Estimated Cost at Completion: Integrating Risk into Earned Value Management

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Abstract: Earned value management (EVM) is an industry standard for monitoring the performance of ongoing projects. The performance baseline is set up in the planning phase to measure any time and cost deviations during project execution. Based on the current progress, an estimate at completion (EAC) is forecasted. Traditionally, EVM only focuses on the project schedule (SPI) and cost (CPI), and does not address other important aspects of health and safety, stakeholder satisfaction, and quality. Despite its superior formulation, EVM forecasts are still influenced by project risks and uncertainties, leading to inconsistency between EAC results obtained through standard formulae. In order to estimate better EAC, a framework is developed that incorporates various key performance indicators into the risk performance index (RPI). Using SPI, CPI, and RPI, an integrated model is developed and a number of case studies are run to validate it. The findings indicate a better EAC when compared to traditional methods. Introducing performance indicators to measure key aspects of the project will provide the stakeholders a better monitoring and decision-making tool. **DOI: 10.1061/(ASCE)CO.1943-7862.0001245.** *© 2016 American Society of Civil Engineers.*

Author keywords: Earned value management; Estimate at completion; Project risk; Risk performance index; Project monitoring and control; Cost and schedule.

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Introduction

Construction projects can be exceptionally complicated and are filled with uncertainty that may adversely affect their outcome (Flanagan and Norman 1993; Mills 2001). To cater for these uncertainties, contingency and management reserve are earmarked into the budget. These and other resources are mobilized to ensure the successful completion of a project (Hillson 2002). Project success is one of the most frequently discussed topics in the field of project management, yet it is the least agreed upon issue (Thomas and Fernández 2008; Hyväri 2006; Baccarini 1999). Project success refers to the successful completion of cost, time, and scope objectives (Ika 2009), quality of the project management process (Baccarini 1999), and satisfying stakeholders' needs (Ika et al. 2012).

According to the management literature, what cannot be measured, cannot be managed (Cioffi 2006). The success of project can be measured using the key performance indicators (KPIs) that include, but are not limited to, cost, time, quality, safety, and stakeholder satisfaction. Though project success is an end, it does not come without means. Thus, to determine the possibility of achieving success, projects are assessed during their execution. Earned value management (EVM) is a key tool for measuring project performance and is widely used in the construction industry for global monitoring of a project (Fleming and Koppelman 2002). EVM uses a performance measurement baseline (PMB) and any variations from the PMB are tracked to monitor the progress. These variations usually affect the project objectives that include cost, quality, scope, and time (Banaitiene and Banaitis 2012). EVM only focuses on schedule and cost aspects of the project and does not explicitly consider other important constraints of the project such as quality, scope, safety, and risk (Narbaev and De Marco 2011, 2013).

Since construction projects are prone to major uncertainties, project risk management (PRM) is used as a planning as well as monitoring and control tool to help projects achieve their targets (Hillson 2002). PRM in nature is forward looking, whereas EVM forecasts the future performance in the form of an estimate at completion (EAC) based on past data. The basic limitation of EVM is its sole reliance on past performance without taking into account the strength of PRM of being able to foresee future uncertainty. This not only restricts the practitioners from getting better EAC but also results in loss of precious data due to the multiple processes employed (Diamantas et al. 2011). To make matters even more challenging, the redundancy of data use in these processes exhausts the already limited resources (Khalili-Damghani et al. 2013). Since the limitation of one technique is the strength of the other and vice versa, there is a strong need to integrate both tools in order to achieve improved results (Hillson 2004). EVM uses two KPIs—cost performance index (CPI) and schedule performance index (SPI)—to measure the past performance (Naeni et al. 2011). In order to expand its focus and functionality, there is a need to involve other indices so that when the EAC is forecasted, it takes into account the uncertainty the project may face in the future. These indices can also provide better insight into the performance of other key aspects of the project, which include, but are not limited to, quality, safety, and stakeholder satisfaction.

