Ontology for Relating Risk and Vulnerability to Cost Overrun in International Projects

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Abstract: Risk management is about identifying risks, assessing their impacts, and developing mitigation strategies to ensure project success. The difference between the expected and actual project outcomes is usually attributed to risk events and how they are managed throughout the project. Although there are several reference frameworks that explain how risks can be managed in construction projects, a major bottleneck is the lack of a common vocabulary for risk-related concepts. Poor definition of risk and patterns of risk propagation in a project decrease the reliability of risk models that are constructed to simulate project outcomes under different risk occurrence scenarios. This study aims to extend previous studies in risk management by presenting an ontology for relating risk-related concepts to cost overrun. The major idea is that cost overrun depends on causal relations between various risk sources (namely, risk paths) and sources of vulnerability that interfere with these paths. Ontology is used to develop a database system that represents risk event histories of international construction projects and to construct a model for estimation of cost overrun. It will form the basis of a multiagent system that can be used to simulate the negotiation process among project participants about sharing of costs considering the risk allocation clauses in the contract, sources of vulnerability, and causal relations between risk events and their impacts. The ontology is constructed by interaction with Turkish contractors working in international markets and extensive literature review on risk-related concepts. The validation test results provide evidence that the ontology is fairly effective to help Turkish contractors to assess cost overrun by considering sources of vulnerability and risk in international construction projects. **DOI: 10.1061/(ASCE)CP.1943-5487.0000090.** *© 2011 American Society of Civil Engineers.*

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Introduction

Risk management is a formal process for systematically identifying, analyzing, and responding to risk events throughout the life of a project to obtain an acceptable degree of risk elimination or control. Successful risk assessment and risk response planning at the tendering stage of a construction project may significantly affect competitiveness as well as profit potential of a construction company. Because risk analysis and response generation are performed considering the predefined risks, risk identification is accepted to be the most critical step in risk management (Al-Bahar and Crandall 1990). However, risk identification is not an easy task; construction projects usually involve a high level of uncertainty, vagueness, complexity and vulnerability to both internal and external conditions.

Although, there are several reference frameworks such as RISKMAN, which was agreed to by the European Community (Carter et al. 1994), Project Risk Analysis and Management Methodology (PRAM) developed by the Association of Project Managers (Chapman 1997), and Risk Analysis and Management for Projects Methodology (RAMP), endorsed by the Project Management Institute (2000) that provide a systematic approach for risk management, it is clear that their success in practice depends on the risk-related information (such as likelihood of risk, potential impact, and risk allocation between the parties) fed into the system. Success of risk models that are used to predict project outcomes under different scenarios also depends on identified risk factors, their interrelations and risk propagation patterns. As pointed out by several researchers (such as Tah and Carr 2001; Gusmão and Moura 2006; Dikmen et al. 2008b), one of the major shortcomings of the mentioned reference frameworks and risk models is the lack of a common vocabulary.

Learning from previous projects and understanding the causal relations between risk events, actions taken by the parties, and their consequences may help in creating realistic risk occurrence scenarios, developing reliable risk models, and successfully estimating cost and time for forthcoming projects. Thus, an information model that can facilitate construction of "risk event histories" is needed.

The aim of this research is to develop an ontology that can be used as the basis of a risk event history database that entails "risk paths" rather than individual risk sources and "vulnerability factors" that affect the impact of risks on a project. The risk event histories will further be used to construct a cost prediction model for international construction projects and develop a multiagent system to simulate the negotiation process between project participants considering cause-effect relations between the sources of risk and vulnerability as well as risk allocation clauses in the contract.

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From the overwhelming number of definitions of ontology existing in the literature, the most cited one is given by Gruber (1993), who defines ontology as "an explicit specialization of a conceptualization". Conceptualization indicates a simplified view of the world and specification refers to a formal representation. The overall aim in constructing an ontology is to create an agreed-upon terminology by specifying the concepts and relationships between these concepts in a way that is computationally utilizable, sharable, and reusable by humans or machines (Holsapple and Joshi 2002; Gruninger and Lee 2002).

Research Background

Previous studies on risk and ontological models are discussed in this section along with the reasons why an ontological model is necessary to relate risk with cost overrun. Illustrative cases are also depicted to demonstrate the relations between risk-related concepts that form the basis of the proposed ontology.

Previous Studies on Construction Risk Modeling

The initial step of risk modeling is risk identification. In the construction risk management literature, generic risk checklists and breakdown structures are proposed to facilitate the identification process. Checklists include a list of risk factors that are usually grouped under different categories with respect to their sources or level of controllability. Wideman (1986) developed a risk breakdown structure that has five categories: external-unpredictable, external-predictable but uncertain, internal (nontechnical), technical, and legal. Flanagan and Norman (1993) classified risk sources as a hierarchy of four layers: the environment, market, company, and project. Similarly, Zhi (1995) identified 60 risk factors about the country, construction industry, characteristics of the company and project conditions. Raftery (1994) defined three separate categories of risk: those internal to the project; those external to the project; and those regarding the client, the project or project team, and project documentation. Han and Diekmann (2001) proposed a structure to classify international construction risks in five categories: political, economic, cultural/legal, technical/construction, and others. The ICRAM-1 method developed by Hastak and Shaked (2000) provides a structured approach for evaluating potential risk indicators involved in an international construction operation by analyzing risks at the macro (or country environment), market, and project levels.

Using these risk breakdown structures, decision-makers may assess the magnitude of different sources of risk and further identify potential risk events that may affect project outcomes. However, these tools do not provide an inclusive approach for risk modeling because they have two major shortcomings:

Shortcoming 1. In risk checklists, the risk source-event relation is usually not considered. In practice, there are cause-and-effect relationships among the risk factors leading to a network form rather than a one-way hierarchical structure. A risk event happens because of uncertainty present in a project, and it is accompanied by at least a cause, a consequence, and the probability of occurrence (Cano and Cruz 2002). Dikmen et al. (2008a) stated that sources, events, and consequences should not be defined in the same checklist as if they are independent from each other; instead, causal maps considering sources, events, and consequences should be constructed to reveal their interrelations. Tah and Carr (2000) also demonstrated the associations between risk factors, risks, and their consequences using cause-and-effect diagrams. Han et al. (2008) discussed the significance of interrelations and proposed the identification of "risk paths" that show the causal relationships between risk sources and events.

It is evident that risk models that simulate project performance should be based on risk paths rather than individual risk sources.

Shortcoming 2. In traditional risk models, the statistical link between the risk events and their consequences is scrutinized. However, this approach is limited because the influence of the "project system" is neglected. During the identification phase, a critical issue, which is defined as "controllability/manageability" by Dikmen et al. (2008a) and "project vulnerability" by Zhang (2007), should be considered to characterize the system's influence on risk consequences.

A system's vulnerability represents the extent or the capacity to respond or cope with a risk event (Zhang 2007). Vulnerability exists within systems independently of external hazards and depends on the characteristics of project organization. Barber (2005) defines the rules, policies, processes, structures, actions, decisions, behaviors or culture within a project organization as internally generated risks. He mentions that imperfect organizations or systems generate new risk,s but in traditional risk management process, these are considered to be less important. Vulnerability assessment is used to define those characteristics of a system that will create the possibility for harm (Ezell 2007; Sarewitz et al. 2003). Vulnerability and risk assessment should be integrated to understand how a project will respond to risk events considering its vulnerability. The actual consequences of risk events depend on a project's vulnerability to risks and an organization's capability to manage risks; therefore, the company factors as well as the project characteristics should be taken into account during risk modeling.

Vulnerability of the project should be considered during risk modeling. Also, risk management should be accompanied with vulnerability management. Effective planning for risk consequences requires that the vulnerability associated with specific processes be understood in parallel with understandings of probabilities of risk, so that decisions can achieve the appropriate balance between risk and vulnerability management (Sarewitz et al. 2003). Integrated vulnerability management into risk management process may help companies to better understand threats, determine acceptable levels of risk, and take action to mitigate identified vulnerabilities (Dikmen et al. 2008c).

