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A Bayesian network framework for project cost, benefit and risk analysis with an agricultural development case study

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ABSTRACT

Successful implementation of major projects requires careful management of uncertainty and risk. Yet such uncertainty is rarely effectively calculated when analysing project costs and benefits. This paper presents a Bayesian Network (BN) modelling framework to calculate the costs, benefits, and return on investment of a project over a specified time period, allowing for changing circumstances and trade-offs. The framework uses hybrid and dynamic BNs containing both discrete and continuous variables over multiple time stages. The BN framework calculates costs and benefits based on multiple causal factors including the effects of individual risk factors, budget deficits, and time value discounting, taking account of the parameter uncertainty of all continuous variables. The framework can serve as the basis for various project management assessments and is illustrated using a case study of an agricultural development project.

1. Introduction

Projects provide a key mechanism that allows organizations to translate strategy into results. There is growing interest across many sectors in ways of becoming more time and cost effective or to demonstrate ‘value for money’ from projects. The need for improved organizational project management appears warranted. For example, the US Government Accountability Office indicated that approximately 72% of federal technology projects, amounting to a total budget of $27 billion, are deemed to be poorly planned with the likelihood of encountering significant schedule and cost overruns (Mishra, Das, & Murray, 2016). The World Bank (2011) found from a review of 86 evaluations of its projects that as many as 41% had non-positive outcomes. The World Bank expressed alarm over the fact that the percentage of their projects that are justified by cost-benefit analysis (which is perhaps the most basic of project assessment tools) has been declining for several decades and attributed this to a decline in adherence to standards and to difficulty in applying cost-benefit analysis (World Bank, 2010).

Project management as a discipline has evolved from a focus on a single project to enhancing project management capacity within the whole organization. The concept of project management maturity has emerged as a measure of the level of capability or effectiveness of an organization in project management (Kerzner, 2001) and there are many project maturity models available (Backlund, Chronéer, & Sundqvist, 2014). A project maturity model usually defines different progressive levels of maturity, for example ranging from the lowest level of ill-defined project management processes applied by individuals on an individual project basis, to the most advanced level, which applies standard project management processes across an organization, uses quantified metrics to evaluate effectiveness and seeks out continuous improvement and innovation (Mishra et al., 2016, Spalek, 2014).

Uncertainty and risks are common elements of all major projects and they must be effectively managed for projects to be successful (Chapman & Ward, 2004, Green, 2001, Ward & Chapman, 2003, Ward & Chapman, 1995). Failure to account for uncertainty is a major cause of time and cost over-runs and disappointing project outcomes (Savage, 2012) but has been given insufficient attention in project management maturity. Project management maturity initiatives tend to seek improvements in management of risks, resources and time in isolation of one another, so that trade-offs are not apparent. Furthermore, treatment of risk in projects is commonly limited to using risk registers, which suffer

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a number of limitations, not least that they treat risks separately, as opposed to adopting a holistic approach that embraces a causal view of interconnected events (Fenton & Neil, 2012).

This paper focuses on uncertainty and risks associated with the cost, benefit and Return On Investment (ROI) of a project. We propose a Bayesian Network (BN) modelling framework that calculates these elements over the duration of the project, taking into account the uncertainty of all parameters while making these calculations. Our framework aims to model multiple risk events, and to enable users to assess the costs and benefits of the project under different risk scenarios. The model incorporates many important causal factors including the effects of having a budget deficit, uncertainty in cost estimates, time value of money, and the impact of inaccurate risk prediction. We illustrate the use of this framework using a case study of agricultural development projects.

Our approach complements previous work on project risk, which has focused on the planning and uncertainty of project time schedules, by focusing instead on costs and benefits of projects and the associated risk factors. Our model offers unique features by using uncertainty and variability of risk factors together with economic and adoption factors for making predictions in different time stages of a project. These features can help project managers especially in project selection, planning and control stages.

The paper is structured as follows: Section 2 provides an overview of BNs, which are proving to be an increasingly popular and effective method for modelling uncertainty and risk and reviews their previous applications in project management. Section 3 presents the proposed framework. Section 4 describes the case study and presents an instantiation of the framework for the case study. Section 5 shows the use and results of the model generated from the framework, and we provide our conclusions in Section 6.

2. Bayesian networks

BNs are powerful tools for making probabilistic inference on complex domains with a large number of variables (Fenton & Neil, 2012, Pearl, 1988). A BN is a probabilistic graphical model that consists of a graphical structure and parameters of conditional probability distributions corresponding to the structure. The graphical structure of a BN is composed of nodes representing variables, and arcs representing the relations between the variables. The parameters of a BN represent the nature and strength of the relations represented by the arcs. It is beyond the scope of this paper to show the technical details of BNs and their calculations; the readers are referred to Fenton and Neil (2012), and Koller and Friedman (2009).