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This study aims to introduce new KPIs to measure the project performance in the areas of quality, safety, and stakeholder satisfaction. It also identifies the constituent variables for effective evaluation of KPIs. The paper models an equation for risk performance index (RPI) that incorporates the results of these KPIs. Furthermore, an empirical relation between RPI and the existing EVM KPIs (CPI and SPI) is developed for better forecasting of EAC. The results are compared with the standard Project Management Institute (PMI 2013) methods, and conclusions and recommendations are made.

Literature Review

Earned Value Management

EVM is defined as "the performance measurement to report the status of a project in terms of both cost and time at a given data date" (Popescu and Charoenngam 1995). EVM is based on combining the project's cost and schedule in a single measurement system and is one of the most widely used methods for monitoring, analyzing, and forecasting project cost and schedule performance (Mubarak 2015). Using the current progress and performance of the project at a given time, the actual status is compared with the PMB and deviations are calculated. Based on these deviations, EAC cost is forecasted (PMI 2013). The primary limitation of EVM when forecasting EAC is its dependency on past cost performance only, unreliable forecasted figures at early stages of the project, and no count of forecasting statistics (Kim and Reinschmidt 2010; Tracy 2005; Fleming and Koppelman 2000; Zwikael et al. 2000).

Estimate at Completion

Projects during their execution phase may deviate from their original planned cost; therefore, the project team forecasts the EAC, which differs from the budget at completion (BAC) and is based entirely on the current performance of the project (PMI 2013). Although a number of studies based on standard formulae and other models are available to forecast EAC, which one offers the best solution is the practitioner's dilemma. In the face of no specific guideline regarding the best model for most accurate results, the choice is left with analysts and project managers to decide the EAC formula to be used for forecasting (Iranmanesh and Zarezadeh 2008). The only possible intuitive advice is offered by the project conditions and level of expertise possessed by the project management team (Christensen et al. 1992). EAC formulae are based on the combination of several data elements, which include budgeted cost of work schedule (BCWS), budgeted cost of work performed (BCWP), and actual cost of work performed (ACWP). According to PMI (2013), three of the most common EAC forecasting techniques for the estimate to complete (ETC) are discussed in the following.

The first method uses the actual cost until the data date and predicts that the rest of the project will be executed at the planned rate. The mathematical representation of this method is given in Eq. (1)

$$\mathrm{EAC} = \mathrm{AC} + (\mathrm{BAC} - \mathrm{EV}) \tag{1}$$

The second method considers the current cost performance index (CPI) of the project and assumes that the rest of the project will be completed at the current rate, as mathematically expressed in Eq. (2)

$$\mathrm{EAC} = \frac{\mathrm{BAC}}{\mathrm{CPI}} \tag{2}$$

The third forecasting equation considers both the SPI and CPI of the project and is mostly useful when the schedule of the project is an impacting factor. This method can be varied by assigning a complimentary weight to each index as per the project manager's decision. However, the sum of these weights usually equates to 1 (Christensen et al. 1992). The mathematical representation of this method is given in Eq. (3)

$$\mathrm{EAC} = \mathrm{AC} + \left(\frac{\mathrm{BAC} - \mathrm{EV}}{\mathrm{CPI} \times \mathrm{SPI}}\right) \tag{3}$$

Project Risk Management

Construction projects are prone to uncertain scenarios, so PRM has been recommended as a vital technique to achieve the project objectives (Alali and Pinto 2009; Perera and Holsomback 2005; Baloi and Price 2003; Akintoye and MacLeod 1997). PRM is an iterative process that is useful when conducted throughout the project's duration, from its planning phase to completion (Banaitiene and Banaitis 2012). When a risk event triggers, it usually has an impact on project aspects such as schedule, cost, quality, resources, deliverables, and performance (Dumbravă and Iacob 2013). The more the risk an activity has, the more cost it would incur if a wrong decision is made in this regard (Jannadi and Almishari 2003). Risks cost stakeholders money and time, so when a risk triggers, the stakeholders suffer the consequences (Zavadskas et al. 2010; Hameed and Woo 2007). As the construction industry inherits a high level of risks due to the complexity and difference in nature of the projects, risk analysis and management has become a crucial tool to help in the decision-making process (Iqbal et al. 2015). As PRM attempts to look ahead at potential futuristic influences on the project objectives, this information can be useful when forecasting EAC (Hillson 2004).