Consequently, in the previous studies, although there is a consensus regarding the existence of causal relations between risks and necessity to integrate vulnerability into risk management process (Zhang 2007; Turner et al. 2003; Busby and Hughes 2004), there is no reported study about how risk paths and vulnerabilities can be integrated into risk models. This study attempts to develop a common vocabulary and an ontological structure to explain interrelations between risk sources, risk events, vulnerability, and their consequences.

Previous Studies on Ontological Models

In recent years, in recognition of the importance of ontologies in collaborative working, there is an increase in ontology engineering studies proposed in the construction literature. Ugwu et al. (2005) developed an ontological model for constructability assessment of steel structures. The study of Aksamija and Grobler (2007) focused on developing an ontology describing principles of building design and relationships among them. Lima et al. (2005) presented the e-Cognos project, which is a comprehensive ontology-based portal for knowledge management in construction. Staub-French et al. (2003) presented the ontology formalized for relating building product models to construction activities and associated construction resources to calculate construction costs. The proposed ontology

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enabled estimators to maintain construction cost estimates more completely and consistently than traditional tools.

Within the context of risk management, Ferreira et al. (2007) proposed a risk ontology in which the risk parameters are grouped under four categories: risk factors, risk events, reactions, and risk effects. In their study, the risk ontology is developed by generating risk scenarios that illustrate the different combination of these four elements in a single logic sequence based on the identified interdependencies and influences among the groups. To overcome the lack of formality in construction risk management, Tah and Carr (2001) also present a basic information model that can support quantitative risk analysis and prototype software implementation. They mention that lack of a common vocabulary results in poor, incomplete, and inconsistent communication of risks. Tah and Carr (2001) also believed that "the development of a common language for describing and dealing with risks will lead to a greater degree of consistency for the treatment of construction risks and a greater understanding of their consequences for projects and organizations."

The proposed ontology in this paper combines and extends the mentioned studies reported in construction risk management literature in several ways. First, it integrates the concept of vulnerability, which is a critical factor that should be considered during risk modeling, with the concept of risk. Second, it includes knowledge, related with risk paths, to represent the source-event relation between risk factors that has been generally ignored in previous studies. Third, rather than a conceptual framework, it develops a formal representation that is computationally utilizable and usable to construct quantitative risk models by specifying the concepts of risk and vulnerability and their interrelations.

Why Do We Need a Risk Ontology?

Within the context of this research, the ultimate aim is to develop a multiagent system to simulate the negotiation process among project parties to achieve an acceptable degree of risk and cost sharing. The risk paths, vulnerability sources and contract conditions throughout the project will form the basis of the negotiations, combined with the long-term and short-term expectations and attitudes of the parties. A database structure was constructed using the ontology described in this paper, and risk event histories associated with 75 real projects were entered into the database. Consequently, the ontology presented in this paper will be used to represent risk event histories that include both risk and vulnerability factors and their interrelations. A prediction model will be developed to estimate cost overrun and probable risk paths for a given project. This model will be used to guide the negotiation process between parties.

Consequently, risk and vulnerability ontology, which is the subject of this paper, will be used to relate risk paths with cost overrun and simulate risk sharing process between project participants. The ontology can also be used to collect risk-related project data, develop statistical models to understand reasons for cost overrun, and facilitate learning from previous projects.

Illustrative Case Studies

Before the construction of ontology, case studies were conducted to question the validity of risk and vulnerability paths in construction projects. To identify a general risk and vulnerability propagation pattern in construction projects, seven completed international construction projects were investigated. The Turkish contractors that are actively working in the international construction market were selected, and experts from these companies were interviewed. All the experts interviewed have at least 10 years of experience in managerial positions in the international construction industry. The projects include two energy transmission projects in Iraq, a process plant project in Jordan, housing construction and infrastructure projects in the United Arab Emirates (UAE), a military facility construction in Afghanistan, and a hydropower plant project in Turkey. The cases were chosen so that different country, company, and project-related features, and consequently different risk paths, could be observed.

Detailed information about the projects was collected through meetings with experts, each lasting for 1–1.5 h. For each project, the participants were requested to give some information about the risk events they faced, reasons for risk events, the triggering factors that affected the occurrence of these events, response strategies used by the company, and their consequences for on project success, particularly cost. A cognitive map of each expert's statements about each case study project was drawn and submitted for the expert's approval. The key concepts raised by the interviewees were identified as potential elements of the risk and vulnerability ontology. More information about the case study projects and associated maps can be found in Dikmen et al. (2008b, b). The aim of the case studies was not to produce a comprehensive set of factors that may lead to cost overrun in construction projects but to identify a general structure that can guide us while developing the risk and vulnerability ontology. The identified structure that explains the causal relations is depicted in Fig. 1.

As it can be seen from Fig. 1, case studies demonstrated that vulnerability factors may affect different stages of the risk realization process. Some vulnerability parameters (V1) influence the probability of risk occurrence. For instance, intensive construction activity within the region triggers the risk of unavailability of local

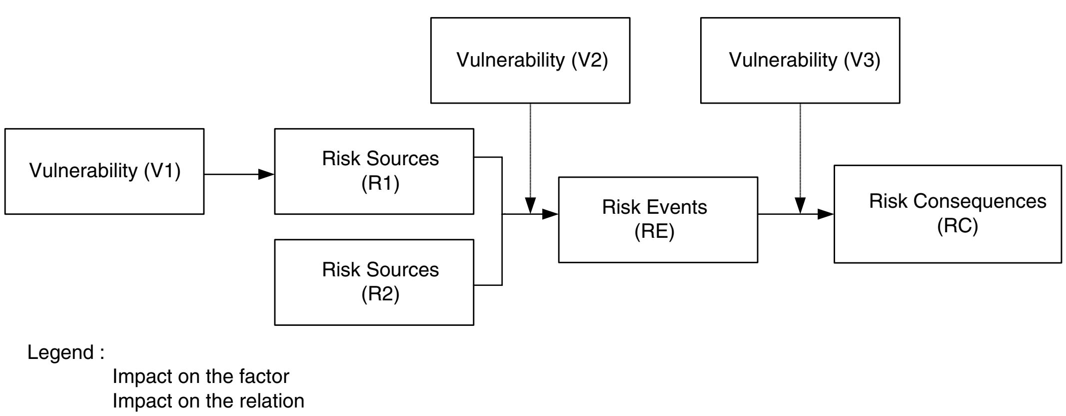

Fig. 1. Risk-vulnerability paths (Dikmen et al. 2008b)

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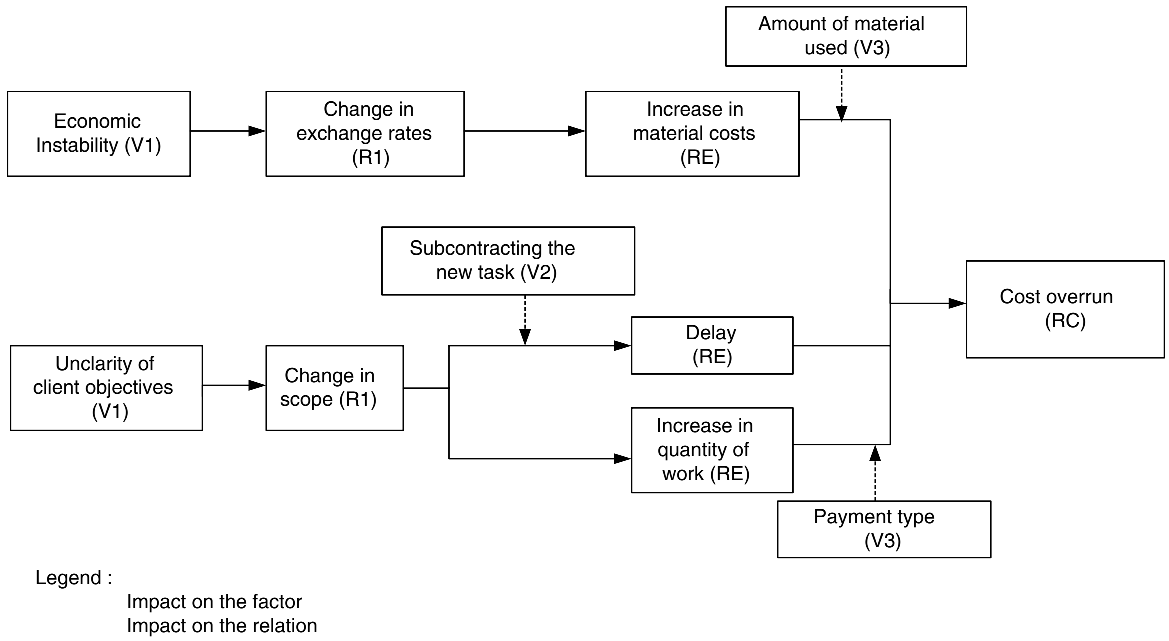

