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EVOLUTION AND APPLICATION OF COST AND SCHEDULE RISK MANAGEMENT ON COMPLEX PROJECTS

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Design and construction of projects is complex endeavor that requires the coordination of a multitude of human, physical, and natural resources. The technical design and construction complexities are frequently outweighed by the uncertainties and risks with the social, financial, and political aspects of the projects. To address these risks and uncertainties, project participants have turned to a series of cost and schedule risk management tools over the past 50 years. This paper summarizes the evolution of probabilistic cost estimating and scheduling tools. It also provides examples of applications on complex projects from the US Department of Energy, the US Federal Highway Administration/Washington State Department of Transportation, the Panama Canal Authority, and the international ITER fusion generator. The paper concludes with a discussion of the remaining cost and schedule risk management challenges, which inhibit project participants from achieving their project performance goals.

Keywords: Project management, Cost estimating, Scheduling, Uncertainty.

1 INTRODUCTION

Large design and construction projects are complex and fraught with uncertainty. Project engineering and design can require thousands of planners, engineers, and architects to work in rapid coordination. Project construction can require a multitude of human, mechanical, and natural resources to physically build the project. Project time constraints can cause aggressive overlapping of design and construction, which can add to project complexity because scope is uncertain and designs are incomplete when construction starts. Internal and external uncertainties and risks compound project complexity. In fact, social, political, and financial risks frequently impact project performance to a greater extent than physical project complexity. Risks and uncertainties have ultimately contributed to cost escalation and schedule delays for both public and private projects (Shane *et al*. 2009).

To cope with risk and uncertainty, project participants have progressively incorporated probabilistic cost and schedule risk management into project planning, design, and construction. This paper provides a brief history of the evolution of cost and schedule risk management techniques. It then discusses applications of these techniques on complex projects over the last 20 years. The paper concludes with a brief discussion of the challenges that inhibit project participants from fully employing probabilistic cost and schedule risk management techniques to improve project performance.

2 EVOLUTION OF COST AND SCHEDULE RISK MANAGEMENT

Methods and tools for assessing project risk and uncertainty have been available to our industry for more than 50 years. The program evaluation and review technique (PERT) was the first and best-known method of incorporating uncertainty into scheduling. It was developed by the US Navy in the 1950s and became more commonplace for research and development projects in the 1960s (Miller 1963, Clough and Sears 1991). The PERT technique is similar to critical path method (CPM) scheduling, but it allows for uncertainty in activities. Where CPM scheduling assumes an average duration for an activity, PERT requires three estimates of activity duration: optimistic, modal, and pessimistic. While the PERT method allows for a range of inputs, it provides what is essentially a deterministic estimate of the final schedule.

Throughout the 1970s as computing became more ubiquitous, researchers and large engineering and construction firms began to develop probabilistic methods for cost estimating (Spooner 1974). Diekmann (1983) describes the evolution of probabilistic cost estimating models. Due to the number of variables in the estimate for a large construction project, the transition from deterministic to probabilistic is not a simple one. Direct analytic techniques become too cumbersome. The use of Monte Carlo simulation is essential for the calculation of probabilistic estimating techniques. While these advances were helpful, there were still two major shortfalls. First, these techniques were primarily addressing uncertainty in base estimates. They did not address risks as events that may or may not occur. Second, these techniques were not yet integrating cost and schedule estimates.

The next significant advances in cost and schedule risk management did not stem from new estimating or schedule tools. Rather, the advancement of the risk management processes in the late 1980s and early 1990s drove the industry's appreciation for the difference between base uncertainty and risk events. The Construction Industry Institute and the Project Management Institute developed guidance on the risk management process through publications and training during this period (Construction Industry Institute 1998, Widemann 1992). The systematic identification and assessment of risks as events (i.e., an event that, if it occurs, has a negative impact on project goals), helped the industry to identify and quantify risks that can impact cost and schedule estimates.

