Developing A Data Gathering Tool For Modeling Uncertainty In Highway Projects

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Abstract

This paper examines the different sources of uncertainties encountered in the construction process of highway projects and its effect on cost and time underestimation towards developing a data gathering tool for modelling uncertainty. The rationale for this examination stems from the view held by scholars that construction of highway projects are often beset by cost overruns and time delays and the lack of appropriate tools and techniques for use in gathering data for modelling uncertainty in the construction process. A review of extant literature in the area of construction estimation and risk management is undertaken to guide the direction of the study. It emerged from the review that there are three sources of uncertainty in the construction process of highway projects namely: variability in the construction process of highway projects, correlations between highway activities costs and times, and disruptive events were identified through analysis. Also, it was found that uncertainties encountered in the construction process of highways impact on cost and time, through a combination of the risk events of individual construction activities. A data gathering tool for modelling uncertainty in the construction process of highway projects is developed using these three sources of uncertainty and the quantitative model of variability by employing probability distribution. This tool will be utilized in future research for data gathering of the uncertain events of individual construction activities in highway projects.

Keywords

Correlation, Disruptive event, Uncertainty, Underestimation, Variability

1. Introduction

This paper examines the different sources of uncertainty in the construction process of highway projects and its effect on the estimated cost and completion time of highway projects, towards developing a data gathering tool for modelling uncertainty in the construction process. Cost overruns and time delays are frequent in infrastructure construction projects specifically in highway construction projects (Flyvbjerg et al. 2003; Poole and Sumuel 2011). Therefore, interest in tools to estimate the uncertainty in the construction process of projects has grown. Predicting construction cost and time estimates for highway projects are a challenging task because the highway project is not a stationary project and perceived to be a linear repetitive project (Rayes 2001, Dzeng and Wang 2003). Such projects encounter different

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conditions and environments at different geographic locations. These subject the highway projects to uncertainties, particularly in the early stages when very limited information about the project is available (Okmen and Oztas 2010). As a highway project progresses, more data becomes available to allow costs and times to be estimated to a greater degree of accuracy (European Commission DG 2008).

The actual cost of construction and time of a highway project is affected by many variables and uncertainties that can influence the estimated cost significantly during the construction process (Flyberg et al. 2003). However, most of the tools and techniques used for gathering data on the uncertainty in the construction process do not appropriately capture the risks and uncertainties involved (Flyberg et al. 2007; Anderson 2007). The focus of this research is on the examination of the different sources of uncertainties encountered in the construction process of highway projects and its effect on cost and completion time, towards developing a data gathering tool, which captures uncertainty on the projects. To do this, the paper will first of all outline the primary sources of uncertainty encountered in the construction process of highway projects and its effect on estimated cost and completion time, thereafter, it presents the results of a literature survey into the existing tools used for gathering data on the uncertainties encountered in the construction process of highway projects and their associated advantages and disadvantages. Finally, it proposes an appropriate tool that can be used in data gathering for modelling uncertainties on construction projects.

2. Overview of Sources of Uncertainty Encountered in the Construction Process and its Effect on Estimated Cost and Completion Time

2.1 Sources of Uncertainty

The three sources of uncertainty in the highway project are further described in the following sub-sections:

2.1.1 Variability in construction process of highway project

The variability in the construction process is the change in an activity cost variable and time variable under normal conditions. When an operation is repeated, the construction cost and time of the activity changes from one repetition to another (Moret and Einstein 2016). Variability is applied to three highway structures: Variability in Earthworks: Variability of cost and time in cut(excavation) activities in five different type of excavation namely: Silt, soft soil, hard soil, rock (mechanical), rock (blasting) and Variability of cost and time in filling activities; Variability in Bridges: Variability of cost and time of three methods of bridges namely: Culvert, precast, and cast-in-place beams/decks; and Variability in Paving: Variability cost and time in different layers of paving namely: Subgrade, Subbase, Base, and Surface. These variabilities are modeled after Fewings (2013) with probability distributions: the lognormal distribution for the variability in cost variables and the triangular distribution for the variability in time variables.