Fig. 2. Example of risk paths

labor and material. Some vulnerability factors (V2) are about manageability of risk. For example, if the company has a strong local partner, the impact of change in local regulations (R1) may be less because the partner may communicate effectively with the local authorities and manage the situation. Vulnerabilities (V3) may also influence the impact of risk events on project success. For instance, the implication of the increase in the quantity of work (RE) differs depending on whether the payment type is unit-price or lump-sum. A risk path example taken from the case studies is given in Fig. 2.

Finally, it should be noted that the concepts identified in case studies primarily reflect the experiences of Turkish contractors in international markets. The risk events and vulnerabilities mentioned during interviews depend on the markets served by the Turkish contractors (mostly developing countries and oil-rich countries such as Libya and the United Arab Emirates) and the perspective, culture, and capabilities of projects frequently carried out by the Turkish contractors abroad. However, it is believed that the structure given in Fig. 1 is applicable for all contractors, regardless of the country of origin. The level of vulnerability may be different among contractors from different parts of the world and the magnitude of risk may differ from project to project, but the components and attributes of risk and vulnerability concepts are similar for all countries.

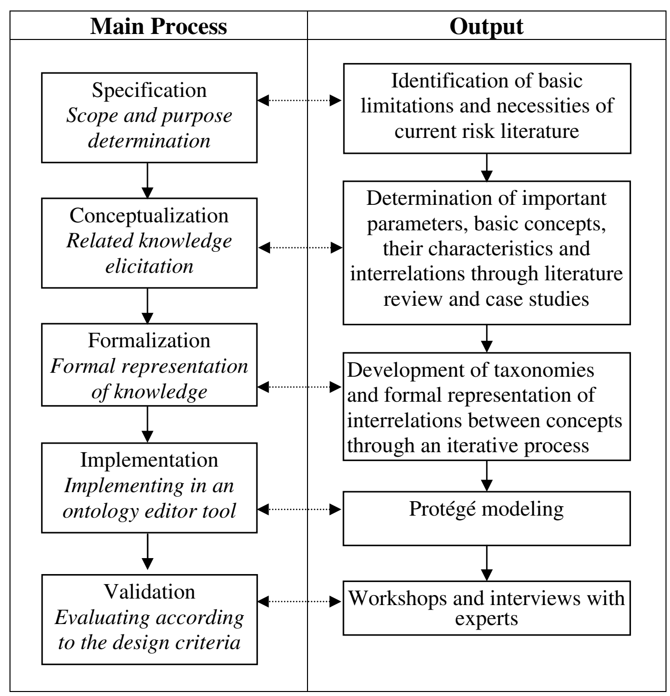

Fig. 3. Ontology development process

Ontology Development

Ontology development included five main stages: specification (determination of the scope), conceptualization (the collection and organization of the relevant domain concepts to be included in the ontology), formalization (the representation of knowledge in a formal way), implementation (converting the formalized knowledge into a machine-comprehensible ontology language), and evaluation (validating the completeness and the generality of the ontology) (Fernandez-Lopez et al. 1997). Fig. 3 demonstrates the ontology development process and supporting activities of each step. An iterative development process and interviews with domain experts are preferred in this study, as suggested by various researchers (e.g., Gruber 1993; McCray and Bodenreider 2002).

The specification step was carried out by elicitation of risk-related knowledge by a detailed literature review and interviews carried out with domain experts. Referring to the findings of the literature survey, an initial model was developed that included 250 concepts, 170 and 80 of which were related with vulnerability and risk, respectively. An interview form that includes these concepts and their interrelations was designed and interviews were conducted with experts about the validity of the concepts. The experts were requested to comment on the comprehensiveness of the list of concepts and the correctness of the relationships. They were also asked to provide project data to capture the risk event histories of the projects. Three of the domain experts were interviewed during the initial case studies, and the remaining experts are from the industry. All have managerial positions in international construction companies. In the light of expert suggestions, some of the parameters were rephrased and grouped. For example, factors such as inflation rate, tax rate, and exchange rate in the country were found to be important for characterizing the economic conditions of the country during the literature survey. During the interviews, it was realized that the specific values of these rates are important for cost estimation. However, for estimating cost overrun, the stability of those rates is more important than their specific values. Therefore, those parameters were grouped under the same heading of "stability of economic conditions." The final version of the model contains 150 concepts related with risk and vulnerability.

In the conceptualization stage, to obtain a more structured organization of the collected data, concepts (classes) were organized into a superclass-subclass hierarchy, which is also known as a taxonomy. The taxonomy helps to bring substantial order to the elements in a model, presents a categorization of the elements for human interpretation, and helps in the reuse and integration of tasks (Welty and Guarino 2001). Noy (1997) considers this stage one of the most difficult activities in ontology design because it involves not only a subjective representation of the world but also a representation of how people see this world and how they categorize things in their minds.

In the formalization stage, an iterative development process was used to produce a mature ontology suitable for real world implementation. A semicomputable absolute representation of the ontology was obtained by illustrating the concepts, their attributes, the restrictions of these attributes, and the interrelations among the concepts. The formalized knowledge was converted into Protégé frame-based representation, which is an ontology development tool from Stanford University. Protégé permits integration of (1) the modeling of ontology of classes describing a particular subject, (2) the creation of a knowledge-acquisition tool for collecting knowledge, (3) the entering of specific instances of data and creation of a knowledge base, and (4) the execution of applications. The most significant advantage of the Protégé is that its knowledge model also facilitates conformance to the Open Knowledge Base Connectivity (OKBC) protocol for accessing knowledge bases stored in knowledge representation systems (Stanford Center for Biomedical Informatics Research 2008). During the implementation process, classes (identified concepts), their slots (defined attributes of concepts), the facets (restrictions of the attributes), instances (the actual data in the system), and relations among classes were entered into the software.

Finally, in the validation stage, the completeness, generality, and effectiveness of the developed ontology were tested. These metrics were examined through interactive workshops and interviews with domain experts.

In the remaining parts of this paper, the risk- and vulnerability-related concepts, attributes, and relations will be explained along with the results of the validation process.

Risk-Related Concepts in the Ontology

Risk is accepted as an event that may cause deviation from predefined objectives (PMBoK 2000). Because of its vital role in understanding the underlying reasons of cost overruns, the identification of risks involves the identification of risk paths from their source to an event rather than particular risk items in the ontology. Risk factors are categorized according to their places within the risk paths, such as risk sources, risk events, or risk consequences. If a factor has the potential to cause a risk event or problem, it is identified as a risk source. If it is the result of a risk event, it is a risk consequence. Fig. 4 shows the main taxonomy of the risk-related topics.