The next round of significant advances in cost and schedule risk management were related to new computing tools. With the increase in computing power during the late 1990s and early 2000s, a number of software developers created systems that could apply Monte Carlo simulations to cost-loaded schedules. PERT estimates could be used to simulate base uncertainty and risk management techniques which led to risk event modeling. The ability to simulate cost and schedule in relatively simple tools has brought probabilistic cost and schedule risk management out of academia and into industry. PertMaster became the most widely used cost and schedule tool in the early 2000s. Its interface and simulation tool was similar to that of a CPM scheduling software (Patterson 2006). In 2006, Primavera bought PertMaster. Over the next few years, Primavera integrated PertMaster's features into the Primavera Risk module making Monte Carlo-based simulations of cost and schedule risk models available to all of its users in the last five years.

3 APPLICATIONS TO COMPLEX PROJECTS

To illustrate the evolution of cost and schedule risk management on complex projects, this section presents a series of project case studies. The first case study is from the United States (US) Department of Energy in the early 1990s. This case study illustrates the deterministic nature of cost risk management at that point in time and the challenges with integrating cost and schedule risk analysis. The next application is from the Federal Highway Administration and the Washington State Department of Transportation (WSDOT). This project illustrates an excellent application of integrated cost and schedule modeling that influenced highway agencies throughout the US. The third application is from the Panama Canal Expansion, which further integrated cost and schedule simulations with risk management. The final application is from the ITER fusion generator. It demonstrates that even with the cost and schedule risk management tools available today, project culture and standard industry processes can inhibit the use of probabilistic techniques.

3.1 US Department of Energy Hazardous Waste Remediation Projects (1990s)

As the US grew though the industrial revolution and into the 20th century, both the government and the private sector created hazardous waste that is detrimental to the health of its citizens. Cleanup of hazardous waste is a complex endeavor. Both the volume of waste and the effectiveness of the treatment technologies may contain a large amount of uncertainty. Risks can stem from changing governmental requirements, unforeseen stakeholder involvement, and many other events. Cost and schedule overruns were documented throughout the late 1980s and into the 1990s (Independent Project Analysis 1993, US GAO 1994). The Department of Energy invested in a number of retrospective research studies to determine how cost risk analysis could have helped combat cost and schedule overruns (Diekmann *et al*. 1994).

The Uranium Mill Tailings Remedial Action (UMTRA) project, located in Durango, Colorado, serves as exemplar of available risk management processes at that time (Diekmann *et al*. 1993). The UMTRA project consisted of the removal of contaminated residual radioactive materials from an abandoned uranium mill at a Durango processing site and disposal of these materials in an embankment with a protective cover. The initial cost estimate for this project was $14.5 million. During the restoration, however, unexpected difficulties resulted in a final cost of $27.3 million, an 88% increase.

The research team identified both internal and external risks on the projects. At the time of this research, software programs were not available to integrate cost and schedule risk models with Monte Carlo simulation. The research developed a novel modeling method that combined influence diagrams for risk mapping and decision trees for Monte Carlo simulation (Diekmann *et al*. 1996). Table 1 and Figure 1 show the basic approach.

Table 1. Example hazardous waste risks.

Internal	External
Mobilization	Regulatory Changes
Dewatering	Scope Changes
Erosion Protection	Community Involvement
Testing/Monitoring	Technology Failures

3.2 WSDOT State Road 167

Large transportation projects have historically experienced significant cost overruns from their conceptual planning estimates. Throughout the 1990s, WSDOT had mixed results with its deterministic cost and schedule estimating methods. In 2002, it took on a significant effort to develop a Cost Estimating Validation Process (CEVP) (Molenaar 2005). CEVP is an intense workshop process, somewhat resembling value engineering. A rigorous peer review and uncertainty analysis process is the foundation CEVP. Each project is examined by a multidisciplinary team of professionals from both the public and private sectors in the disciplines of engineering, construction, planning, and risk management. CEVP uses systematic project review and risk assessment methods, including statistics and probability theory, to evaluate the quality of the information at hand and to describe cost and schedule uncertainties. Figure 2 shows a probabilistic schedule output for the State Road 167 project with a 90% certain cost of $1.84B.