EVM and PRM Integration

Pertinent research has been carried out in the domain of probabilistic planning methods, but no framework has been developed for project performance measurement that takes into account the risks in an activity as well as its cost, duration, and progress (Barraza et al. 2000). Barraza et al. (2004) formulated a method that uses stochastic S-curves (SS-curves) developed after finding variability in the cost and duration of each activity for probabilistically monitoring and forecasting the project performance.

PRM and EVM have similar objectives, i.e., providing information about the factors affecting the project performance. However, no framework exists for interconnection of the results obtained from each technique. As the same problems are being addressed by both tools, there is a lot of interest in combining their results. If the PMB of a project consists of well-equated risk factors, uncertainties can be foreseen and a better EAC can be forecasted (Hillson 2004). It is thus suggested to perform time and cost risk analysis and quantify the identified risks in terms of cost. This cost is to be added in the PMB as a contingency and the new project baseline can be used for both project monitoring and forecasting a better EAC (Diamantas et al. 2011).

The approach suggested by the Association of Project Management (APM 2008) is based on interfacing the two methods rather than integrating them. The difference between APM's approach and that of Barraza et al. (2000) and Hillson (2004) is that the PMB uses the percentile of the project probability density function (PDF) rather than the expected value method. The PDF for both time and

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cost is calculated using Monte Carlo simulation (MCS), which can help in estimating the contingency reserve.

Key Performance Indicators

Cox et al. (2003) highlighted that in terms of effectiveness, efficiency, and quality of work, KPIs play a crucial role to compare the actual and scheduled performance. KPIs are a collection of measurable data, either qualitative or quantitative, that can provide an insight to the performance of any construction project. Chan and Chan (2004) suggested eight KPIs to measure construction performance, which include time, cost, quality, participant's satisfaction, user's expectation/satisfaction, environmental performance, commercial profit/value, and health and safety. Furthermore, according to Kim (2010), the risk performance index (RPI) mainly constitutes a schedule risk performance index and cost risk performance Index. Lee et al. (2013) identified KPIs for assessing quality of expressway construction and used them to develop a quality performance index (QPI) equation. Kim (2010) identified quality, stakeholder satisfaction, and safety as KPIs for measuring project performance.

Methodology

The relevant literature regarding EVM, PRM, the integration of EVM with PRM, and use of KPIs for monitoring project aspects was studied to develop a methodology for this research. The literature wass searched using the libraries of ASCE, Google Scholar, Taylor and Francis online. and SCOPUS. The keywords-based searching method used *earned value management*, *estimate at completion*, *project risk*, *risk performance index*, *quality performance index*, *safety performance index*, *construction performance indicators*, and *project monitoring and control* as search criteria within the areas of construction and project management. As a result, 57 relevant research papers published during the period 1995–2015 are retrieved. A total of 55 constituent variables (CVs) were identified from these research papers. The corresponding frequency of each CV was then recorded. To avoid duplication, the literature is properly organized to carefully record the frequency of each CV. These CVs are then integrated into relevant KPI equations of quality, safety, and stakeholder satisfaction with an input value from 0 to 1 on a numeric scale based on input from semistructured interviews. The range represents worst performance/conditions (0) and perfect performance/conditions (1). Individual KPI equations are then merged into the RPI equation. Finally, RPI, CPI, and SPI values are determined to derive the EAC.

Following the methodology of Lee et al. (2013), preliminary structured interviews are conducted by online and physical meetings to rank and find the respective weight of identified CVs. The sample size for this data collection is kept between 10 to 40 as per Hertzog (2008) and Van Belle (2011). As a result, a total of 39 responses are gathered from 12 different countries from which 31 are of industry experts, mainly working as project managers, and the rest are from academia. A total of 84.6% respondents have experience of more than 5 years, while the remaining reported experience of 3–5 years.

Before the face-to face-interview, as part of the semistructured methodology, a pilot study questionnaire in English is sent to the respondents' official email addresses. They are asked to rank the CVs on a scale of −3 to +3 where −3 represents the maximum negative effect (increasing the cost of project), +3 represents the maximum positive effect (adding value without increasing the cost of project), and 0 represents no effect.