Risk Source

Risk source is defined as something that has a potential to cause harm to a project (Standards Australia 2004) either owing to an adverse change from initial project conditions or an unexpected situation. Several research projects have focused on the identification of the causes and sources of risks. The risk sources given in the taxonomy of risk-related topics were identified in previous studies (such as Al-Bahar and Crandall 1990; Han and Diekmann 2001; Chapman 2001; Baloia and Price 2003; Chua et al. 2003; Hastak and Shaked 2000) that focus on the causes and sources of risks in international construction projects and the factors identified through analysis of constructed case studies.

Considering their origins, the risk sources are investigated under two headings within the ontology: adverse change and unexpected situation.

Adverse Change: Adverse change implies an unfavorable variation from the initial conditions of the project, such as an adverse change in performance or a client's attitude. Changes occur because of high level of vagueness or weaknesses in projects (vulnerability sources) and lead to risk events. For example, a vagueness in client objectives (vulnerability) may cause an unfavorable change in the scope of a project (risk source) and result in additional work (risk event).

The adverse changes that occur during the progress of a project are characterized by magnitude, manageability level, impact level, name, and description in the ontology. Fig. 5 shows all defined attributes and the restrictions of these attributes for the adverse change concept in addition to the sources and the possible values of these attributes. As given in Fig. 5, impact level, magnitude of change, and manageability level attributes are allowed to take values from a set containing zero, very low, low, medium, high, and very high. Magnitude of change implies the degree of the variation from the initial conditions. The change occurs because of vagueness in the project, so the magnitude of this change is influenced by the degree of the vagueness in the project. Manageability level of an adverse change is to demonstrate the capability of the project system to resist this change; therefore, the value of this attribute can be decided based on the characteristics of the project system, or, in other words, by vulnerability. The impact level attribute shows the effect of an adverse change on the occurrence of a risk event.

To illustrate the adverse change concept and its attributes, the verbal analysis of a phenomenon taken from one of the conducted case studies (a process plant project constructed in Jordan) is as follows:

"In the project, the Turkish contractor was responsible for the construction whereas the design was under the responsibility of the Canadian partner. Individual companies, both Turkish and Canadian contractors, are well-known companies with an extensive experience in the field. However, owing to their unfamiliarity with the Engineering, Procurement and Construction (EPC) project delivery system and the vagueness in the responsibilities of the companies (there was no contract clause about responsibilities related with procurement), the performance of both parties was much worse than expected and the original schedule of the project was revised many times. Changes in the original plan led to delay in progress payments."

In this example, the changes in performance of the contractor and designer and change in the original schedule are instances of the adverse change class in the ontology because these items

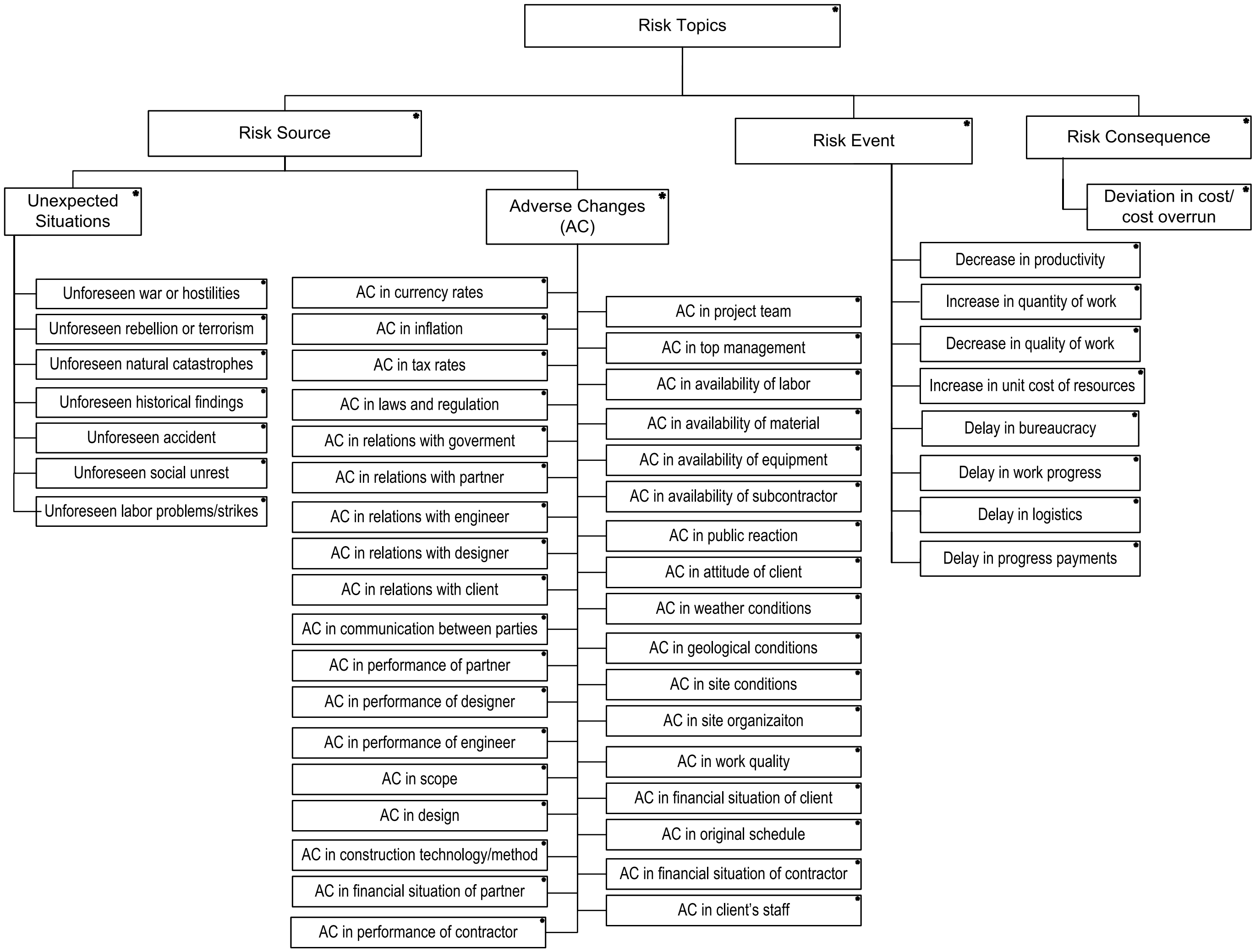

Fig. 4. Taxonomy of risk-related topics

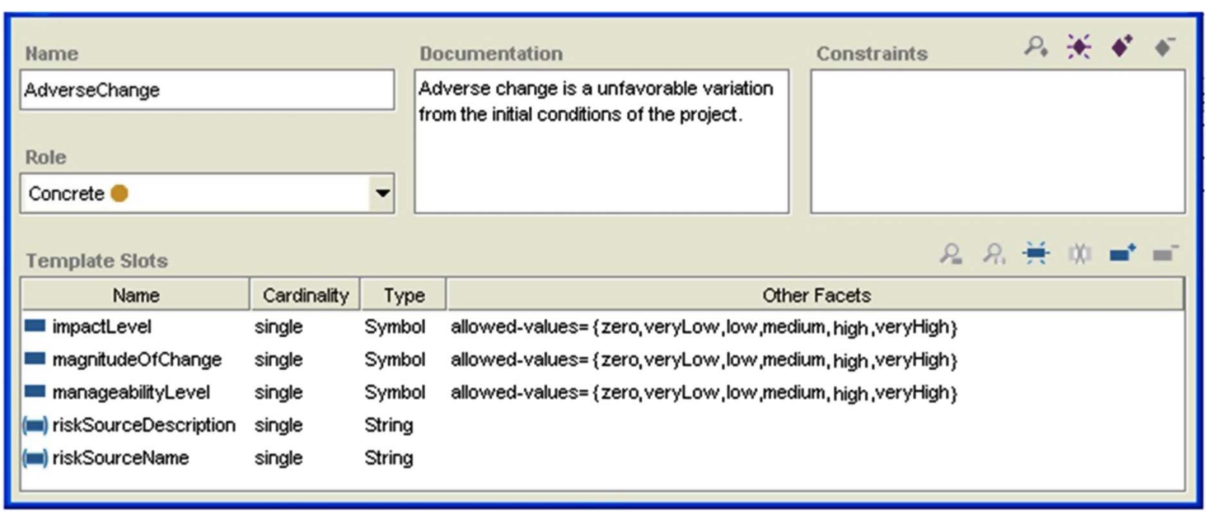

Fig. 5. Attributes of adverse change concept from Protégé user interface

refer to an unfavorable change from initial project conditions. Also, the changes have a name, a description, a magnitude level, an impact level, and a manageability level. The levels and description of the items are decided by the expert/project manager.

