; attributes of current project are compared to past cases; similarity is used in calculating whether critical parameters will (or will not) have an unacceptable slippage
Risk assessment system for construction schedules (Mulholland and Christian 1999)				
Prototype system developed using HyperCard	Input: minimal Output: pages of information providing data and information on schedule risk factors	Product, process, and environmental models are absent	A Hypertext system is used to store information on previously experienced risks; the information can be in the form of text, graphics, or pictures; risk factors relating to four dimensions (engineering design, procurement, construction, and project management) are contained within the body of information; examples of risk factors include productivity, design errors, and design criteria; the importance of the risk factors is characterized as "high" and "low" broadly for all projects; the confidence of the risk factors occurring is also expressed using similar linguistic expressions; the system allows the user to easily navigate through the information by providing mini-maps of documents visited	Risk identification

Table 1 (*concluded*).

Implementation	Input–output	Model of product–process–environment	Nature of knowledge base	Risk management functions supported
Knowledge-based risk-identification system (Leung et al. 1998)				
Prototype developed for extra high voltage transmission line construction projects	Input: selection of project activities and risk factors from list Output: risks and risk-related work packages	No product model; work breakdown structure (WBS) is used to model the processes; activities of the WBS serve as arguments of the rules; attributes of activities are not modeled; environmental conditions are modeled implicitly as risk factors	Rule based; forward chaining; rules take the form "IF Public consultation AND Permits and government approvals THEN Design changes"	Risk identification
Human–computer cooperative system for knowledge-based risk management in engineering (Niwa 1989)				
Working system; has been applied to construction projects	Input: project components and activities; risk factors applicable to the project need to be selected by the user Output: probable risks that will be encountered on the project are identified; backward chaining to verify the hypothesis that a risk will occur is also possible	Models of project components and activities that take the form of a list are utilized; no environment models; some environmental components are incorporated through the risk factors; attributes that describe the context of the project being analyzed are not used in the models–factors	Rule based, with the ability to chain both backward and forward; related risks are also identified by associating them through keywords	Risk identification
Expert risk system (Kangari and Boyer 1987)				
Microcomputer-based prototype implemented using INSIGHT 2+ expert system shell; integrated with databases containing cost data, weather data, productivity data, etc.	Linguistic input–output (I/O) through the use of fuzzy sets Input: selection of risk factors from list, definition of risk policy to be adopted, magnitude of risk factors in linguistic terms Output: expected cost of activities and their variance, and risk responses	No product or environmental models; activities serve as arguments in rules; attributes of the activities are not considered	Consists of a set of production rules; use of fuzzy logic is made in combining values provided by user for different risk factors, to calculate overall risk; rule base is used to reason about suitable responses for risk factors; examples of the factors considered are "uncertainty of inflation," "public disorder," and "labor disputes risk"	Risk quantification, by providing a linguistic measure for overall risk; risk response development, by suggesting management actions
Intelligent risk-identification system (Ashley and Perng 1987)				
Prototype	Input: selection of a specific problem category, project type, contract type Output: problems associated with specific problem areas, and the influence diagram that sets out the "influenced by" and "influence on" problems–variables	Project type and other characteristics provide the abstraction of the product; attributes such as contract type provide a definition of the environment; process models are absent; output refers to problems associated with processes	Rule-based representation along with the query evaluation capability of a database management system holding information on problem statements	Risk identification; quantification of the probability of occurrence of problems through the use of influence diagrams and Bayesian probability

knowledge bases of most systems would require altering the rule bases, which are their primary repositories of knowledge. The necessity to ensure consistency in terminology among existing rules and newly added or edited rules could make this procedure potentially difficult, especially in cases where a large number of rules are involved. More fundamentally, the system architectures are not open and thus do not allow the end user to have direct access to the knowledge base. A governing premise seems to be that the knowledge is static, or that an expert is required to modify it, lessening the ability of practitioners to add lessons learned. Only a few systems require information about the physical characteristics and attributes that describe the context of the project being analyzed, and a handful require information about the processes of the project. Most of the systems do not incorporate information about the environment in which projects are located, despite the important role environmental components can play in risk generation. In this paper the term project environment is used to refer to the physical, regulatory, political, stakeholder, social, financial, economic, contractual, and organizational context of a project.

The systems summarized in Table 1 support the different risk management functions at varying levels of detail. Most systems support only a subset of the risk management process such as risk identification or quantification. Rule- and case-based reasoning seem to be the most popular approaches that have been taken in modeling the risk management knowledge. However, some systems such as TRIMS use templates as repositories of knowledge.

