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Traversing and querying constraint driven temporal networks to estimate construction contingencies

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ABSTRACT

Effective estimation of possible project futures is crucial to the success of construction projects. The focus of this paper is identifying and classifying possible construction crisis scenarios using an interactive simulation. We present a mathematical representation of construction processes, with foundations in temporal constraint networks, that can be used to infer alternative futures of a project as it unfolds. We present algorithms that can traverse the network in time, reason about the constraints driving the construction project, and present the combinatorial possibilities of futures that can emerge from one or more constraint violations during project implementation. The graphical depictions of the traversal results will aid construction managers in anticipating and reacting to crisis scenarios as they evolve in time. We present a case study and illustrate how the proposed algorithms can be used to represent and model uncertainty and estimate contingencies in construction projects. This research is part of a broader framework that integrates construction education, the study of expert decision making, and intelligent decision making aids.

1. Introduction

Effective anticipation of the possible futures of a project is fundamental to project management. Flexibility in analyzing the results of such forecasts is equally important. In this paper, we describe an intelligent decision-making aid that will allow construction managers to anticipate and mitigate crisis scenarios dynamically during the execution of a construction project. Our system supplements the diverse body of discrete event simulations in construction by providing a unified framework which can represent time, uncertainty, the constraints that define a project, the events that may change the course of a project, and the impact of events to project outcomes.

Our framework uses a mathematical representation of construction processes that has foundations in temporal constraint networks [1], which are widely used in Computer Science. We augment temporal constraint networks with stochastic events that can change the course of a project, and with detailed information on the impact of these events. The augmented network is called a TONÂE (Temporal Network with Activities and Events). We present algorithms that can traverse a TONÂE network in time, query the probabilities of alternative futures, and calculate associated impacts. We graphically depict aspects of the alternative futures that were computed. The result is a system that can be used to represent and reason about the constraints driving a construction project and provides deeper insight into the combinatorial possibilities that can emerge from one or more constraint violations during project implementation. The system will aid construction managers in anticipating and reacting to crisis scenarios as they evolve in time and estimate suitable contingencies. This research is situated within the broader context of research in situational simulations. Previous research has discussed the conceptual and formal foundations of educational situational simulations [2,3] and its implementation [4]. In this paper, we have developed algorithms that will further enhance the ability of situational simulations, to serve as interactive decision support systems. The focus of this paper is in identifying and classifying possible construction crisis scenarios and estimating contingencies.

2. Background

Simulation tools provide a valuable mechanism to aid the effective design, implementation, and overseeing of construction projects. There is a diverse body of discrete event simulators that can model construction projects and provide forecasting information. In this section, we briefly discuss two points of departure from existing work, for this research: uncertainty and contingency planning using construction simulations, and temporal reasoning and contingency planning in artificial intelligence.

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It should be noted that the terms *uncertainty*, *risk*, and *contingency* have different meanings in different contexts. We therefore begin with providing our interpretations.

The study of uncertainty in construction has predominantly involved estimating cost overruns and schedule delays in projects, and estimating input parameters in simulating construction operations and processes. In both of these areas, uncertainty is characterized by statistical distributions that describe the underlying variability. Uncertainty in a construction project may also arise due to the design of the construction schedule and the layout of the construction site. Violations in schedule constraints may arise due to various events that may occur within (internal events) or without (external events) the construction project. While some of these uncertainties are impossible to predict, some of them are possible to predict even if they are difficult to foresee. The first type of events is often referred to as *aleatory events* (The word *alea* pertains to chance). Examples of such events include entirely uncharacteristic weather events and uncharacteristic changes in the economy that may significantly impact schedule, cost or the completion of the project. The second type of events is called *epistemic events* that arise from reasons pertaining to the underlying schedule and cost constraints in a construction project. Examples of epistemic events are congestion and reduced productivity on a construction site due space conflicts between different crews resulting from a delay in a previous activity. Uncertainty arising from aleatory events is usually very low and given the history, may be characterized probabilistically. Uncertainty arising from epistemic events on the other hand is combinatorial in nature as they often result from combinations of constraint violations and predictable external events — such as bad weather conditions. The predictable external events are not to be confused with aleatory events, because even though they are entirely external to the project and are not definite, historical records and context can be a good indicator of their likelihood. Indeed, they can be adequately characterized using statistical methods.