The graphical structure of a BN is suitable for modelling causal relations (Pearl, 2000). Therefore, BNs offer unique features in integrating expert knowledge (Fenton & Neil, 2012, Yet, Perkins, Fenton, Tai, & Marsh, 2014, Yet, Perkins, Rasmussen, Tai, & Marsh, 2014) and data (Cheng, Bell, & Liu, 1998, Heckerman, 1997) into model building. This is especially beneficial in domains where the availability of relevant data is limited but where extensive expert knowledge is available. As a result, BNs have been used for complex problems in many diverse domains including medicine (Yet et al., 2013, Yet, Perkins, Rasmussen, 2014), law (Fenton, Berger, Lagnado, Neil, & Hsu, 2014, Fenton, Neil, & Lagnado, 2013), finance (Neil, Hager, & Andersen, 2009), and sports (Constantinou, Fenton, & Neil, 2012, Constantinou, Fenton, & Neil, 2013).

Until recently, one of the main limitations of BNs was in building and calculating models that contain both discrete and continuous variables (such models are called ***hybrid BNs***). Standard inference algorithms (such as the junction tree algorithm) and associated software packages require all variables to be either discrete or Gaussian. This turns out to be a major limitation for project risk models as they inherently contain many continuous variables that do not necessarily have a Gaussian distribution. However, recent advances in BNs, for example, the development of the dynamic discretization algorithm (Neil, Tailor, & Marquez, 2007), have made it possible to build and solve hybrid BN models - involving arbitrary continuous distributions- accurately, efficiently and conveniently. These powerful algorithms have been implemented in a freely available BN software package with a graphical interface (AgenaRisk, 2015, Fenton & Neil, 2014). This software is used for the BN models in the paper.

2.1. Bayesian networks for project risk

BNs are especially suited to model the attributes of uncertainty and risk that are common to all projects (as discussed in Section 1). BNs are powerful in reasoning about uncertainty as they are able to represent and make inference about complex joint probability distributions with numerous random variables. In addition to uncertainty and risk, all projects are unique by definition (PMI, 2013) and many, such as long-term development projects, have sparse relevant historical data. Moreover, the data collected from one project may not apply to others due to their differences and, it is often costly and time-consuming to collect data from long-term projects. However, expert knowledge is often available in abundance both in project management and the application domain and when available, it can be profitably used as a source of evidence (Shepherd et al., 2015). BNs offer powerful and unique features to use and combine this expert knowledge with available data, where available (Neil, Fenton, & Nielson, 2000, Renooij, 2001, Yet, Perkins, Fenton, 2014).

Despite their clear potential benefits, the use of BNs in project management has been quite limited (possibly because of the previous limitations on hybrid BNs). The earliest published article devoted to using BNs explicitly in a general project management context appears to be Khodakarami, Fenton, and Neil (2007), which proposes a BN model to deal with the uncertainty in project scheduling. This model implements the critical path method (CPM) into a BN model, and extends CPM by reasoning with the causes of delays. Similarly, Luu, Kim, Van Tuan, and Ogunlana (2009) compute the risk of having an overall schedule delay using a discrete BN model without parameter uncertainty. Fineman, Fenton, and Radlinski (2009) use a simple BN model to reason about the trade-off between the time, cost and quality aspects of a project. Lee, Park, and Shin (2009) use a BN model to estimate the risk of exceeding budget and time schedule, and of having insufficient specifications. They apply their model in the shipbuilding domain. Khodakarami and Abdi (2014) use BNs to estimate only the project costs based on the causes of the costs.

In contrast to the relatively few applications of BNs to general project management, there has been more extensive use in the specific context of management of software engineering projects (possibly because of the proximity of this domain to computer scientists). Fan and Yu (2004) proposed a framework that continuously assesses and manages risk in different aspects of software development. Fenton et al. (2004) demonstrate a static BN model for making resource decisions in software projects. Their model takes the trade-off between quality, time and costs into account, and it is able to make inference about the resources required to achieve a target quality value. de Melo and Sanchez (2008) use discrete BNs to assess risks and predict delays in software maintenance projects. Hu, Zhang, Ngai, Cai, and Liu (2013) use constraint-based structure learning algorithms on BNs to learn causal relations and make predictions about the risk factors of software development projects. Perkusich, Soares, Almeida, and Perkusich (2015) use BNs to identify problematic processes in software development projects.