Unexpected Situation: The second category of unexpected situations regards unforeseen events and cause problems in a project, such as *force majeure* events and accidents. Unexpected situations differ from adverse changes in that an unexpected situation will

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either occur or not; it does not have a level of occurrence/magnitude or a manageability level. Therefore, an unexpected event is characterized with the attributes of name, description, state (to specify whether it has occurred or not), and level of impact in the ontology. State deals with whether the unexpected situation has occurred and level of impact indicates the impact of the situation on the project. Whereas state, level of impact, and definition attributes are specified by the contractor or the ontology user, the name of the unexpected situation will be any of the seven parameters given in the risk-related concepts taxonomy under the unexpected situations category given in Fig. 4. The other difference between this concept and the adverse change concept is that no factor influences the occurrence of an unexpected situation, but as for the adverse change concept, the occurrence of an unforeseen situation generates a risk event.

Risk Event

A risk event is the occurrence of a negative happening (Standards Australia 2004). Risk events mainly include variations and delays. As recommended by Al-Bahar and Crandall (1990), items related to productivity, performance, quality, and project economy are included under this concept. Risk events are mainly about variations (decreases or increases) in productivity or quantity of work and variations in schedule, such as delays in logistics or progress payments. Risk events occur because of a risk source and lead to a risk consequence.

The attributes of this concept include magnitude of event, impact level of event, description, and name. Information about the magnitude of events (magnitude of variation/delay) and their impact level on risk consequences is defined to represent the causal relation between risk sources, events, and consequences. The identified risk events in the case studies include additional work, delay in payments, and increase in unit prices. which correspond to increase in the quantity of work, delay in progress payments, and increase in unit cost of resources, respectively. Magnitude and impact level attributes take values from the set that contains the values zero, low, very low, medium, high, and very high. Zero means that the risk event did not occur, and the other values represent the magnitude of the risk events.

Risk Consequence

Risk consequence describes the outcome of a risk event that causes deviation in project objectives. It is clear that the contents of this category can be determined according to the project objectives, such as duration, cost, quality, and safety (Tah and Carr 2000; Al-Bahar and Crandall 1990). However, in this study, risk consequence is defined as the deviation in cost. The multiagent system that will be developed in the forthcoming steps of this study will simulate only cost sharing between the project parties. Thus, the effects of risks on project duration, quality, and safety are ignored. Risk consequence can be characterized by the magnitude of cost overrun, or, in other words, by the change in project cost. Description and percentage of increase are the defined attributes of this class, and the values of these attributes are decided by the user.

Vulnerability Related Concepts in the Ontology

In spite of the fact that all companies and projects are exposed to risk, some characteristics of firms and projects will influence the impact of risk in the event of its occurrence (Khattab et al. 2007). The term "vulnerability" is used to explain inborn characteristics of a system that exist within systems independently of external hazards and depend on an organization's capability to manage risks. Similar to risk-related concepts, all vulnerability parameters are gathered by investigation of real cases in addition to literature findings. As Twigg (2001) mentioned, in order to understand the factors that increase a system's vulnerability, one should diverge from the risk event itself and consider a set of influences. For international construction projects the factors related with the contract, company, project and project participants come together to create these influencing factors. In this research, the identified vulnerability sources within a project system are categorized considering their places within a risk path as follows: robustness sources, resilience sources and sensitivity sources. The taxonomy of the vulnerability related topics included in the ontology are given in Fig. 6.

Robustness Source

Sources of robustness are the factors that indicate the "weaknesses" within a project system that affect probability of occurrence of risks. The sources of robustness are grouped under four categories: contractor, country, parties, and project. Contractor-related issues mainly include the weaknesses attributable to lack of company resources, company experience, or managerial ability. Country parameters are about vulnerabilities attributable to the economic, political, social, legal, and market conditions of the country. As discussed by Han et al. (2007), many risks of international construction projects are closely related with fairness of construction laws, regulations of the host country, local material supplies, cultural issues, and the attitude of government. Key project participants include clients, partners, subcontractors, suppliers, designers, and engineers. As Chan et al. (2004) state, "a construction project requires team spirit; therefore team building is important among different parties." Thus, the abilities, workload, and financial strength of each party and the relations between these parties will influence the occurrence of an adverse change in the project. Robustness in project conditions also stem from the inadequate design, construction, contract, managerial requirements and external conditions of a project. The robustness level of the project system in terms of these parameters determines whether the project is more or less vulnerable or insecure to the occurrence of adverse changes.

To characterize robustness sources within a project, the attributes of name, description, priority level, and magnitude level are defined in the ontology. All these attributes indicate project-specific characteristics, except priority. Priority indicates the potential of vulnerabilities to create risks, and it is assessed by considering the general international construction environment. The information related to priority levels of robustness parameters will be collected through a questionnaire in further stages of this study. Priority information will be used not only for the calculation of vulnerability level in a project but also to normalize the collected information from the contractors. Level of priority and magnitude attributes of robustness source class can take values from a range containing values from very low to very high.

To illustrate the robustness concept, an example from conducted case studies (the residential construction in Dubai) is as follows:

"In the project, although there were several types of buildings that require individual design, there were no contract clause/specifications mentioning the order of the construction of the buildings. Besides the contractor did not inform the designer about the required order of the design that could minimize the idle time owing to changing the position of tower cranes. As a result, the designer submitted the designs in such a order that the contractor had to change the location of tower cranes frequently, which means lots of idle time and unexpected delays." In this case, the sources of robustness are vagueness of contract clauses and poor planning of the contractor.

Resilience Source

Sources of resilience are the factors that affect manageability of risk. For instance, changes in construction technology may lead to a less significant risk event if the company has the necessary