Risk is defined as a result of uncertainty, arising from a lack of predictability about structure, outcomes, or consequences during planning [5]. *Risk analysis*, involves estimating probabilities required for the evaluation of decision alternatives. Hence, there can be risk arising from aleatory events as well as epistemic events. Epistemic risk results from the lack of predictability of the underlaying structure of the project plan as represented by project constraints and relationships.

There are many different methods of estimating construction contingency. Traditionally, it has been estimated as a fixed percentage of the total construction cost [6], based on previous experience with similar projects. It has also been estimated by identifying risks that are associated with individual activities. The limitations of such approaches is that they are based on subjective judgment making it difficult to quantify the degree of confidence associated with the contingencies identified. Touran [7] explored probabilistic methods of assessing and allocating contingencies to construction projects. His premise was that the events causing delays and budget impacts during construction projects can be described using a Poisson process. This assumption requires event arrivals to be independent and non-overlapping, such as arriving change-orders. While, this probabilistic approach to estimating contingencies can be suitably applied during the early stages of project development, the approach is limited to accounting only for events that are independent and does not take into account dependent events that can occur due to cascading constraint violations during the project implementation.

In this paper, we are focusing on analyzing risk arising from uncertainty due to epistemic events and predictable external events. We are not considering aleatory events, because by definition they are very difficult to imagine and their consequences are entirely unpredictable. We present a temporal network based representation that will allow the representation of the underlying structure and constraints of a construction project plan, and the ability to simulate the impacts of cascading constraint violations and predictable external events on the final out come of the project. Our definition of contingency, is not just a sum of money or an alternative plan, instead its a probability distribution of project outcomes given the project constraints and a reasonable estimate of probabilities of external events. It is arrived at by utilizing the simulations to explore *what-if* scenarios.

2.1. Construction simulations

Research in construction simulations has produced general purpose platforms such as Simphony [8] and STROBOSCOPE [9] that have been used to model construction processes and operations with an emphasis on optimizing resource use and allocation. Simphony has been applied to simulating projects that are repetitive in nature, such as tunneling construction projects [10]. Such simulation systems have used statistical distributions to characterize uncertainty associated with different model inputs and parameters, in order to increase the accuracy of simulation output and parameter estimates. Bayesian methods have been used to update the distributions of simulation input parameters — for example, penetration rates of a tunnel boring machine in a Simphony simulation of a tunneling operation [11]. Similarly, STROBOSCOPE allows statistical distributions to be incorporated in the model to reflect variations in simulation input parameters [12]. Concurrent interruptions such as random equipment failures or prescheduled worker break times [13] were modeled using the Simplified Discrete Event Simulation Approach (SDESA) to account for uncertainties resulting from them. When these events were included in the simulation, activity end times could be predicted more accurately.

The approach in this paper is to explore uncertainties arising from the underlying structure of the construction management domain. The domain structure includes relationships between processes and events, and critical temporal and resource constraints that drive the construction project. Belief networks have been used to represent underlying structure in construction [14,15] and model relationships between construction processes and events. The focus of such research has been to query the belief networks to analyze and optimize the performance of simulated construction operations.

The significance of the research presented in this paper is that instead of modeling specific crisis scenarios or specific construction operations, it models the general behavior and interaction between relevant variables that define the underlying construction domain structure within an interactive simulation. This allows a very large number of possible scenarios to be automatically simulated and investigated, thus providing an improvement over existing research in uncertainty analysis, while taking advantage of underlying domain structure. The simulation is also dynamic, allowing the impact of external events and changes in the variables to be propagated through out the project. In addition, human decision-making interaction within the simulation allows us to investigate the sensitivity of the project variables and parameters to human-resource interactions (decisions) rather than just resource interactions. While this research builds on existing research, it also contributes a temporal constraint network representation and associated algorithms that can be applied with relative ease to existing construction simulation systems to further the study of construction decision-making and contingency estimation.

2.2. Temporal reasoning and contingency planning

Simple Temporal Networks (STNs) [1] and their associated polynomial time algorithms are widely used in temporal reasoning. An STN includes nodes which represent events and edges between pairs of nodes which represent temporal constraints between events. A temporal constraint such as $2 \leq x_2 - x_1 \leq 5$ means that the duration $[x_1, x_2]$ between time points x_1 and x_2 can be between 2 and 5 time units. Deadlines are represented by posing constraints between the