Requirements for a knowledge-based system for risk

The systems described in Table 1 have contributed to the formalization of the economic risk management process by focusing on the application of knowledge-based approaches to risk identification and in some cases to risk quantification. While acknowledging the pioneering work carried out by the authors of the systems described, we believe that a need remains for a methodology that can assist in comprehensively managing knowledge relevant to all aspects of the risk management process and that enables the selective application of such knowledge to a particular project context. Desirable characteristics of such a knowledge management methodology include the following:

(1) Support for different stages of risk management — As described earlier, risk management is a process that consists of several distinct stages, namely risk identification, risk quantification, and risk response and control. These stages are joined by a critical flow of information that occurs between them. Selection of a risk quantification method requires the characteristics of the identified risks as input, and risk responses may depend on the assessment of the significance of the risks determined in the risk quantification stage. The responses themselves can trigger additional risks that need to be identified in turn. Therefore, the pools of knowledge relating to these different stages are inexorably linked. A system that supports all stages of risk management and facilitates information flow from one risk management function to another is therefore desirable.

(2) Ability to capture and apply the different types of risk-related knowledge — Risk-related knowledge can have many forms. For example, knowledge regarding risk identification might include a comprehensive listing of economic risks along with types of large engineering projects they apply to, the interrelationship between them, and the factors that contribute to their realization and magnitude. Risk quantification knowledge would include information regarding available quantification methodologies, their data requirements, and the type of output they produce. Similarly, risk response knowledge can include applicable response methods, the project parties they relate to, and their scope in terms of whether they are risk transfer measures, risk reduction measures, etc. It is also important to recognize that certain types of knowledge, such as those on risks associated with the project delivery type, are applicable to the overall project, whereas some pieces of knowledge (e.g., related to productivity, weather susceptibility) may be applicable only to specific project components. Therefore, a knowledge-based system should be capable of supporting the different types of knowledge, possibly with a combination of knowledge modeling methodologies.

(3) Support for physical, process, and environmental dimensions of a project — A central premise of our work that emerges from conducting risk analysis assignments coupled with an extensive review of the literature is that the risk management process must embrace the physical, process, and environmental dimensions of a project. The physical dimension treats what will be built, the process dimension describes how the project will be procured and constructed, and the environmental dimension describes the physical, political, social, regulatory, and other contexts in which the project will be executed.

(4) Ability to track risks throughout the project life cycle — The system should be capable of tracking and (or) monitoring risks throughout the project life cycle, i.e., which risks were realized, outcomes in terms of cost, time, capacity, quality, etc., how they were managed, risks that surfaced and were not previously identified, and so forth. In other words, the system should provide both an as-planned and an as-built picture of the project, thus allowing lessons learned to be captured. Further, the system should allow the level of detail at which information is modeled to change during the project life cycle. At the outset, a coarse granularity in terms of project description may suffice. As work progresses and more information becomes available, a finer granularity in the project description may be sought. Complementing this feature, the system should act in such a manner that the set of risks identified as being likely to be encountered on the project evolves dynamically, reflecting changes in the project and its environment. Such changes would occur as a result of modifications brought on by risk-mitigation strategies such as risk transfer that could lead to other previously unidentified risks, by changes in the design of the project, and as additional information is obtained about the project and its environment.

(5) Flexible architecture allowing continuous revision of knowledge — The lack of flexibility for changing the

information and knowledge that is encoded within a system are considered to be major shortcomings of knowledge-based systems currently available to support a variety of project management functions including risk management (Laptali and Bouchlaghem 1995). Therefore, an architecture that allows the user to update the system to capture knowledge through revisions and additions to the knowledge base would be desirable.

(6) Intelligent interface for users — The knowledge management system should provide an intelligent interface that assists the user in all the stages of risk management. Assistance for risk identification can be provided through a risk screening procedure that yields risks that are likely to be encountered on the project in question given the characteristics of the project and the physical, social, political, contractual, regulatory, organizational, and economic environments in which it is located. Suggestions for the most appropriate quantification methodologies available given the risk that is being analyzed and the detail that is required can be provided to aid risk quantification. Similarly, applicable response strategies could be suggested by the system to assist in developing responses to the risks.

Although each of the systems reviewed in Table 1 reflects a subset of the foregoing requirements, we have been unable to identify previous work that embodies all of these requirements. In our work, we have sought an approach to developing a computer-based methodology that incorporates all of these requirements and exploits past work by others that addresses effectively one or more of these requirements. We have broadly divided our methodology into a risk-identification component, a quantification component, and a component that assists in response development and the tracking of risks. These components are intended to assist the user in reusing knowledge in carrying out different risk management functions according to a systematic process similar to that proposed by CIRIA (1996) and Chapman and Ward (1997). Some of the requirements identified previously, such as the ability to support different stages of risk management and the ability to track risks throughout the project life cycle, apply to the methodology as a whole. Since this paper treats the risk-identification component of the methodology, we have focused mainly on the provision of flexibility and on the provision of an intelligent screening procedure that assists the user in identifying risks that are relevant to the physical and environmental context of a project.