2.1.2 Costs and times correlation in highway project

Costs and times correlation are the relationships between costs and times of two highway structures and activities expressed with correlation. In the construction process of the repetitive project such as highway construction project, the construction cost and time of the activity change from one repetition to the other (Bakhshi and Touran 2012), hence different types of correlations between each construction activity and structure are identified. The following relationships between construction costs and times of highway structures and/or activities are documented in literature (Moret and Einstein 2012a): Correlation between the costs/periods of a repeated activity in a structure at the same segment; Correlation between the costs/times of the same activities in same structure at different segments; Correlation between the cost and time of the same activity in a structure; Correlation between the cost and time of the same activity in a structure; Correlation between the costs/times of different activities in a structure; Correlation between

the cost/times of operations in adjacent structures; and the Correlation between the costs/times of adjacent structures.
The correlation with the largest impact will be analyzed further and modeled with the NORTA (NORmal-To-Anything) method.

2.1.3 Disruptive event
A disruptive event is an event with a low probability of occurrence and massive impact on cost and time (Howick et al. 2010). Five major sources of disruptive events are considered in this uncertainty model namely: Technical, Economic, Political, Legal, and Environmental. The occurrence of a disruptive event is modeled at every unit of highway activity. If on the one hand, the disruptive event occurs, the cost and time impact of the disruptive event on the construction are also modeled. The occurrence or non-occurrence of these events are modeled with a simple random number generation. Disruptive events are modeled with triangular distribution (Moret and Einstein 2011), which is used to generate the cost and time impacts of the disruptive events. These cost and time impacts are added to the initial cost and time of highway activity.

2.2 The Effect of Uncertainty on Estimated Construction Cost and Completion Time

Typically, in the estimation of highway projects, several variables are not known since highway construction projects are populated by uncertainties. It is an opportunity if it has a positive impact, a threat if it has an adverse impact on the project objectives (Kurowicka and Cooke 2006). A different source of uncertainty has different impacts on infrastructure construction cost and time and their cumulative impact cause significant variations in estimated construction cost and completion time of infrastructure projects (Moret, and Einstein 2016).

3. Tools and Techniques Used for Data Gathering on the Uncertainties Encountered in the Construction Process

Most available data gathering tools/techniques [Three Point Estimating, Analogous Estimating, Expert Judgment Estimating, Parametric Model Estimating, Published Data Estimating, Reserve Analysis, Vendor Bid Analysis, and Bottom-up Analysis] do not capture the uncertainty in construction project (Poole and Samuel 2011; WSDOT 2012). These conventional cost and time estimating techniques provide the finest scenario assessment, which is rarely the case in practice.
In additional, the current approaches to modeling risk and uncertainty such as Anticipated Final Cost, Cost Planning Model, Schedule Risk Analysis, Quantitative Risk Assessment Model contain two limitations. First, the reliance on modeling risks without an in-depth understanding of the construction process of infrastructure project that does not ensure that all uncertainties in the construction process are captured. Second; modeling only risks rather than capture the cumulative effect of different sources of uncertainty in construction cost and time of highway projects (Moret, and Einstein 2012).

4. Proposed Tool that can be used in Gathering Data for Modelling Uncertainty

To overcome these limitations, the researcher has developed a simulation tool that models the highway construction as a sequence of primary structures in highway projects. An advanced feature of this tool is the capacity of identifying and modeling different sources of uncertainty in highway projects and capturing their cumulative impacts on cost and time of highway projects. The highway uncertainty model simulates the construction processes of every single activity of highway construction to the entire project based on the different sources of uncertainty. These are modeled jointly through each highway activity by using the probability distributions to model the impact of cost and time. The construction model of highway and uncertainty model will be integrated into the simulation program to consider different construction activities and various uncertainties. Based on input data the cost and time of uncertainty in the construction of the highway are simulated.

4.1 Highway Construction Model

The construction process of highway projects depends on the different parameters such as highway construction methods, geology, terrain, the location of the highway, etc. (Zayed et al. 2008). The construction process of highway consists of sequential, parallel and repeated activities. Therefore, construction of highway categorized as linear repetitive construction project (El-Rayes 2001). To evaluate these dependencies relation and its impact on the cost and the time of highway construction, the construction of the highway is modeled as a sequence of three main structures of highway construction namely Earthwork structures, Bridge structures, and Paving structures. The construction model analyses every single activity and sub-activity in the construction processes of the three most important structures identified. Activity networks are developed in the highway construction model to represent the particular construction process and calculate the construction cost and time of the highway project. In the highway construction model, the activity network consists of activities and sub-activities that are repeated numerous times during the construction of each structure. Thus, the interconnection of activities and sub-activities models one structure and the interconnection of the different structure networks model the construction of the highway project. The representation of the construction process of highway projects with activity networks depends on an understanding of the construction process and provides the starting point to identify the sources of uncertainty in the construction of the highway (Moret 2011).

The following sections examine the three most important structures of highway construction.

