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A decision support system for selecting the optimal contracting strategy in highway work zone projects

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ABSTRACT

Highway work zone projects are challenging for state highway agencies and contractors as they are often located in urban areas and impact local traffic, business community, and neighborhood leading to a multi-party involvement. There is a dynamic relationship between the involved parties and the performance of any highway work zone project is governed by this dynamic relationship. This paper presents a decision support system to assist state Departments of Transportation in selecting suitable contracting strategies for highway work zone projects by considering, at a macro level, the interrelationships between the stakeholders as well as the critical factors impacting the project. The proposed methodology supplements the current project decision-making process with regard to important project performance variables such as cost, schedule, quality, safety, and public satisfaction.

1. Introduction

In recent years, as the existing roads in the National Highway system are aging and deteriorating at a fast rate, public agencies have shifted their emphasis from construction of new transportation facilities to restoration, resurfacing, rehabilitation, and reconstruction of existing facilities known as 4-R type highway work zone projects [1–3]. Such projects are challenging for state highway agencies and highway contractors as they are often located in urban areas and impact local traffic, business community, and neighborhood leading to a multi-party involvement. There is a dynamic relationship between the involved parties impacting the performance of highway work zone projects. The decisions made or actions taken by a stakeholder on a particular project during the planning and execution phases may not only cause a direct impact on the main performance indicators of the project, i.e., cost, schedule, quality, safety, and public/motorist satisfaction, but also create an indirect impact on the same through the feedback (reaction) received from other stakeholders. For example, the restrictions on available work hours on a particular project have a direct impact on the duration of the project. However, such restrictions mandated by the state highway agency or legal authorities have also an impact on the contractor in terms of the mobilization/demobilization costs, availability of material and equipment, and productivity of workers, which in turn will have an indirect impact on the final cost and duration of the project.

Failure to consider such interrelationships between the stakeholders to a highway work zone project as well as the critical factors impacting the project might lead to schedule delays, cost overruns, and legal problems. A marginal cost overrun can deteriorate the profit of the contractor [4], and schedule overruns can lead to increased agency costs and public dissatisfaction. The performance of highway work zone projects are affected by several interrelated tangible and intangible factors such as: (i) technical factors (e.g., location, work zone length, work window, difficulty of work, site constraints, traffic volume, planned detour, and lane closure strategy), (ii) social/political factors (e.g., inconvenience to users, disturbance to nearby community, business disruption, public perception, and other political considerations), (iii) financial considerations (e.g., traffic maintenance cost, fuel cost, delay cost, accident cost, and liabilities), (iv) contractual requirements (e.g., type of contract, incentives, penalty, risk sharing, and other legal considerations), and (v) other factors (e.g., utility issues, right-of-way issues, and environmental permits). To date, various methodologies have been developed for the analysis of trade-offs among the important project variables in highway construction. However, existing methods search for an optimal resource utilization plan at the activity level and do not consider at a macro level the influence of many important factors on the project commencing from the dynamic relationship between the stakeholders with competing interests.

This paper aims to explain and model, at a macro level, the dynamic relationships between the stakeholders to a highway work zone project with respect to their influence on the cost, schedule, safety, quality, and public/motorist satisfaction of such projects. The main difference of the proposed model from the current methods is that it provides a macro-level view on the decision making problem in

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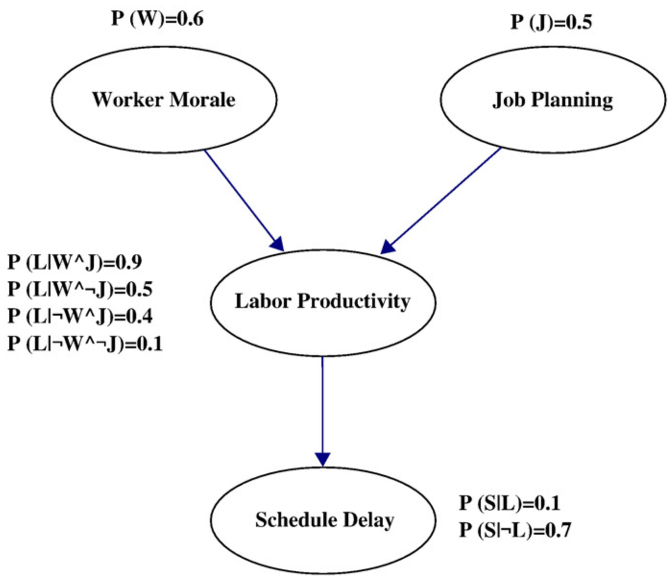

Fig. 1. Simple schedule delay belief network with conditional probabilities.

highway work zones using a comprehensive list of interrelated factors (a total of 52) impacting the success of work zone projects. The decision support model introduced in the paper can assist highway agencies in developing suitable contracting strategies while taking into account factors related to the agency, contractor and public such as worker morale, public relations, contractor's experience, availability of utilities, community attitude.