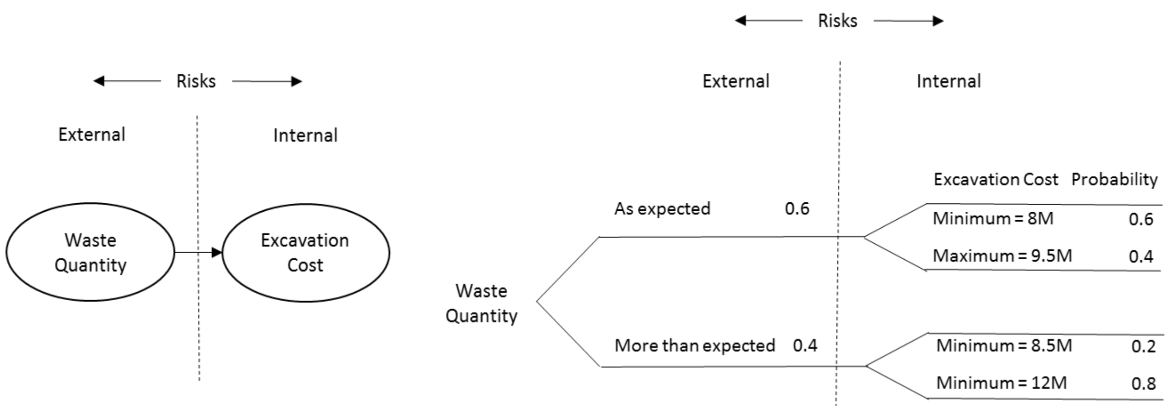

Figure 1. Influence diagram and probability tree.

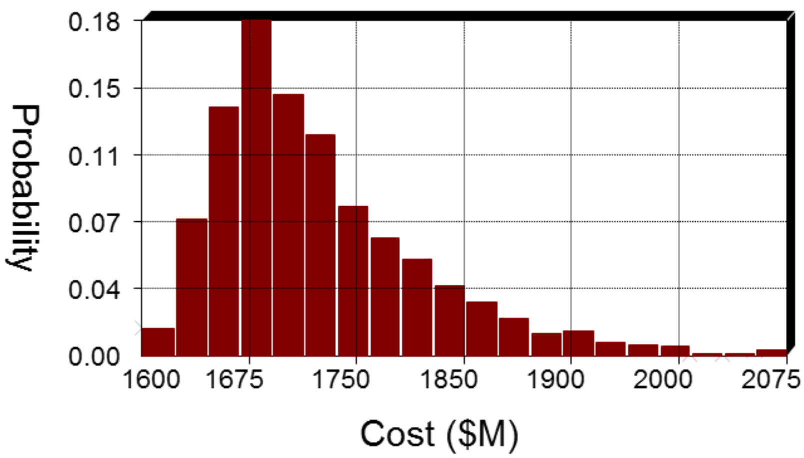

Figure 2. Probabilistic cost estimate for the WSDOT State Road 167 project.

As previously stated, the CEVP process advanced the state of practice by integrating cost and schedule risk. The CEVP process used the following steps to produce its results:

1. Identify and screen a comprehensive set of risk and opportunity events.
2. Assess the cost and schedule impacts for each event if it occurs.
3. Assess the probability of each event and its associated impacts occurring.
4. Combine base costs and risk costs into a final range estimate of project costs.
5. Conduct a sensitivity analysis to identify the most critical risks.

3.3 Panama Canal Expansion

The growth in global market demand led the Panama Canal Authority to prepare a formal proposal for expansion of the canal through the Third-Lane Locks and Access Channel Expansion Program (Canal Expansion Program). The Canal Authority wished to gain the support of the citizens for the project through a public referendum while the project was still in its early design stages. Noting the success of probabilistic estimating on other large infrastructure projects, and the CEVP process in particular, the Authority undertook a risk based cost and schedule estimating process to baseline the project for the referendum (Alarcón *et al*. 2011).