4.1.1 Earthwork structure

The construction of earthwork structure is modeled with two activities: cut (excavation) and filling. The construction of a cut(excavation) is modeled as a sequence of three following sub-activities: excavating the cut, improving the area, and stabilizing the trenches. Similarly, the construction of a filling is modeled as s sequence of the four following sub-activities: Clearing the soil, improving the area, filling, and compacting.

The construction cost and time of cuts are depended on the geology condition of excavation. Therefore, construction cost and time of five different cuts in various geology with appropriate excavation methods are considered: excavating Silt, excavating Soft Soil included Sand and Gravel using bulldozer below 150HP, excavating Hard Soil included Cobbles and Boulders using bulldozer below 300HP with ripper, excavating Rock using bulldozer above 300HP with ripper, excavating Rock using blasting. Differently, the construction of filling is characterized by recycling the good materials from excavated in the cuts, which is reused in the fillings. Thus only one cost and time are considered for filling activities.

The cost and time of the earthwork structure are characterized by quantifying cost and time of each sub-activity in each earthwork activity (Cut and filling) as a function of the cost per unit volume, the production rate, and the volume and mathematically modelled as shown in Equations 1 and 2.

$$\text{Cost} = \text{cost per unit volume of sub-activity} \times \text{Volume of sub-activity} \quad (1)$$
$$\text{Time} = (\text{Volume of sub-activity})/(\text{production rate of sub-activity}) \quad (2)$$

4.1.2 Bridge structure

The construction of a bridge is modeled with an activity network, which depends on the construction method of the bridge. Three most common bridge components used in highway projects are namely culvert, precast, and cast-in-place. The construction of culvert bridge is modeled with a combination of the following five sub-activities: Set Up Site, Culvert Bedding, Set Up Precast Culvert, Wing Wall, and Backfilling. The construction of the precast bridge is modeled with a combination of eight following sub-activities: Set Up Site, Footing of Abutment, Abutment, Footing of Pier, Pier, Wing Wall, Set up Precast Deck, Backfilling. Also, the construction of cast-in-place bridge is modeled with a combination of the

following eight sub-activities: Set Up Site, Footing of Abutment, Abutment, Footing of Pier, Pier, Wing Wall, Cast-In-Place Deck, Backfilling.
The bridge structure is modeled with more complex activity network compare to earthwork structure. The activities can be either parallel or sequential, where the sequence of the operations depends on the bridge method and site condition. For bridges with a large number of spans, the activity network becomes proportionally larger. Since details of bridges are varied such as a number of spans, each bridge needs a customized activity network.
The cost and time of the bridge construction are characterized by quantifying the cost and the time of construction of each sub-activity of the bridge. The cost and time of bridge construction are mathematically modelled as shown in Equations 3 and 4.

$$\text{Cost} = \sum \text{Activity cost} \quad (3)$$
$$\text{Time} = \sum \text{Activity time on critical path} \quad (4)$$

4.1.3 Paving structure

The construction of a pavement is modeled as a sequence of four following layers: Subgrade, Subbase, Base, and Surface. The cost and time of paving structure are characterized by quantifying the cost and time of each layer as a function of the cost per unit volume, the production rate, and the volume. The cost and time of bridge construction are mathematically modelled as shown in Equations 5 and 6.

$$\text{Cost} = \text{cost per unit volume of layer} \times \text{Volume of layer} \quad (5)$$
$$\text{Time} = (\text{Volume of layer})/(\text{production rate of layer}) \quad (6)$$

4.2 Highway Uncertainty Model

To overcome the existing limitations in current estimation tools and approaches to modelling risk and uncertainty (modelling risks without an in-depth understanding of the construction process of highway as a linear repetitive construction project, and modelling only risks rather than uncertainty) it is necessary to create a highway uncertainty model to estimate the cost and time of the project, based on an in-depth understanding of the construction process and model its different sources of uncertainty in the highway projects. Therefore, three sources of uncertainty which have a significant impact on the cost and time of the highway projects are identified: the variability in construction process of the highway; the correlations between construction cost and time of highway structures and/or activities; and the occurrence of disruptive events in highway project (Moret and Einstein 2016). The uncertainty model compares the impact of the different sources of uncertainty in highway projects and captures the cumulative impact of all three source of risks on the construction cost and time of the projects.