Project scenario

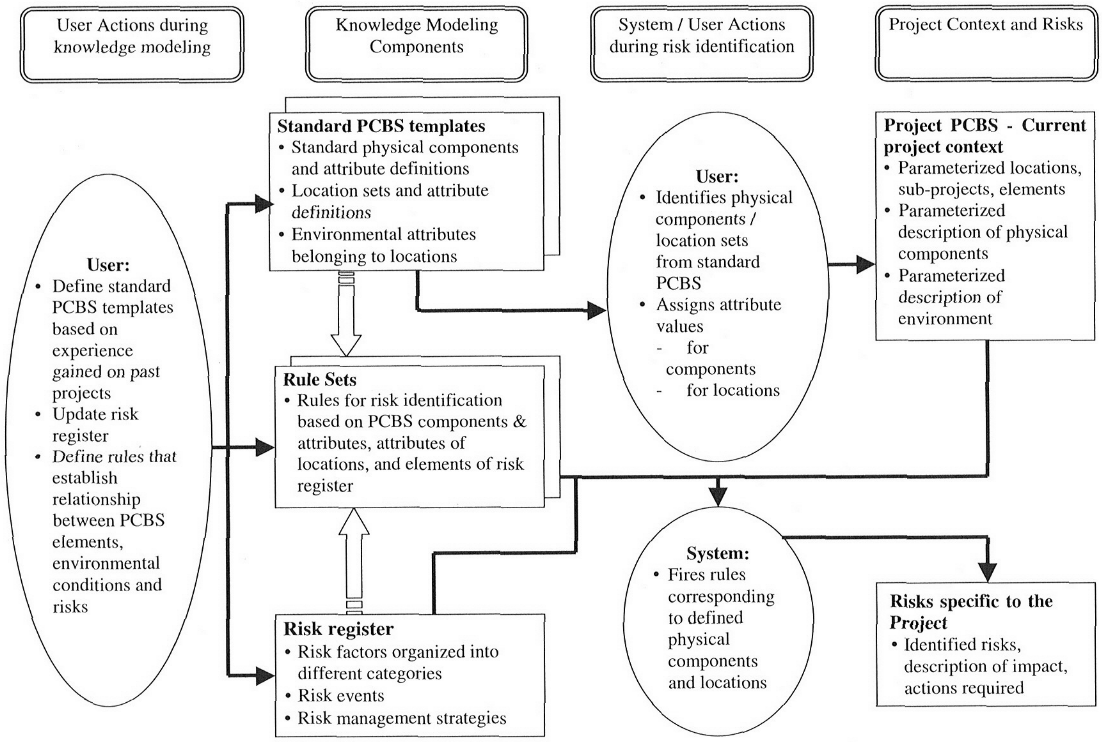
To assist in presenting the aspects of the approach adopted by the authors, an example scenario is presented in this section. It reflects some of the dimensionality associated with complex physical infrastructure projects. The scenario is as follows.

A public–private partnership venture is to be undertaken to expand a 19.6 km section of a two-lane highway in a mountainous and environmentally sensitive area to four lanes. A railroad located directly below the highway follows it along a major part of its length. In several sections, residential properties are located below the railroad. The expansion involves four road sections, a bridge, a viaduct, and a tunnel. Moving south to north, the configuration consists of a road section of 3 km, a 50 m bridge, a road section of 7.5 km, a viaduct of 1 km, a road section of 5 km, a 1 km tunnel, and a road section of 2 km. The road sections cross a number of streams, some of which are fish bearing, and the use of culverts is made as appropriate. This 19.6 km section of the highway also traverses several municipalities. Local government support for the highway expansion varies among these jurisdictions, as do the construction, traffic, and other types of bylaws. Throughout the construction phase, traffic will have to be maintained on the existing two-lane road, and the desire is to minimize the number of scheduled road closures. The project is envisioned to be undertaken as a build–operate–transfer enterprise and will likely need to be fast-tracked to meet deadlines sought by the provincial government. A foreign consortium is among several parties that have responded to the request for expressions of interest by the government. The consortium has successfully passed through this phase and is now preparing its responses to the requests for proposals call. At this stage, the consortium wishes to carry out an evaluation of the risks associated with the project to properly price its proposal and indicate its preferred strategy for sharing risks.