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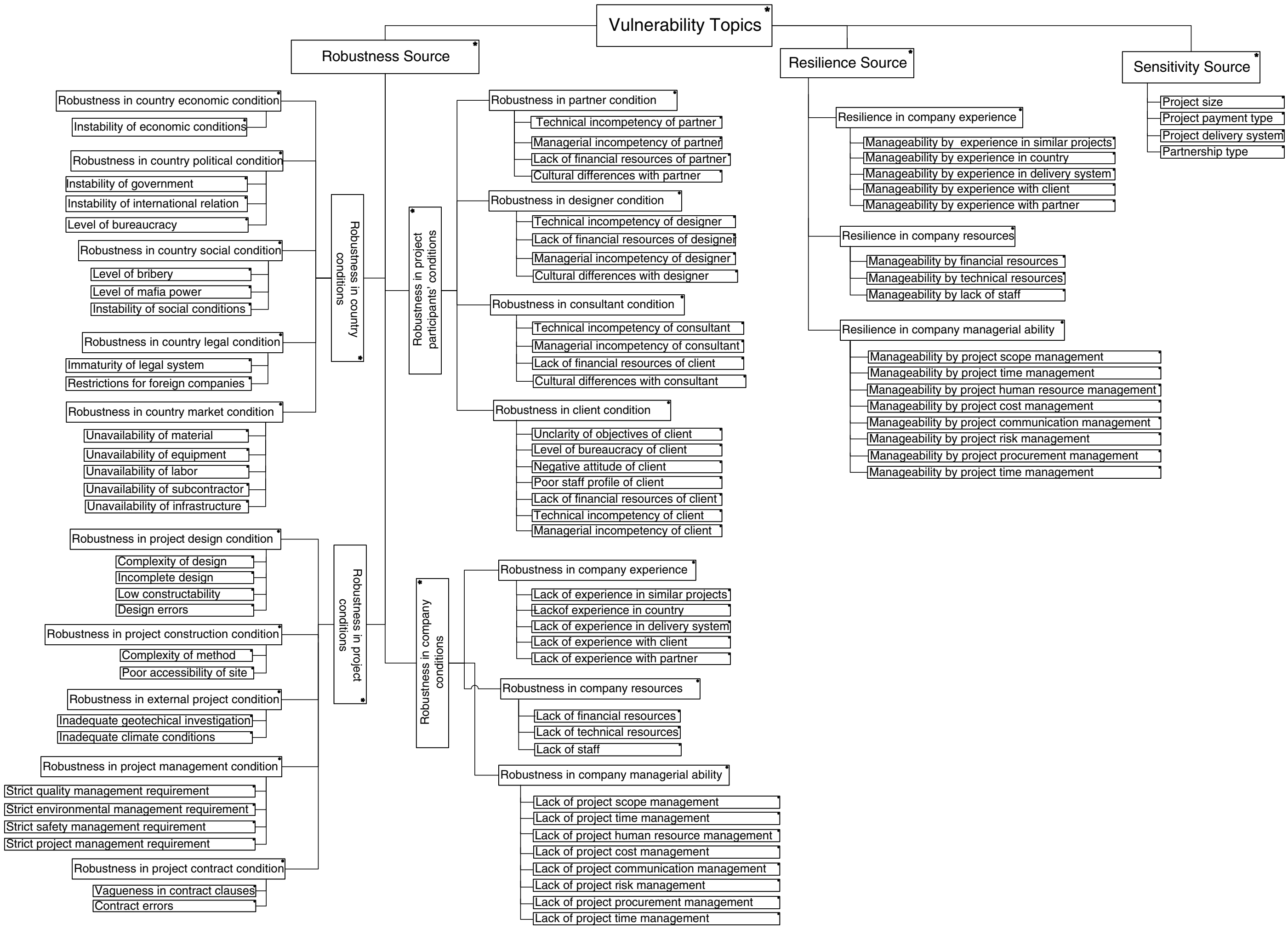

Fig. 6. Taxonomy of vulnerability-related topics

know-how about the new technology and an adequate change management system.

Resilience directly influences the manageability level of an adverse change. Like the source of robustness, resilience source also has a magnitude that indicates the capacity of the company (in terms of experience, resources, and managerial abilities) to cope with the changes. The magnitude of a resilience source should be determined by the system user, and it can take any value within the range from very low to very high.

Sensitivity Source

Sources of sensitivity are the factors that influence the impact of risk events on cost. In other words, they are the factors that affect the magnitude of risk consequences. For instance, if there is an increase in the quantity of work owing to change in scope, the implications for the contractor in terms of price are different depending on whether the contract payment type is by unit price or lump sum. Sensitivity factors include several project-related parameters such as project delivery system and payment type.

The attributes of these factors include name, description, and magnitude. Whereas name can be any parameter given in the vulnerability taxonomy (Fig. 6), description and the value of magnitude attributes are determined by the expert or the system user. As for all other concepts, the magnitude attribute can be very low, low, medium, high, or very high.

Relationships among Classes

In the previous section, while defining each concept, the relations between the concepts were also mentioned. Case studies play a vital role in the identification of these relationships because there is no analogous study that focuses on the details of integration of vulnerability and risk in the literature.

Four main relations are distinguished among the concepts in the ontological model: association relationships (e.g., a project has zero or more risk and vulnerability sources), navigable association relationships (e.g., robustness source influences the risk source, and risk source causes risk event), aggregation relationships (e.g., risk is composed of source, event, and consequence), and inheritance relationships (e.g., robustness source, resilience source, and sensitivity source are the child classes of vulnerability source class).

Fig. 7 shows the class diagram for the graphical notion of these relations in the risk and vulnerability ontology. The class diagram gives an absolute representation of the ontology by illustrating the concepts, their attributes, the restrictions of these attributes, and interrelations among the concepts.

The causal relations (Fig. 7) between vulnerability and risk that lead to cost overrun can be summarized as follows:

Every project inevitably has certain risks and vulnerability sources. Robustness source, resilience source and sensitivity source concepts are the child classes of these vulnerability sources.

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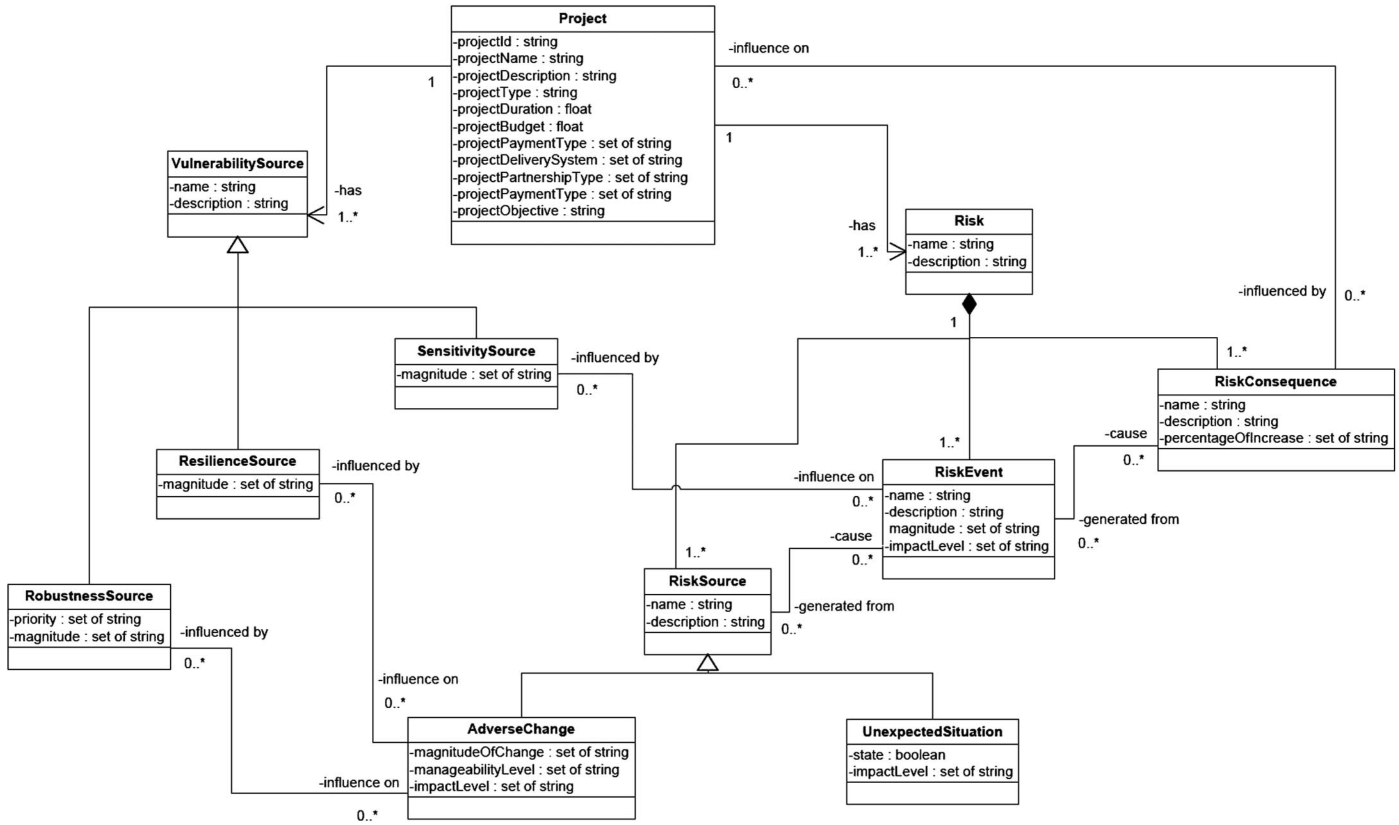

Fig. 7. Data model for the risk and vulnerability ontology

Robustness source (indicating weaknesses that exist within the project) influences the occurrence of adverse changes in the project. The magnitude of robustness sources influences the magnitude of adverse changes. Adverse change and unexpected situations are the child classes of the risk source. Both adverse changes and unexpected situations lead to risk events in a project. However, the strength of the causal relation between adverse change and risk event is influenced by the resilience parameters of the project. Resilience source influences the manageability level of the adverse change, and thus the impact level of the adverse change on a risk event varies with respect to level of manageability. Risk events lead to risk consequence, which is cost overrun. However, because the sensitivity sources influence the impact level of a risk event, the magnitude of risk event does not directly affect the magnitude of risk consequence. Risk consequence indicates a deviation from original cost of a project. Therefore, it is accepted to influence the project.