5. Input Data and Data Gathering Tools

From the preceding, it can be deduced that the proposed uncertainty model requires a significant amount of input data. Additional to the historical data in cost and time for each highway structure, the following supplementary input data are also needed to model the uncertainties in highway construction: probability distribution of highway activities cost and time; correlations between the costs and times of highway activities; likelihood of occurrence of disruptive events and distributions of their cost and time impacts during the construction of the highway.

According to Moret and Einstein (2012), data are often not freely available because cost and time of activities are considered sensitive information. As a result, correlations are rarely analysed, and the infrequent occurrence of disruptive events makes it difficult to gather data on them. However, historical datasets are available on the costs and times of highway projects and all detailed information such as a variation on the construction process and the cost and time correlation can be extracted from the historical datasets. To calibrate extracted information from the historical datasets and also to obtain inaccessible data such as the probability of occurrence and cost and time impacts of disruptive events, the expert opinions, and estimation values are obtained.

In developing the uncertainty model, earthwork experts, bridge experts, and paving experts are approached to estimate and provide the required information on cost and time variability, cost and time correlations and disruptive events. Experts with over 20 years of experience in the construction of highway projects and their respective fields will be used as sources of expert judgment.

Table 1: The Input Data in Highway Structures and Uncertainties

Highway Structure	Variation		Correlation		Disruptive Events		
	Cost	Time	Cost	Time	Occurrence	Cost Impact	Time Impact
Earthwork	Historical Data Expert Estimate		Historical Data Expert Estimate			Expert Opinion	
Bridge	Historical Data Expert Estimate		Historical Data Expert Estimate			Expert Opinion	
Paving	Historical Data Expert Estimate		Historical Data Expert Estimate			Expert Opinion	

Table 1 shows the different components of the highway structure, distributed by the sources of uncertainty in the construction process of highway construction projects. Table 1 details the areas in which expert opinion will be sought. Variation: experts are to provide estimates of the construction cost and time of the unit volume of each activity of main highway structures. To model variability of cost and time, it is required that the expert estimates the possible construction cost and time of each activity at a minimum cost, most and maximum. Regarding the correlation uncertainty construct, experts are to specify the variation in cost and time of each activity and structure if the cost and time of previous activity or structure increases or decreases. While for the disruptive event, experts estimate the probability of occurrence and severity of outcome and the impact of each disruptive event on the construction cost and time of the structure. Similarly, to the variation section, the sequence of the minimum, most and maximum impact of disruptive events on cost and time of each highway structure are requested from the experts.

The networks modelling of the highway construction process and quantitative model of the three sources of uncertainty of highway project are after that combined in the Monte Carlo simulation tool. The required probability distributions, the NORTA method, and Markov processes are used in capturing the cumulative impact of each source of uncertainty in construction cost and time of highway projects. By simulating a highway project repetitively, it generates probability distributions for total construction cost and total time of highway project. Monte Carlo simulation generates input distributions in the aims of calculating the total cost and the total time output variables for each simulation run.

6. Conclusion and Recommendation

This paper examines the different sources of uncertainty in the construction process of highway projects and its effect on the estimated cost and completion time of highway projects, towards developing a data gathering tool for modelling uncertainty in the construction process. The study established from literature survey that the sources of uncertainty in highway construction projects are variation, correlation and disruptive events and these have an adverse effect on construction cost and completion time of highway construction projects. A data gathering tool for use in modelling uncertainty in highway construction projects, using the main structures of highway construction and expert opinion.

The proposed highway construction uncertainty model makes several improvements to the field of cost and time estimation of a linear repetitive construction project such as highway projects. Modeling the uncertainties of cost and time in highway projects involves two steps: identification and quantification and most of the existing tools use estimation as a conceptual or template based construction management tool. By incorporating historical data and expert evaluation/opinions, the proposed model aims to bring the conceptual environment closer to reality. The highway uncertainty model, simulates the different sources of uncertainties in highway projects using two sources of data: historical data and expert estimation/opinions to improve the quality of the input data, and defines the outcomes of uncertainty to be positive or negative, resulting from three different sources of uncertainties, which allows construction managers to anticipate both opportunities and adverse events.

Sources of Uncertainty are identified from the literature review of previous researches and clarified through brainstorming of the experts. The identified uncertainties are quantified depending on the appropriate classification uncertainty type: variability is quantified by defining the probability distribution and the distribution parameters; cost correlations are quantified with correlation coefficients; a disruptive event is quantified with its likelihood of occurrence and the probability distributions of the cost impact and time impact. The highway construction uncertainty model provides a holistic four steps process in the aims of quantitatively analysing the overall uncertainty of the highway projects. The model computes the distributions of the total cost and the total time of highway project; it combines uncertainties to model their cumulative impact on total cost and total time of highway project; it quantifies the impact of each uncertainty on highway cost and time, and finally it visualizes the highway project cost and time.