The risks that are faced by the consortium are numerous and diverse. Leaving aside revenue risks, of particular interest are the risk of slope failures both within the narrow construction corridor between the railroad and the highway and above the highway, which might require that design revisions be made to modify the alignment of the highway; possible oversights in obtaining permits from the various government agencies within different jurisdictions, thus delaying the start of critical activities; the risk of delays brought on by restrictions that may be imposed by local authorities on the timing of construction activities adjacent to residential areas; an inability to limit road closures to posted times and maintain reasonable traffic flow during nonclosure times; and risks associated with environmentally sensitive areas. These examples serve to illustrate that the risks are heavily dependent on the specificities of the current project context in terms of the attributes of its physical, process, and environmental dimensions.

If one attempted to apply the systems identified in Table 1 to identify the risks of this project, a striking feature that would become evident is that many of these systems do not allow the current context of the project, i.e., the project characteristics and the characteristics of the environment in which it is located, to be comprehensively accounted for. Consequently, the output of these systems tends to be generic, which means that some of the risks would not be applicable to the current project. A further disadvantage brought on by the generality of these systems is that they may fail to identify some risks that are dependent on the value of a project attribute or the existence (or nonexistence) of a particular project component. For example, certain risks associated with environmental impact assessment (EIA) regulations might be applicable when attributes of project components (e.g., number of lanes in a highway) exceed values stipulated in the regulations. Our methodology aims to build upon the best aspects of current knowledge-based systems and overcome their shortcomings by placing extensive em-

Fig. 1. Conceptual model of knowledge-based approach for risk identification. PCBS, physical component breakdown structure.



phasis on characterizing the project context in which the risk management process is carried out. It is based on the observation that risks are inexorably linked to the components of the project, the processes used to construct them, and the environment in which they are located.

Methodology for risk identification

Figure 1 provides a conceptual view of part of the structure that is being used in implementing the proposed risk-identification methodology as a computerized system. The knowledge modeling components shown on the left-hand side of the figure allow experience gained from past projects to be stored in a reusable format. This is done with the aid of a template library developed using a standard project component breakdown structure (what is to be built), attributes defined using a standard vocabulary, and user viewable and editable rule bases built to link project and environmental attributes for specific project (or subproject) types. The system allows the user to define the current project context using the standard templates and to assign attribute values reflective of the project at hand. Rules corresponding to the selected components and attributes are then fired by the system to identify risks associated with the project. A detailed description of the elements of the system follows. Not shown in Fig. 1 is the process aspect of the project, i.e., how the various components will be constructed. The approach taken to treat process risks mirrors the approach shown in Fig. 1, with the physical and process views being associated with each other. Also not shown in Fig. 1 is the functionality of tracking risks throughout the project life cycle. Lastly, it should be noted that substantial support for risk identification is provided, even if one just uses the standard templates and the risk register, i.e., one can use the system as a mnemonic device for identifying potential risks without having to develop formalized rules. This is of particular use for very unique, nonrepetitive projects.

Standard physical component breakdown structure

The standard physical component breakdown structure (PCBS) used in representing the project is based on the hierarchical model for representing the project physical view presented previously by Russell and Chevallier (1998). A hierarchical approach towards modeling the project is intuitively appealing, as it allows the user to conveniently develop a model based on the level of information that is available and at the detail required for different management functions. At the root of the hierarchical model is the project itself, under which all other components can be defined and described. The current component set includes subproject, system, subsystem, element and subelement, content, material, location set, location, and sublocation. Attributes of importance, i.e., those which can assist in the risk management process, can be attached to each of these component types. It is useful to view the physical-component structure as comprising two branches, one branch consisting of locations and one branch consisting of temporary or permanent physical components that have to be constructed to realize the project. For the project PCBS (see discussion later in the paper), the two branches of the tree are mapped onto each other so that the physical components are located in space.

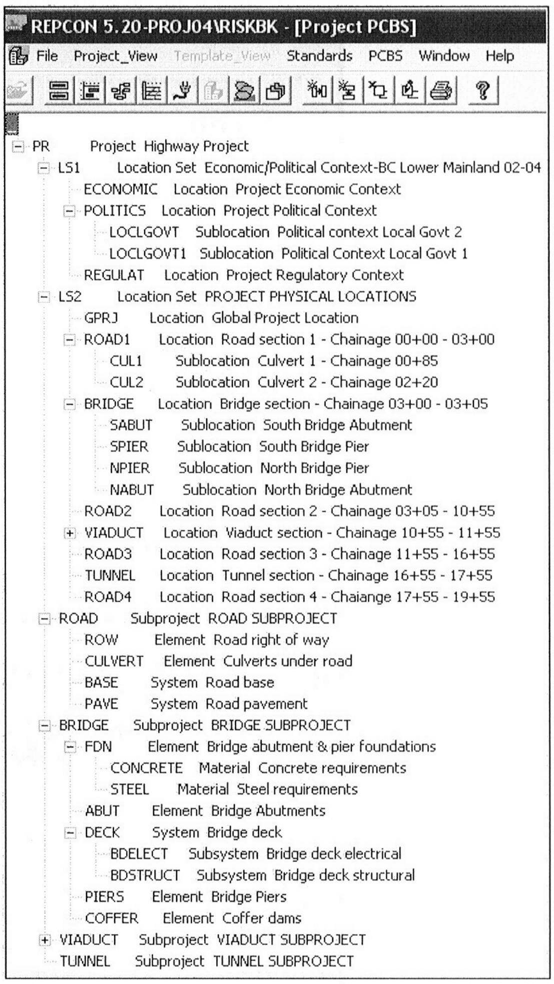
The environmental context of the project is modeled through the location and sublocation components of the PCBS. Locations show the context of a spatial or temporal position. Attributes of importance, such as soil type and the presence of endangered species, are attached to locations to define the state of the environment. Locations of a more global nature are used to describe conditions such as the economic and financial climates and the political and regulatory conditions. (In theory, an additional component type could be defined for modeling the environment. Currently, location attributes are used for this task. How best to model the environmental dimension is still being explored.)

