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High-level integrated deterministic, stochastic and fuzzy cost-duration analysis aids project planning and monitoring, focusing on uncertainties and earned value metrics

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ABSTRACT

Integrating deterministic, fuzzy and stochastic analysis of cost-duration progress of complex projects under varying conditions of uncertainty at a high-level (at the work-item rather than the individual activity level) can be beneficial for decision makers in planning and monitoring infrastructure and other complex projects. Incorporating various facets of cost-duration uncertainty analysis with the principles of earned value management (EVM) can provide significant insight to the budget and schedule performance of projects with multiple parallel pathways of work items, plus reliable to-completion forecasts as a project evolves. Focusing on the critical path, stochastic analysis is able to quantify criticality, cruciality, uncertainty and downside risk measures at project, work item and budget levels. A project network and critical path analysis built around work breakdown progress diagrams calculating the progress to completion of between 20 and 50 work items at regular intervals (e.g. 2%–5%, involving 50 to 20 points equally spaced in time) along a baseline planned project schedule, provides a useful framework for a high-level cost-duration model. That framework can be rapidly and consistently evaluated for each case selected applying deterministic, fuzzy and stochastic analysis, each providing complementary insight to a project's performance at specific points in time, to-completion cost-duration forecasts, and quantify downside risks and uncertainties on a range of budget and schedule targets. A methodology is proposed that calculates earned duration and related duration performance index for critical path items weighted for their planned durations provides a measure of project duration performance that is more focused on critical path and crucial work items than standard earned schedule and earned duration metrics. Fuzzy analysis associated with the inability to establish precisely what progress has been truly achieved on each work items adds an additional component to uncertainty analysis not provided by stochastic analysis. Through careful selection of fuzzy set definitions and defuzzification methods fuzzy and stochastic models can be tuned to provide comparable and reliable EVM performance measures and improved to-completion forecasts with low mean absolute percentage errors to actual outcomes. The proposed methodology provides decision makers with a flexible and easy-to-interpret analysis, on a scale that is easy to produce in VBA driven spreadsheet without recourse to proprietary software, integrating multiple perspectives of uncertainty.

1. Introduction

The gas and oil industries do not have convincing track records of delivering large-scale facilities construction projects on time and/or on budget. Indeed, there are many instances in recent years of such projects, operated by global companies, that have overrun their planned schedules and budgets quite spectacularly. To name a few well-known projects that suffered this outcome: Snohvit LNG project in Norway (operated by Statoil; Mosbergvik, 2007); Escravos GTL project in Nigeria (operated by Chevron; Reuters, 2011); Sakhalin 2 offshore gas field, pipeline and LNG project in Russia (operated by Shell; Financial Times, 2005); and, Kashagan oil field offshore Kazakhstan (operated initially by ENI in a consortium including ExxonMobil, Shell and Total; Financial Times, 2014). There are also many smaller, lower-profile projects that have suffered similar fates.

A common feature is that initial front-end engineering and

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design (FEED) studies for these projects significantly underestimated costs and failed to adequately consider the appropriate uncertainties that ultimately led to unforeseen and/or unconsidered problems resulting in significant delays and cost overruns. Moreover, in the cases mentioned, the true magnitude of delays and cost overruns went undetected by the operators and project financiers (i.e., debt and equity fund providers) for far too long before remedial actions were initiated. Of course, there are many causes and unique events that contribute to delays and cost overruns in mega-infrastructure projects in the sector, only some of which could have been prevented by better monitoring and modelling techniques (EY, 2014).

Although the industry embraces earned value management (EVM) techniques, project network analysis using state-of-the art project management software, and, in some cases stochastic cost-duration modelling, there is much scope to improve the way the industry integrates uncertainty analysis into its cost-duration planning and forecasting models for investment sanctioning and monitoring purposes. Cost-duration project analysis, no matter how comprehensive its scope and framework, is never going to be able on its own to prevent all potential budget and schedule overruns. Nevertheless, clear benefits can be derived from high-level (i.e., at the work-item level – involving groups of activities - rather than at the individual-activity level), easy-to-implement methodologies that can provide greater insight to project cost-duration uncertainties. Such approaches can identify crucial stages and/or work items vulnerable to problems, and, enable monitoring that can rapidly detect potential bottlenecks, delays and their associated cost impacts, as early as possible. This study describes and evaluates such a methodology.