It should be noted that all factors under a specific category are not necessarily affected by all factors given under the preceding category. For example, all of the factors under "adverse change" are not influenced by all "robustness source" parameters. There are individual relations among the factors that lead to a number of risk-vulnerability paths, some of which coincide whereas others are completely independent.

Validation

This study aims to develop an ontology for relating risk and vulnerability to cost overrun. The quality attributes of the ontology are defined as generality, completeness, and effectiveness. Ontology can be considered complete if it covers all necessary attributes to relate risk and vulnerability with cost overrun. It can be accepted as general if it has the ability to represent a variety of cases (Staub-French et al. 2003; El-Diraby et al. 2005). Effectiveness of the ontology is ensured if it is capable of helping estimators to generate realistic estimates with high degree of confidence. Table 1 summarizes the quality attributes and their metrics used during the validation process.

Validation Method

To assess whether the ontology complies with the predefined quality attributes, an interactive workshop and interviews with industry practitioners were performed.

Interactive Workshop

An interactive workshop was conducted with six domain experts, each having at least five years of experience in cost estimation of international construction projects. The background information about the experts is given in Table 2.

At the start of the workshop, each expert was given necessary information about a real international construction project. The general information about the projects included the role of the company in the project, country name, project type, estimated budget, duration, payment type, and project delivery system. The projects were selected so that different project types and countries having different risk and vulnerability levels could be considered during the workshop. After the experts studied their individual cases, a questionnaire including 14 questions was administered to them. To answer the questions, the experts had to follow a three step process, which is summarized as follows:

1. The experts were requested to specify the information about the project that would be required to estimate cost overrun (e.g., does the company have enough staff? How is the relation between contractor and client?). This step was important for assessing completeness of the ontology. Because the

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Table 1. Metrics for Ontology Validation

Question	Attribute	Metric
Does the ontology cover all attributes that are necessary to relate risk and vulnerability with cost overrun?	Completeness	Number of concepts/attributes identified by the experts that are not within the ontology Subjective rating of experts about "completeness of the ontology"
Does the ontology improve the cost overrun estimation process?	Effectiveness	Comparative error in cost overrun estimates (with and without ontology) Subjective rating about level of confidence in cost overrun estimates (with and without ontology) Number of critical attributes considered during cost overrun estimation (with and without ontology)
Does the ontology have the ability to represent a variety of cases?	Generality	Number of cases that can be represented by the ontology with respect to different project size, types, delivery systems, countries, contract types, payment types, and different company roles

Table 2. Background of Experts

Expert	Level of experience (years)	Position
A	5	Cost engineer
B	15	Construction management consultant
C	19	Cost engineer
D	6	Cost engineer
E	9	Cost engineer
F	15	Risk management consultant

metric of completeness is defined as the number of factors that are found important by the experts but not included within the ontology, information about potential missing attributes was sought. After the experts were provided with the additional information they requested, they were asked to identify the possible risk events of the given project. The answers of the experts to this question were critical for checking the completeness of the risk-related attributes in the ontology. Finally, experts were asked to estimate the cost overrun in the project by using any method they suggested or using their expert judgment only, without utilizing any methods. Also, they were asked about their level of confidence in these estimates.

2. The ontology, including all of its parameters and their interrelations, was given to the experts. The main concepts related with risk and vulnerability and possible interrelations among the concepts were explained. In addition to the general information about their projects, in this case, the magnitudes of all robustness sources that describe the initial conditions of the project were also provided to each expert. They were again asked to estimate cost overrun, but this time by considering the ontological relations and the parameters given in the ontology. They were also asked to indicate their level of confidence in these estimates. Because the projects were already completed and actual cost overrun values were known, the errors in cost overrun percentages estimated when using and not using the ontology were calculated. The comparative error and confidence levels as stated by the respondents were intended to check the effectiveness of the ontology.
3. In the last step, as they got familiar with the ontology, the experts were asked about potential improvements to the developed ontology. They were asked how familiar they were with the terms used in the ontology, whether the used terminology was appropriate or not, and whether the ontology covered the main domains of construction management for cost overrun estimation. Finally, they were asked to specify whether there were any items that were not covered by the ontology. The answers to these questions were intended to assess completeness.

Interviews with Industry Practitioners

Interviews with 25 industry practitioners from 18 different construction companies were conducted. Interviews were intended to test whether the information about completed projects having different characteristics, such as project type, country, project delivery system, contract, and payment type, could be represented by the ontology. The variety of the cases that could be represented by the ontology would be used as an indicator of its generality. Using the ontology, practitioners were asked to indicate the magnitude of risk and vulnerability associated with the already completed projects and state the actual cost overrun percentages. Moreover, practitioners were asked to denote additional factors that could be included in the ontology.

Validation Results

Table 3 shows the results of the interactive workshop. In Table 3, actual cost overrun percentages and the number of critical factors that led to cost overrun in the already completed projects are presented. Actual cost overrun percentage is calculated by dividing the difference between the actual cost and the estimated budget by the estimated budget. None of the experts preferred to use a "method," but they used their intuition and judgment to estimate cost overrun. The average absolute error with respect to actual values is around 20% without using the ontology, whereas it is 14% when the ontology is used. The average level of confidence of the experts about their estimates also increases to 3.7 from 2.7 when they use the ontological representation. Moreover, the average number of critical factors that were considered by the experts during cost overrun estimation was 16 and 10 with and without using ontology, respectively. These results demonstrate that the ontology helps users to make better predictions, consider a higher number of factors that may lead to cost overrun, and increase their confidence in estimates, which points out the effectiveness of the ontology. However, it is important to note that the ontology in its current form is not expected to be used for cost overrun estimation; rather, it will constitute the basis of a case-based reasoning prediction model. The most significant indicators of its effectiveness are believed to be metrics related to improvement in the cost overrun estimation process (particularly, a higher number of factors that can be considered during cost overrun estimation and increased confidence of estimators) rather than the accuracy of estimates.

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Table 3. Summary of the Workshop Findings

Cases	Actual Values	Without using the ontology			Using the ontology		
	Cost overrun (%)	CI	Cost overrun estimate (%)	LoC	CI	Cost overrun estimate (%)	LoC
Case 1	50	14	23	3	20	29	4
Case 2	25	9	14	3	12	21	4
Case 3	10	6	15	2	7	10	3
Case 4	30	9	14	3	14	24	4
Case 5	75	12	45	3	29	45	3
Case 6	65	8	35	2	15	45	4

Note: CI indicates the number of critical factors that are considered while estimating cost overrun, whereas LoC indicates the level of confidence of the experts about their estimates using a Likert scale of 1 (very low) to 5 (very high).

The experts who participated in the workshop indicated that the terminology used in the ontology is appropriate and that the ontology is complete enough to relate risk and vulnerability with cost overrun (with an average rating of 4.7 out of 5). During the cost estimation exercise that did not use the ontology, none of the experts required information about factors that are not included in the ontology. Although there were some differences in expression of similar factors with respect to those given in the ontology, they did not spell out any extra risks, vulnerabilities, or project characteristics that could lead to cost overrun. These findings demonstrate the completeness of the ontology.