The knowledge management side of the system contains a library of PCBS-based templates for different project types. The templates provide the PCBS structures for a generic project of a particular project type, such as a bridge or road, using a standard vocabulary to identify the physical components and their attributes. Standard templates for various types of project can be developed, as such projects are undertaken by a particular organization. The standard templates defined by the user can correspond to individual components at a lower level in the PCBS hierarchy or to descriptions of entire projects or subprojects. If additional attributes deemed to be important for risk identification surface, the standard PCBS can be readily updated with this information. The creation of a library of templates based on experience with different types of projects allows knowledge regarding the components of such projects to be captured in a format suitable for reuse. The ability to add attributes, and PCBS templates themselves, to the system brings about the desirable characteristics of editability and updatability into the system. Another point of importance is the use of a standardized vocabulary for identifying project components and their attributes, which is crucial for the rule-based risk-identification process described later in the paper. Identifying a rich set of attributes that are important from a risk-identification perspective, and incorporating them into the standard vocabulary, is part of research currently underway.

Project physical component breakdown structure

The use of the standard templates allows the user to conveniently develop the PCBS for a specific project by assembling suitable project, subproject, or lower level templates that can be chosen from the standard template library. The ability to reuse previously defined components in defining a project as opposed to starting from scratch minimizes the burden on the user in carrying out such a definition and leverages past experience. For example, in the highway project being considered, standard templates for a bridge, road, tunnel, and viaduct would be used in developing the project PCBS. Location and sublocation components would then be defined for the project at hand, and the mapping required to position the physical components in space (defined by locations) would be made. The selected templates would be extracted and combined into a PCBS structure such as shown in Fig. 2. (Considerable thought is required as to how best to represent a project both in terms of locations and components. The particular format of Fig. 2 is for illustrative purposes only.) The structure can then be instantiated by specifying the component attributes and the attributes of the different locations. Figure 2 also illustrates the hierarchical nature of the PCBS, i.e., the project is divided into four subprojects, a road subproject made up of several noncontiguous segments, a bridge subproject, a viaduct subproject, and a tunnel subproject. The bridge subproject is further described in terms of foundation, pier, and abutment elements and a deck system. The deck system is divided in terms of a structural subsystem, an electrical subsystem, and so on. Multiple occurrences of components such as the four road segments are conveniently accommodated as shown in Fig. 2 by mapping them onto different locations. The system as currently implemented allows the user to assign linguistic, Boolean, and quantitative values to attributes at each location as shown in Fig. 3*a*. Physical-component attributes are assigned values in a similar manner, as shown in Fig. 3*b*. Work is underway to allow outcome values to be specified in one of two ways for quantitative variables. They are (*i*) 5, 50, and 95 percentile values, which allow robust estimates of mean and variance to be made (Pearson and Tukey 1965), and (*ii*) discrete scenarios with probabilities of occurrence of outcomes for each state to be specified.

Fig. 2. PCBS structure for example highway project.