2. Project cost-duration analysis literature review

Methodologies exist that integrate earned value management (EVM) principles, project uncertainty, duration and cost analysis applying stochastic techniques (e.g., Yang, 2011; Pajares and Lopez-Paredes, 2011; Acebes et al., 2015). These have evolved from many years of research rooted in work breakdown scheduling (WBS), project network analysis, the program evaluation and review technique (PERT) (Clark, 1962), critical path analysis (CPA; Krishnamoorthy, 1968). Recognition of the significance of "criticality" and "cruciality" of specific project activities and activity pathways has progressively provided insight to the complexities of projects involving multiple pathways (Kelley, 1961; Kelley and Walker, 1989; Fulkerson, 1962; Dodin and Elmaghraby, 1985; Hagstrom, 1990; Williams, 1992; Soroush, 1994; Mummolo, 1997; Elmaghraby, 2000; Yang and Chen, 2000; Fatemi Ghomi and Teimouri, 2002).Applications of stochastic, Monte Carlo simulation analysis (Metropolis and Ulam, 1949) to better quantify project cost and duration uncertainties in PERT networks are well established (Van Slyke, 1963; Fisher et al., 1985; Casti, 1997; Cho and Yum, 1997; Hahn, 2008; Du et al., 2016).

The ability to respond to unexpected information concerning a project's work items and activities typically varies in an irregular manner over a project's life cycle (Williams, 2002). Unexpected events impact, positively or negatively a project's uncertainty and downside-risk exposure, and the potential scale of those impacts cannot be adequately forecast by deterministic analysis alone. Stochastic, Monte Carlo simulation, project cost-duration models have demonstrated their value in complement, rather than replacing deterministic analysis of project risk and uncertainty (Wood, 2002; Barraza et al., 2004; Bruni et al., 2009; Khamooshi and Cioffi, 2013; Azeem et al., 2014).

Earned Value (EV) evolved from a cost-management technique (Fleming and Koppelman, 1994) and its principles are now widely applied as EVM (Christensen, 1998, 1999; Anbari, 2003; Kim et al., 2003; Webb, 2003; Fleming and Koppelman, 2005, 2008; Stratton, 2007), to such an extent that it is now recommended as a best-practice technique (PMI, 2005; 2013). EVM, as routinely applied, involves a framework of metrics, such as: cost variance (CV); cost performance indicator (CPI); schedule variance (SV); schedule performance indicator (SPI); estimates at completion (EaC for cost and time); and, To-complete Performance Indicator (TCPI and TSPI). As originally configured, EVM derived its metrics by monitoring project costs incurred, resulting in erratic to-complete-project-duration projections (Henderson, 2003; Lipke et al., 2009). Lipke, (2003, 2004) proposed the Earned Schedule (ES) metric and its related indices: schedule performance indicator (SPIt); and, projected project duration at-completion (PPDt) for a specified point in time (t) along the project schedule. Despite its more elaborate calculation, still reliant on the cost-based EV, ES has become accepted as the most-reliable EVM metric for deriving to-completion duration forecasts (Lipke et al., 2009). However, ES sometimes is a less-reliable to-completion indicator for projects with multiple parallel work paths (Vandevoorde and Vanhoucke, 2006, 2007).

Developing more-accurate EVM metrics to monitor and forecast has been a fertile area of research in recent years. For example, Lipke (2011) proposed a method for incorporating the effects of "rework" associated with certain items into the ES metric, while Chen et al. (2016) explored improvements to planned value predictions. Vanhoucke (2011) developed ways of incorporating schedule risk into EVM analysis, whereas Elshaer (2013) recommended activity sensitivity analysis, Caron et al. (2013) described a Bayesian approach, and Colin &Vanhoucke (2014) suggested setting statistical limits to control EV, all in attempts to better address uncertainty in EVM.

Perhaps the most significant recent proposal for a more reliable EVM duration-related metric is the proposal to replace ES with the earned duration (ED) metric and SPIt with the duration performance index (DPI) (Khamooshi and Golafshani, 2014). This approach involves only duration -based (not cost-based) metrics in the to-completion duration forecasts and is a metric considered further here. Batselier and Vanhoucke (2015b) compared the performance of ES and ED metrics over many projects, concluding that ED-DPI resulted in slightly more reliable to-completion duration forecasts, but that both methods were still unreliable in certain projects.

As generally applied, EVM involves relatively simplistic deterministic calculations. In doing so, it ignores, to a large extent, the remaining cost-duration uncertainties associated with work yet-to-be initiated or completed and the potential consequences of unforeseen events. Stochastic models applied to EVM aim to address such uncertainties applying various methodologies (Vandevoorde and Vanhoucke, 2007; Pajares and Lopez-Paredes, 2011; Acebes et al., 2015). Stochastically-derived metrics that focus on downside risk exposure relative to specified targets, such as semi-standard deviation (SSD), guide attention towards problematic budget and schedule targets (Wood, 2001, 2002).

Fuzzy numbers have also been systematically applied to EVM metrics to address certain project uncertainties, not easily incorporated into stochastic models (Noori et al., 2008; Naeni et al., 2014, 2014). For example, incorporating ambiguities associated with assessment or reports of work completed to-date on a project.

Experience in deploying EVM across many industries has demonstrated its benefits, but there are also drawbacks making it often difficult to apply successfully (e.g., Lukas, 2008). Some studies have demonstrated that as a project's network topology becomes more parallel the accuracy of to-completion-project-duration forecasts derived from ES deteriorate (Vanhoucke, 2012; Lipke,