2. Bayesian belief network as the modeling environment

The underlying premise of this paper is that the dynamic relationship between the stakeholders to a highway work zone project is facilitated through certain interrelated tangible and intangible factors including but not limited to project location, work zone length, work window, difficulty of work, site constraints, traffic volume, planned detour, lane closure strategy, inconvenience to users, disturbance to nearby community, business disruption, public perception, political considerations, fuel cost, delay cost, accident cost, and contractor incentives. Therefore, for achieving the optimal trade-offs under different contracting strategies and constraints, it is important to identify the factors that are relevant to highway work zone projects as well as study their cumulative impact on the project performance indicators that establish the relevant trade-offs in project planning, i.e., cost, schedule, safety, quality, and public satisfaction.

To facilitate the evaluation of the trade-offs in highway work zone projects, a detailed list of the factors that have a potential impact on those project variables were identified through a comprehensive literature review and a series of interviews with personnel from the Indiana Department of Transportation that are involved in various aspects of highway work zone projects. Based on the interrelationships between the factors, a generic influence pattern illustrating the influence of the factors on each other and also on the project variables under consideration was established.

In establishing the influence pattern of factors for the purposes of this research, a probabilistic Bayesian belief network model was developed to identify the relationships between the different factors under consideration. A Bayesian belief network is a formal statistical modeling framework that facilitates analysis of relationships using the Bayes theorem where predictions are represented probabilistically using a confidence interval [5]. It consists of nodes that represent variables that are connected with directional arrows that represent conditional dependence relationships between those nodes.

The Bayes theorem' is defined as:

$$P(B|A) = \frac{P(A|B)^{*}P(B)}{P(A)}.$$

Bayes' theorem may also be used to analyze multiple conditional probabilities as:

$$P(B_i|A) = \frac{P(A|B_i)^{*}P(B_i)}{\sum_{k=1}^{n} P(A|B_K)^{*}P(B_K)}.$$

The traditional approach in developing and using probability networks is viewing the model as a graph. A Bayesian network or Bayesian belief network is a directed acyclic graph of nodes (i.e., there is no loop in the network) which represent variables along with arcs which illustrate dependence relations among the variables. Nodes of a Bayesian network are usually illustrated as circles or ovals. In the graph, nodes represent important system variables, whereas an arrow from one node to another represents a causal dependence between the corresponding variables [6,7]. The joint probability distribution represented by a Bayesian belief network is subjective and this subjective probability distribution can be updated based on the new evidence using the Bayes' theorem [6].

Belief networks have been used extensively in medicine and computer science. In recent years, researchers have started to apply belief networks to engineering and natural resource management problems. The current application of Bayesian belief networks to construction research is limited. McCabe et al. [6] developed an automated approach using belief networks to provide diagnostic functionality to the performance analysis of construction operations. McCabe and AbuRizk [8] introduced Bayesian belief networks for engineering applications. Attoh-Okine [9] presented the application of belief networks to make inferences in highway construction costs. Nasir et al. [7] developed a construction schedule risk model using a Bayesian belief network as the modeling environment.

In this section, a simple belief network isolated from the model created for this research will be solved to present the use of Bayes' theorem and concepts of conditional probability in evaluating belief networks. The model shown in Fig. 1 illustrates the conditional probabilistic dependence among a group of factors causing schedule delay in work zone projects. It is important to note that this is a simplified example and does not provide an exhaustive analysis of factors leading to schedule delays in such projects. As such, the belief network is limited to only four nodes with only two states each including Schedule Delay (S), Labor Productivity (L), Worker Morale (W), and Job Planning (J) (Table 1).

The network shown in Fig. 1 implies that Schedule Delay (S) is dependent on Labor Productivity (L) which, in turn, is dependent on Worker Morale (W) and Job Planning (J). Hence, once the probability values for Labor Productivity are available, the probability values for Worker Morale and Job Planning are not necessary to predict the probability values for Schedule Delay. This conditional independence is presented by the absence of a directly connecting arrow between Worker Morale or Job Planning and Schedule Delay. The conditional probabilistic relationships can be acquired from statistical analysis of

Table 1
Node states for schedule delay analysis network.

Nodes	States	
	True	False
Worker morale (W)	High	Low
Job planning (J)	Proper	Improper
Labor productivity (L)	High	Low
Schedule delay (S)	Yes	No