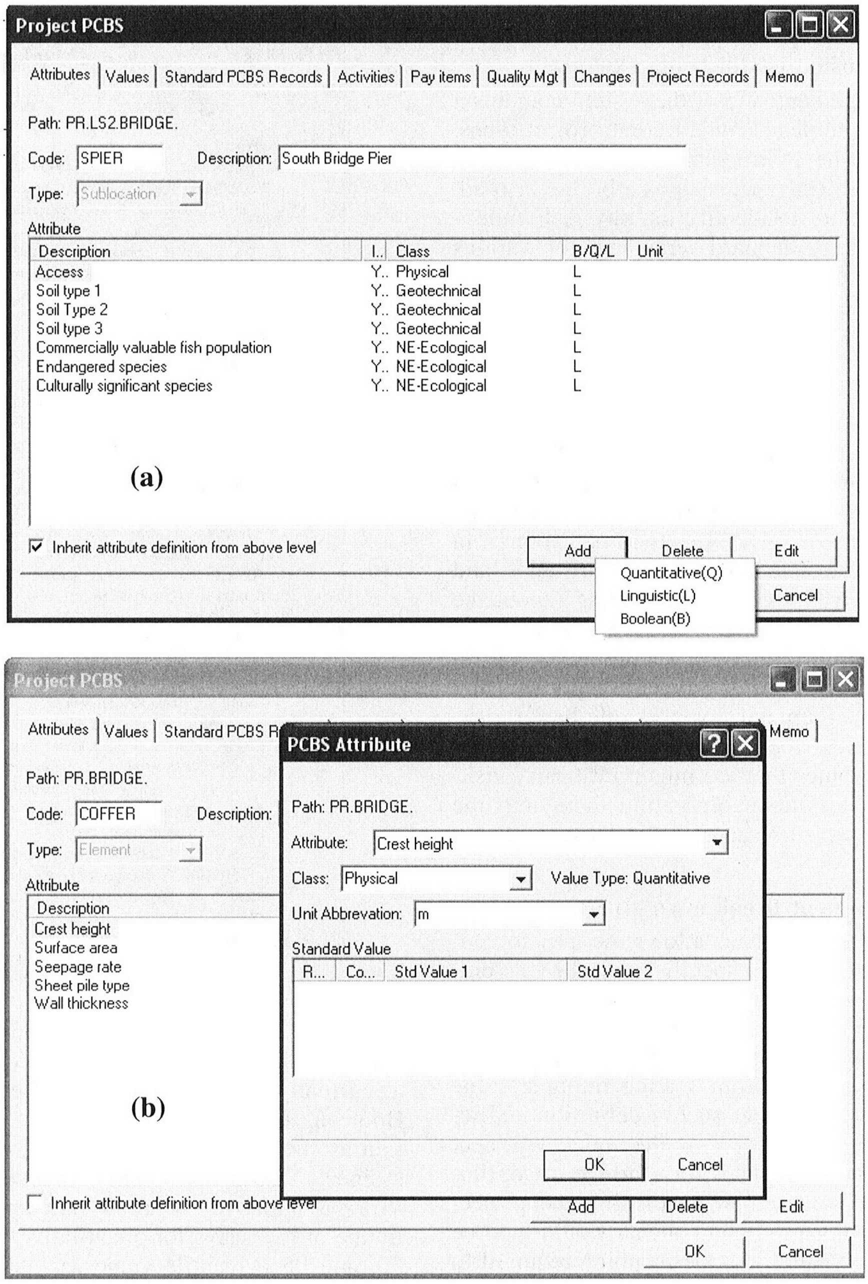


```
⊟ PR        Project  Highway Project
   ⊟ LS1        Location Set  Economic/Political Context-BC Lower Mainland 02-04
        ECONOMIC    Location  Project Economic Context
      ⊟ POLITICS    Location  Project Political Context
           LOCLGOVT     Sublocation  Political context Local Govt 2
           LOCLGOVT1    Sublocation  Political Context Local Govt 1
        REGULAT     Location  Project Regulatory Context
   ⊟ LS2        Location Set  PROJECT PHYSICAL LOCATIONS
        GPRJ        Location  Global Project Location
      ⊟ ROAD1       Location  Road section 1 - Chainage 00+00 - 03+00
           CUL1         Sublocation  Culvert 1 - Chainage 00+85
           CUL2         Sublocation  Culvert 2 - Chainage 02+20
      ⊟ BRIDGE      Location  Bridge section - Chainage 03+00 - 03+05
           SABUT        Sublocation  South Bridge Abutment
           SPIER        Sublocation  South Bridge Pier
           NPIER        Sublocation  North Bridge Pier
           NABUT        Sublocation  North Bridge Abutment
        ROAD2       Location  Road section 2 - Chainage 03+05 - 10+55
      ⊞ VIADUCT     Location  Viaduct section - Chainage 10+55 - 11+55
        ROAD3       Location  Road section 3 - Chainage 11+55 - 16+55
        TUNNEL      Location  Tunnel section - Chainage 16+55 - 17+55
        ROAD4       Location  Road section 4 - Chaiange 17+55 - 19+55
   ⊟ ROAD       Subproject  ROAD SUBPROJECT
        ROW         Element  Road right of way
        CULVERT     Element  Culverts under road
        BASE        System  Road base
        PAVE        System  Road pavement
   ⊟ BRIDGE     Subproject  BRIDGE SUBPROJECT
      ⊟ FDN         Element  Bridge abutment & pier foundations
           CONCRETE     Material  Concrete requirements
           STEEL        Material  Steel requirements
        ABUT        Element  Bridge Abutments
      ⊟ DECK        System  Bridge deck
           BDELECT      Subsystem  Bridge deck electrical
           BDSTRUCT     Subsystem  Bridge deck structural
        PIERS       Element  Bridge Piers
        COFFER      Element  Coffer dams
   ⊞ VIADUCT    Subproject  VIADUCT SUBPROJECT
     TUNNEL     Subproject  TUNNEL SUBPROJECT
```