Further, statistical tests are applied, including Cronbach's alpha for data reliability, the Anderson Darling test for normality, and Spearman's rho for correlation between the frequencies of identified CVs in literature and pilot survey. The relative importance index (RII) of the CVs within their respective groups is then evaluated using Eq. (4)

$$\mathrm{RII} = \frac{\sum W}{AxN} \quad (0 \le \mathrm{RII} \le 1) \tag{4}$$

where W = weight given to each factor by the respondents; A = highest weight, i.e., 3 in this case; and N = total number of respondents. Muhwezi et al. (2014) considered factors having RII less than 0.599 to be insignificant, but to capture the wider impact, a minimum limit of 0.50 is set and factors with lower RII are discarded from further analysis. As a result, a total of 16 factors having an RII > 0.5 are considered for the study.

In order to calculate the RPI, the value of a particular KPI is determined by summing the normalized individual weight of a CV multiplied with its value, which is based on the current performance of project at any data date. The value of RPI is calculated by adding these individual group values multiplied with their respective normalized group weightings as shown in Eq. (5)

$$\mathrm{RPI} = \omega_1\left[\sum_{i=1}^{n}\alpha_i\kappa_i\right] + \omega_2\left[\sum_{\substack{i=1\\ j=n+1}}^{m}\beta_i\kappa_j\right] + \omega_3\left[\sum_{\substack{i=1\\ k=m+1}}^{p}\gamma_i\kappa_k\right] + \omega_4\left[\sum_{\substack{i=1\\ l=p+1}}^{q}\rho_i\kappa_l\right] + \cdots \infty \quad (0 \le \mathrm{RPI} \le 1) \tag{5}$$

where ω_1, ω_2, ω_3, and ω_4 = group weightings; κ_i, κ_j, κ_k, and κ_l = perspective values of CVs at the data date ranging from 0 to 1; and α_i, β_i, γ_i, and ρ_i = internal weightings of the respective CVs.

The shortlisted CVs of quality, safety, stakeholder satisfaction, and others are incorporated in the generalized model given in Eq. (5) to calculate the respective KPIs. Particularly, the quality performance indicator (QPI) is given by Eq. (6), the safety performance indicator (SFPI) by Eq. (7), the stakeholder satisfaction performance indicator (SSPI) by Eq. (8), and the other performance indicator (OPI) is given by Eq. (9). It is important to note that a number of CVs share weighting and influence from each other. Thus, in order to avoid their multiple effects, CVs are rationally simulated into KPIs considering their global influence

$$\mathrm{QPI} = \alpha_1\kappa_1 + \alpha_2\kappa_2 + \alpha_3(0.34\kappa_3 + 0.33\kappa_4 + 0.33\kappa_1) + \alpha_4\kappa_4 + \alpha_5\kappa_5 \tag{6}$$

$$\mathrm{SFPI} = \beta_1(0.5\kappa_6 + 0.5\kappa_7) + \beta_2\kappa_7 + \beta_3\kappa_8 + \beta_4\kappa_9 \tag{7}$$

$$\mathrm{SSPI} = \gamma_1\kappa_{10} + \gamma_2\kappa_{11} + \gamma_3(0.34\kappa_{12} + 0.33\kappa_{10} + 0.33\kappa_{11}) \tag{8}$$

$$\mathrm{OPI} = \rho_1(0.3\kappa_{13} + 0.2\kappa_1 + 0.2\kappa_5 + 0.2\kappa_3 + 0.1\kappa_{13}) + \rho_2\kappa_{14} + \rho_3\kappa_{15} + \rho_4(0.6\kappa_{16} + 0.4\kappa_{10}) \tag{9}$$

The respective equation of aforementioned indices when multiplied with their respective KPI weights gives the mathematical relationship for RPI as shown in Eq. (10)