Beside actual cost and time estimation and assessment of uncertainty impacts in highway projects, the proposed quantitative analysis has further uses. The quantitative analysis is a dynamic model that can be utilized during the life of the project to analyse new uncertainties, the effectiveness of countermeasures to mitigate threats or to take into consideration that some uncertainties have been eliminated. In principle, it can be used iteratively during the construction of the project to model the changing uncertainties. Contrary to other existing tools developed for construction infrastructure projects in general, the proposed data gathering tool is particularly well suited for projects characterized as being complex. This degree of complexity is given by the type of structure, the number of interconnected activities and the sources of uncertainty.

7. Further Research

The paper recommends further research that will examine the quantified uncertainty encountered in the construction process of a highway project based on historical data and probability distributions and whether these can be used in explaining the theoretical uncertainty model developed. The data gathered will also be used in testing the effectiveness and validity of the proposed construction and uncertainty models.

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9. References

Anderson. D, Molennar. R and Schexnayder. J, (2007), "NCHRP 574: Guidance for cost estimation and management for highway projects during planning, programming and preconstruction", Transportation Research Board, Washington, D.C.
Bakhshi. P, and Touran. A, (2012)," A Method for Calculating Cost Correlation among Construction Projects in a Portfolio" International Journal of Architecture, Engineering, and Construction, Vol 1, No 3, September 2012, 134-141.
El-Rayes. K, (2001), "Object-oriented model for repetitive construction scheduling," Journal of construction engineering and management, ASCE 127(3) 199-205
European Commission DG (2008), "Understanding and Monitoring the Cost-Determining Factors of Infrastructure Projects," A User's Guide, Brussels.
Fewings. P, (2013), "Construction Project Management: An Integrated Approach 2nd edition", Routledge, New York.
Flyvbjerg, B., Holam. M, and Buhla. S, (2002), "Underestimating costs in public works project: Error or Lie?", Journal of the American Planning Association 68(3), 279-295.
Flyvbjerg. B, Bruzelius. N, and Rothengatter. W, (2003), "Megaprojects and Risk: An Anatomy of Ambition," Cambridge University Press, Cambridge.
Flyvbjerg.B, (2007),"Policy and planning for large-infrastructure projects: problem, causes, cures," Environment and Planning B: planning and design, 34 (4), 578-597.
Flyvbjerg. B, and Wee. B, (2008), "Public Planning of Mega-projects: Overestimation of Demand and Underestimation of Costs." Cheltenham, UK, and Northampton, MA, USA: Edward Elgar, pp. 120-144.
Howick. S, Ackermann. F, Eden. C, and Williams. T, (2010), "Understanding the causes and consequences of disruption and delay in complex projects: how system dynamics can help," Soton, England.
Kurowicka. D, and Cooke. R, (2006), "Uncertainty Analysis with High Dimensional Dependence Modelling," John Wiley & Sons, USA.
Moret. Y, and Einstein. H, (2016), "Construction Cost and Duration Uncertainty Model: Application to High-Speed Rail Line Project." J. Constr. Eng. Manage., 10.1061/(ASCE)CO.1943-7862.
Moret, Y. and Einstein, H. (2012a). "Modeling Correlations in Rail Line Construction." J. Constr. Eng. Manage., 10.1061/(ASCE)CO.1943-7862.0000507, 1075-1084.
Moret, Y. and Einstein, H. (2012b). "Experience in Expert Estimation of Probabilities and Correlations for Rail Line Construction." J. Constr. Eng. Manage., 10.1061/(ASCE)CO.1943-7862.0000505, 1103-1106.
Okmen. O, and Oztas. A, (2010), "Construction cost analysis under uncertainty with correlated cost risk analysis model," Construction Management and Economics, 28(2), 203-212.
Poole. R, and Samuel. P (2011), "Transportation Mega-Projects and Risk," Reason Foundation, Loa Angles, California.
WSDOT (2012), "Wsdot guidelines for CRA-CEVP workshops (includes common assumptions)," Technical report, Washington state Department of Transportation (WSDOT), Olympia, WA.
Zayed. T, Amer. M, and Pan. J, (2008), "Assessing risk and uncertainty inherent in Chinese highway projects using AHP," International Journal of Project Management, 26(4): 408–419. .doi:10.1016/j.ijproman.2007.05.012.