Rule sets

A second type of knowledge structure that is stored in the system is made up of rules that link physical component and attribute definitions to the attributes of their locations to capture reasoning about risk identification. A large part of the reasoning about the occurrence of risks is based on the central concept of a shared location. That is, physical components occupy a location, and the location has environmental attributes that may impact the physical component or vice versa, with the resultant interaction creating possible risk implications. This concept can be illustrated by considering a cofferdam located in the south bridge pier sublocation of the highway project (see Fig. 2). Assume that commercially

Fig. 3. (*a*) Specifying type of value for location attributes, and (*b*) specifying physical-component attributes.



(a)

Path: PR.LS2.BRIDGE.

Code: SPIER Description: South Bridge Pier

Type: Sublocation

Attribute

Description	I..	Class	B/Q/L	Unit
Access	Y..	Physical	L	
Soil type 1	Y..	Geotechnical	L	
Soil Type 2	Y..	Geotechnical	L	
Soil type 3	Y..	Geotechnical	L	
Commercially valuable fish population	Y..	NE-Ecological	L	
Endangered species	Y..	NE-Ecological	L	
Culturally significant species	Y..	NE-Ecological	L	

☑ Inherit attribute definition from above level

(b)

Path: PR.BRIDGE.

Code: COFFER Description:

Type: Element

Attribute

Description
Crest height
Surface area
Seepage rate
Sheet pile type
Wall thickness

☐ Inherit attribute definition from above level

PCBS Attribute

Path: PR.BRIDGE.

Attribute: Crest height

Class: Physical Value Type: Quantitative

Unit Abbrevation: m

Standard Value

R...	Co...	Std Value 1	Std Value 2

valuable fish such as Chinook salmon migrate through this physical location in early spring each year. Thus, the population of commercially valuable species will be an attribute in characterizing the south bridge pier sublocation as shown in Fig. 3. In this case, the salmon migration can create possible implications for the erection of the cofferdam at the same location. A need to avoid construction activity in the water would arise to minimize any adverse impact on the salmon. Owing to their commercial value, it is very likely that regulatory requirements that govern such a need would be present. The combination of these factors would result in a limited time window for cofferdam erection, as it would need to be completed before the onset of the migration season. Thus, there is a risk that the cofferdam erection activity may be interrupted if the migration season commences earlier than expected or in the event of a duration overrun in the cofferdam erection. Such a scenario would mean that critical foundation activities that were scheduled to be completed inside the cofferdam would be delayed, with possible implications for the overall project duration.

Numerous risks such as those described previously may be encountered on a large infrastructure project. Logically categorizing these risks has been identified as an aid to risk identification by many researchers, as it can provide coherence to a large risk list and can assist in the identification of similar risks that could occur on a project (Al-bahar and Crandall 1990). An extendable and updatable risk register is being developed to assist in categorizing and storing information related to risk events. The register contains a list of risk factors under categories such as technical factors, economic factors, stakeholder factors, and force majeure factors, identifies them as being local or global in the context of the project, and provides insights into how they can be expressed or quantified and mitigated or managed.

In the knowledge-based system, the rules for encoding knowledge regarding risks are specified using physical components and attributes, the location components and attributes, and the elements of the risk register as their arguments. The standard vocabulary adopted in the PCBS is also used in the rules, thus allowing them to be bound with the standard templates. Similar to updating and editing of the standard templates, rules can be added to the rule base as experience is gained on projects. The use of a standard vocabulary (component types and risk types) ensures that new rules that are defined are integrative and compatible with preexisting rules. This lessens the difficulty in modifying the knowledge base, as compared to the systems described in Table 1, where compatibility of terminology with related preexisting rules has to be examined prior to the insertion of additional rules. The philosophy that has been pursued in encoding rules has been to flag conditions that give rise to risks that affect economic variables and suggest actions that could be taken to manage or eliminate them.