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$$\begin{aligned}\mathrm{RPI} = {} & \omega_1[\alpha_1\kappa_1 + \alpha_2\kappa_2 + \alpha_3(0.34\kappa_3 + 0.33\kappa_4 + 0.33\kappa_1) \\ & + \alpha_4\kappa_4 + \alpha_5\kappa_5] + \omega_2[\beta_1(0.5\kappa_6 + 0.5\kappa_7) \\ & + \beta_2\kappa_7 + \beta_3\kappa_8 + \beta_4\kappa_9] + \omega_3[\gamma_1\kappa_{10} + \gamma_2\kappa_{11} \\ & + \gamma_3(0.34\kappa_{12} + 0.33\kappa_{10} + 0.33\kappa_{11})] \\ & + \omega_4[\rho_1(0.3\kappa_{13} + 0.2\kappa_1 + 0.2\kappa_5 + 0.2\kappa_3 + 0.1\kappa_{13}) \\ & + \rho_2\kappa_{14} + \rho_3\kappa_{15} + \rho_4(0.6\kappa_{16} + 0.4\kappa_{10})] \quad (0 \le \mathrm{RPI} \le 1)\end{aligned} \tag{10}$$

Following Narbaev and De Marco (2011), EAC can be calculated using Eq. (11)

$$\mathrm{EAC} = \mathrm{AC} + \frac{\mathrm{BAC} - \mathrm{BCWP}}{\mathrm{W1CPI} + \mathrm{W2SPI}} \tag{11}$$

Other than the general EVM parameters, Eq. (11) uses W1 and W2, which are complementary weights assigned to CPI and SPI and their sum is usually 1.

To incorporate the influence of RPI [Eq. (10)] in EAC [Eq. (11)], complementary weightings are assigned to CPI, SPI, and RPI, which sum up to 1. Eq. (12) demonstrates the new derived equation of EAC incorporating the influence of RPI

$$\mathrm{EAC} = \mathrm{AC} + \frac{\mathrm{BAC} - \mathrm{BCWP}}{\mathrm{W_1CPI} + \mathrm{W_2SPI} + \mathrm{W_3RPI}} \tag{12}$$

where W1, W2, and W3 = complementary weightings assigned to each index, respectively.

To find the complimentary weightings for each index in Eq. (12), a detailed survey is conducted. Adopting the methodology from Riedel and Chance (1989), index values for each quarter of project completion are used to forecast a better EAC. This is in line with Pinto and Prescott (1988) who suggested that the relative importance of KPIs changes significantly based on lifecycle stages. Incorporating this insight, respondents are asked to give weightings in terms of percentage from 0 to 100% to CPI, SPI, and RPI during the four quarters of physical progress of the project, i.e., 0–25%, 26–50%, 51–75%, and 76–100%.

The survey form is prepared in English using Google forms and is distributed using official emails, and through social and professional websites. To get a broader input, the audience of the survey is kept global. Sample size was calculated as per Conroy (2006) who states that for a larger population with a margin of error of 10%, the acceptable sample size is 96. For the current study, a total of 170 respondents were contacted through the previously described means. Of these 170, 126 responded to the survey, of which 101 responses from 13 countries are accepted as being complete and useful for further analysis, giving an accurate response rate of 59.41%. The remaining 15 responses were rejected due to inappropriate selection or incompleteness. Also, all respondents belonged to high to medium managerial positions with who have completed at least two construction projects. A total of 81 respondents work in the industry and 20 are from academia. With a minimum reported experience of 4 years, 83 respondents had more than 5 years of experience. Further, 66 respondents worked with private companies, 20 with semigovernment organizations, and 15 belong to the public sector. Cronbach's alpha test is applied to check the reliability of the data obtained from the survey, and yielded a value of 0.8278, confirming that the data are highly reliable.

The results obtained for each index are normalized to 1 and are incorporated in Eq. (12) to develop the final equation for EAC forecasting. For validating the proposed methodology, data obtained from completed construction projects were compared using existing PMI equations and the developed ones and results were drawn. Further, to statistically validate the differences between the described equations, one-way ANOVA analysis was conducted.

Results

Based on the detailed literature review, the identified CVs are ranked using their RII based on 39 responses from preliminary interviews. The acquired data are checked for reliability using Cronbach's alpha test and yielded a value of 0.9652, making the data highly reliable.