During the interviews, 25 industry practitioners confirmed that the ontological concepts are appropriate to reflect the risk event histories of their projects. In total, 75 different international projects performed in 18 different countries were examined and used to question whether the ontology can capture different conditions regarding different projects. Project budgets had a wide range from US$4 million to US$300 million, and durations varied from 12 months to 96 months. The projects were completed with different cost overrun percentages ranging from 0 to 200%. Detailed information about the tested 75 projects is given in Table 4. The successful representation of 75 projects with diverse characteristics indicated that the ontology has the ability to capture risk and vulnerability parameters embedded in different kinds of projects for cost overrun estimation. The collected 75 projects will also be used in the development of the case-based reasoning model for cost estimation in further stages of this study. Table 5 summarizes the major findings of the validation process.

Although the validity of the ontology was confirmed with respect to the metrics of effectiveness, completeness, and generality, the following issues were revealed during the validation process:

- There were no experts/practitioners who totally disagreed with the ontological concepts, relations, or attributes, and there were no additional items suggested for inclusion in the ontology. However, it was observed that some experts used different expressions for the concepts included in the ontology. The comparison of the expressions of the experts with the ontological representation is given in Table 6. Some experts preferred to use a more specific, more general, or different representations compared with the ontology.
- A small number of experts evaluated some concepts as irrelevant to the domain. Experts who had limited experience regarding particular project types and who were unfamiliar with some risk and vulnerability factors mentioned that some concepts could be eliminated. However, as the majority of the experts considered them relevant and provided real evidence from their own projects, it is believed that they should not be eliminated. Historical finding supports such instances.

Finally, the evaluation process that aimed to validate the content of the ontology from the viewpoint of the experts showed that the ontology can capture all significant issues related to risk, vulnerability, and cost overrun. It improves the cost overrun estimation process and the confidence level of the estimator. In spite of different preferences of the experts on particular items existing in the

Table 4. Characteristics of the Projects Identified during Interviews

Feature	Category	Number of Projects
Project type	Building (shopping mall, hospital, etc.)	13
	Coastal structure (harbor, breakwater, etc.)	3
	Dam	7
	Energy (nuclear or hydroelectric plant, etc.)	4
	Housing	3
	Industrial plant (chemical plant, refinery, factory, etc.)	12
	Infrastructure	9
	Pipeline (petroleum or natural gas)	3
	Transportation	14
	Other	7
Contract type	FIDIC	37
	Local contract	38
Project delivery system	Turnkey	45
	Traditional (design bid build)	21
	Engineering, procurement, construction (EPC)	3
	Build operate transfer (BOT)	6
Payment type	Cost plus fee	5
	Lump sum	34
	Unit price	32
	Combination of lump sum and unit price	4
Company role in the project	Member of a consortium	12
	Member of a joint venture	14
	Sole contractor	40
	Subcontractor	9
Country	Asia	35
	Africa	19
	Europe	21
Project size	Smaller than US$100 million	43
	Greater than US$100 million	32
Actual cost overrun	Smaller than 50%	60
	Between 50 and 100%	11
	Greater than 100%	4

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Table 5. Outputs of Validation Process

Metric	Formulation	Value
Number of parameters/attributes identified by experts that are not within the ontology	Number	0
Average subjective rating of experts about completeness of the model	$\text{Rating} = \sum(\text{Expert Rating})/\text{Number of experts}$	4.7
Average absolute error in cost overrun estimates (with and without ontology)	$\text{Error} = \sum \lvert\text{actual cost overrun\%-estimated cost overrun\%}\rvert/\text{Number of experts}$	20% (without ontology), 14% (with ontology)
Average subjective rating of level of confidence in cost overrun estimates (with and without ontology)	$\text{Rating} = \sum(\text{Expert Rating})/\text{Number of experts}$	2.7 (without ontology), 3.7 (with ontology)
Average number of critical factors (CI) considered during cost overrun estimation (with and without ontology)	$\text{Average} = \sum(\text{CI})/\text{Number of experts}$	10 (without ontology), 16 (with ontology)
Range of project size that can be represented	USD	4–300 million
Number of countries that can be represented	number	18
Number of different project types that can be represented	number	> 9
Number of different contract type that can be represented	number	2
Number of different project delivery system type that can be represented	number	4
Number of different payment type that can be represented	number	4
Number of different company roles that can be represented	number	4

Table 6. Differences among Expressions Used by Experts and Ontological Representations

		Examples	
Category	Description	Expert	Ontology
Similar concept but different wording	Expert prefers a different wording/expression to define the classes, subclasses, or interrelations	Embargo	Restrictions for foreign companies
Specific representation	Expert prefers a more specific expression to define the classes, subclasses, or interrelations	Differences between partner and contractor with respect to organizational culture	Cultural differences between partner and contractor
General representation	Expert prefers a more general expression to define the classes, subclasses, or interrelations	Experience of the company	Company experience in similar projects, company experience in the same country, company experience with respect to the project deliver system

ontology, there was no case that the ontology was insufficient to represent. The majority of the experts confirmed the completeness and effectiveness of the system. As a result, the ontology can be accepted to be fairly effective in relating necessary risk and vulnerability factors to cost overrun, and it can be used for both risk path analysis and cost overrun estimation for international construction projects. The fact that validation results reflect the perception of Turkish contractors only may be a shortcoming that limits the generality of the ontology. However, it is believed that although magnitude of risk and vulnerability may be perceived differently depending on the risk attitude of a decision-maker, which may also be related to his or her nationality, the attributes of risk and vulnerability are similar for all countries, and the ontology can be accepted as general enough to relate the attributes of risk and vulnerability with cost overrun regardless of risk attitude and perception. It is also worth mentioning that the projects mentioned during the interviews reflect mainly the emerging markets served by the Turkish contractors. Although it is believed that the range of countries considered during the validation phase is representative of the global construction activity, it would be better if the generality of the ontology could be tested by considering a higher number of countries, including the developed countries served by international contractors.

Conclusion

This paper demonstrates a formal ontology for relating risk and vulnerability to cost overrun. The ontology has three main usages. (1) It provides a common vocabulary that forms the main framework of an information model for risk assessment in international projects. Such a common vocabulary upholds the focus on the most important concepts of risk and vulnerability domain related with cost overrun. (2) It shapes the basic structure of a risk event history database. It proposes a complete glossary of notions with their interrelations that should be included in the database. (3) It outlines the integrated risk and vulnerability assessment method to be used for cost overrun estimation in international construction projects.

The major shortcoming of the study is that the concepts that appear in case studies primarily reflect the experiences of Turkish contractors in international markets. However, validation tests provide evidence that although the level of vulnerability may be

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different among contractors from different parts of the world and magnitude of risk may differ from project to project, the components and attributes of risk and vulnerability are believed to be generic enough to make the ontology applicable for all contractors, regardless of the country of origin.

The scope of the ontology is limited to cost overrun estimation. Other possible project objectives (such as quality, duration, and client satisfaction) are not included in the system. The validation tests were conducted for the verification of risk and vulnerability knowledge and the interrelation among these concepts only by considering the cost overrun percentage as the outcome.

The ontology presented in this paper is the first step of an ongoing research project that aims to develop a database to represent risk event history regarding international construction projects and a multiagent risk modeling platform. Post-project information regarding various international projects is being collected via the ontological model, obtained knowledge is stored in the ontology-based database structure, and projects in the database will be used to predict cost overruns and possible risk paths in forthcoming projects by case-based reasoning. The outcome of the prediction model will be the basic input of a multiagent system that will be used to decide on sharing of risks by referring to sources of risk, contract clauses, and the short- and long-term objectives of parties in a given project. Validation tests also provide evidence that the ontology successfully relates risk and vulnerability with cost overrun. The ontology is fairly complete, general, and effective in capturing risk event histories to be used for the prediction of cost overrun.

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