Project-specific risks

In selecting the standard templates for a specific project from the template library, rule subsets that correspond to components and attributes contained within the templates are selected. The system will chain through these subsets of rules to reason about risks that are applicable to the project PCBS once attribute values have been assigned for the project at hand. Two rules that correspond to the scenario set out in the previous section involving the erection of a cofferdam are used as examples to illustrate the rule structure. These rules have been encoded using the syntax of the AION Business Rules Expert software (Computer Associates International Inc. 2000). The first of these rules examines the natural environment to identify the presence of commercially valuable fish species and the regulatory environment to identify regulations that relate to such species. The rule recognizes the fact that the regulations would only be applicable in the presence of a significant population of commercially valuable species, by querying the value of the fish population attribute of locations, which is modeled as a linguistic variable. All physical locations and sublocations are queried using a pointer to the set of locations, as salmon may also be present in streams that are encompassed by road locations, in addition to their presence in the river. The "regulatory context" location that sets out the characteristics of the regulatory environment is examined to determine the presence of fisheries protection laws, which is modeled as an attribute taking on Boolean values.

```
Rule "Commercially valuable fish & Fisheries protection laws"

IF plocation.CommerciallyValuableFishPopulation = "large"
   AND LocationRegulatoryContext.FisheryProtectionLaws = TRUE
THEN
   plocation.FisheryProtectionMeasures = TRUE
```

Should this rule fire, the locations in which fisheries protection measures are applicable will be identified by the assignment of the value "TRUE" to the "FisheryProtectionMeasures" attribute. This result can then be used in reasoning about various risk impacts that arise at different locations due to the fishery protection laws. In reasoning about risks related to cofferdams which arise due to these laws, the system first identifies the presence of cofferdams in the current project context by querying the project PCBS.

```
FindObjs("*CofferDam*,pObjs)
```

If a valid list of pointers is obtained, a rule is fired that examines whether locations at which cofferdams are present (bridge pier locations) are among the locations impacted by the fishery protection laws. In the case of such an event, the system appraises the user of the possibility of risk and preliminary actions that may be taken in response to the uncertainty as shown in the following:

```
FreeList
FindObjs("*Pier*location*",pObjs)
RULE "Risks: Protecting Fish & Cofferdams"
IF pObjs.FisheryProtectionMeasures = TRUE
THEN Risk = "Time window for the erection of the coffer
   dam may be restricted. It would be required to be com-
   pleted prior to the onset of the migration periods of fish
   such as salmon. Subsequent risks include delays in suc-
   ceeding activities due to non-completion of cofferdam
   and cost overruns due to the use of excessive resources
   to meet time window constraints. Actions that may be
   taken include (i) identifying available time windows
   and estimating the duration of the cofferdam to estab-
   lish suitable time frames for construction; (ii) establish-
   ing cost contingencies that may required to cover costs
   related to expediting construction; (iii) establishing du-
   ration contingencies; and (iv) exploring opportunities
   for redesign to eliminate the need for a cofferdam."
END
```

The rules can be further enriched by considering the process dimension of the project. A query could be structured to determine the activities associated with the cofferdam and their time windows. A rule that examines the overlap between the migration time of the salmon and the activity schedules can then be used to alert the user to potential risks that could occur.

At present, we envisage processing the entire project PCBS by firing appropriate rules and then providing an output report to the user organized in accordance with the PCBS structure. This output would necessarily be sensitive to the characteristics of the project and environment as defined in the project PCBS, thus providing the user with a screened list of risks that are likely to be encountered. Several improvements to the current rule base are envisaged as part of future research. These include the addition of rules that define the linkage in chains of risks, i.e., the triggering of one risk by another, and the addition of rules that account for synergy between risks, i.e., simultaneous occurrence of several risks bringing catastrophic effects on project performance.

Conclusions and future research

We have identified the significance of portraying the process and physical aspects of a project and its environmental context to gain a sharper focus on risks that may be encountered on a large infrastructure project. Flexible, user-definable models of the project and its environment that carry out this portrayal and a register of risks are part of the knowledge-based methodology that is presented. The hierarchical representation scheme that has been adopted for modeling physical project components brings about flexibility, allowing information modeling to be carried out at varying degrees of detail.

Several areas for future research have been identified in the paper. Among these are several improvements to the rule base and research on identifying and standardizing a rich set of project and environmental attributes that could be used in defining standardized project templates. Other work will also be focused on possible improvements that could be made in modeling the environment for the purpose of risk identification. The adoption of a class, subclass structure for environmental components and matching these classes to locations in a manner similar to project components is currently being examined, as opposed to modeling the environment through location attributes. Identifying means of incorporating project process information into the risk-identification reasoning procedure through a process view that can be associated with the physical view is also being pursued. Modeling of how the project will be built including administrative processes is important, as project processes can in some cases assist in mitigating risks, whereas in other cases they can exacerbate risks.

Other research on system development will also be focused on addressing the quantification of risks. Expected research challenges include the identification of meaningful metrics for expressing the uncertainty and selecting suitable quantification methods, especially for linguistic variables.

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