The Panama Canal Authority advanced the previous examples by creating an estimate that fully integrated into their project management system. At the front end of planning, they used the probabilistic estimate to determine when to acquire finances. At the tail end of planning and into early construction, they used it to determine when contingency could be spent or retired. A brief summary of their project risk management process is as follows:

- Identification: Pinpoints potential project risks and documents their characteristics. Risk identification is best done in a group setting with representation from all project disciplines.
- Analysis: Involves qualitative and quantitative methods to evaluate each of the identified risks. It includes risk rating and prioritization in which risk events are defined in terms of their probability of occurrence, severity of consequence/impact, risk modeling, and precedence analysis.
- Planning: Develops an organized, comprehensive, and interactive strategy and methods for tracking risk areas and developing risk management plans.
- Implementation: Executes the recommended risk management strategies and follows specific instructions on what should be done, when it should be accomplished, who is responsible, and what are the associated cost and schedule.
- Monitoring: Systematically tracks and evaluates the performance of risk managing actions against established metrics throughout the project and develops further options, as appropriate.
- Control: Performs continuous risk assessments to determine how risks change and assigns adequate resources.
- Documentation and communication: Records, maintains, and reports assessments, handles analysis and plans, and monitors results. It includes all plans and reports for the project management and decision authorities.

3.4 ITER Fusion Project

The ITER project will result in the first nuclear fusion facility at a reactor scale and will demonstrate the scientific and technical feasibility of fusion energy (https://www.iter.org/). The technical complexities and risks on this first-of-a-kind project are compounded by the multicultural nature of the seven Domestic Agencies (DAs) that are working together to bring it to a reality. The DAs include China, the European Union, India, Japan, Korea, Russia, and the US. Unfortunately, the project has suffered from years of project delays. In 2016, the ITER director general set the goal of fully implementing cost and schedule risk management to achieve its baseline goal of first plasma by 2025. At this time, many of the DAs were already doing risk management as part of their own management processes. In 2017, the ITER organization combined the separate DA risk management processes into one process with a single risk register.

At the time of writing this paper, the success of the cost and schedule risk management process in unknown. However, the project has found some significant difficulties in applying practices similar to that of WSDOT and the Panama Canal Authority. The challenge is not stemming from the complexity of the project as one might expect. The challenge is stemming from the DAs views on contingency and general project management practices. For example, the US team is carrying a contingency of ~40% that is based on the Monte Carlo simulation output of an integrated cost and schedule model and covers the entire time to first plasma. India is carrying a 3% contingency based on standard management practices. Russia funds the project on a year-to-year basis and does not include a stated contingency. In summary, the ITER project is actively identifying and managing individual risks, but the variance in project management approaches is prohibiting the project from taking full advantage of the integrated cost and schedule risk analysis.

4 CONCLUSIONS

The design and construction industry takes time to adopt new methods and tools. The fact that probabilistic scheduling and estimating has taken more than 50 years to advance from academic research to industry adoption is not too surprising. The most significant advances have come from two primary areas. The ever-increasing speed of computing provides for rapid simulations and elegant user interfaces. The second impetus of advancement is the initial adoption of standard risk management processes and a common industry vocabulary. Challenges remain in a number of areas. First, computing speed will not mitigate a lack of training in probability theory and project management techniques. In fact, computing speed and ease of interfaces can produce results that appear correct, but are fundamentally flawed if users do not have proper training. In addition, as demonstrated by the ITER project, the lack of common international project management practices can create challenges. As project teams grow and become more diverse, common management practices and vocabulary will become increasingly important. In conclusion, the industry is moving in the right direction. Given the strides that have been made in the last 10-15 years, it appears that probabilistic scheduling and estimating techniques, based on common risk management practices, will continue to become more commonplace on projects.

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