To find the correlation between the RII of CVs calculated from their frequency in the literature and the RII of the CVs from the interview scores, the Spearman rank order correlation test is conducted. Correlation is identified between the two results using the Spearman rank order correlation coefficient (r_s), valued at 0.5832. Some of the CVs like rework and stakeholder satisfaction have higher ranks in both the literature and interviews, showing consensus between literature and industry. On the other hand, some of the CVs like nonconformance rate, personnel quality training, strategic quality management, design process, and project management activities have a lower ranking in the literature score but the industry ranks them otherwise, indicating relatively higher importance in the field compared to academia. Similarly, there are some CVs like safety trainings and jobsite toolbox meetings, which have a higher ranking in the literature but have relatively lower ranking in the interviews, indicating that industry is reluctant towards adopting safety procedures and considers them less important. The RII scores of the CVs within their KPI group and the KPI weight are normalized to 1. The complete details of the CVs and KPIs are shown in Table 1.

The equation for RPI is acquired after incorporating all the weightings of CVs, their interdependency, and KPIs in Eq. (10) and is mathematically constructed as shown in Eq. (13)

$$\begin{aligned}\mathrm{RPI} = {} & 0.29902[0.187\kappa_1 + 0.184\kappa_2 + 0.196(0.34\kappa_3 + 0.33\kappa_4 \\ & + 0.33\kappa_1) + 0.249\kappa_4 + 0.184\kappa_5] \\ & + 0.23513[0.268(0.5\kappa_6 + 0.5\kappa_7) + 0.279\kappa_7 + 0.223\kappa_8 \\ & + 0.230\kappa_9] + 0.21739[0.351\kappa_{10} + 0.367\kappa_{11} \\ & + 0.282(0.34\kappa_{12} + 0.33\kappa_{10} + 0.33\kappa_{11})] \\ & + 0.24844[0.225(0.3\kappa_{13} + 0.2\kappa_1 + 0.2\kappa_5 + 0.2\kappa_3 \\ & + 0.1\kappa_{13}) + 0.246\kappa_{14} + 0.271\kappa_{15} \\ & + 0.257(0.6\kappa_{16} + 0.4\kappa_{10})] \quad (0 \le \mathrm{RPI} \le 1)\end{aligned} \tag{13}$$

Scores from the survey are normalized to 1 for each quarter of the project, as shown in Table 2. The complementary weightings for the CPI in each quarter from the survey indicate its relative importance when forecasting EAC. The weight of CPI drops slightly in the 2nd quarter by 0.09 but then increases in the last half of the project duration. The CPI plays a major role in determining the EAC amount. Further, the weight assigned to the SPI follows a bell-shaped distribution with the highest weight in the 2nd quarter (0.3209) and then losing its significance as the project moves on to the last quarter (0.3027). Christensen et al. (1992) suggested assigning a lower weight to SPI towards the end of the project as SPI loses its predictive value towards the end. Although SPI starts a declining trend from the 2nd half of the project, it still remains relatively more important than the RPI throughout each quarter but less significant than the CPI. According to Ford (2002), schedule

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Table 1. Normalized Weight of PIs

KPI report	Normalized KPI weight	CV report	CVs	CV weightings report	CV RII	Normalized CV weight
			Quality			
ω_1	0.29902	K_1	Nonconformance rate	α_1	0.53846	0.187
		K_2	Personnel quality training	α_2	0.52991	0.184
		K_3	Quality systems	α_3	0.5641	0.196
		K_4	Rework/defects	α_4	0.71795	0.249
		K_5	Strategic quality management	α_5	0.52991	0.184
			Safety			
ω_2	0.23513	K_6	Accident frequency ratio	β_1	0.60684	0.268
		K_7	Management personnel with standard certification	β_2	0.63248	0.279
		K_8	Safety equipment and maintenance	β_3	0.50427	0.223
		K_9	Safety training	β_4	0.52137	0.230
			Stakeholder satisfaction			
ω_3	0.21739	K_{10}	Change orders	γ_1	0.73504	0.351
		K_{11}	Conflicts/disputes/claims	γ_2	0.76923	0.367
		K_{12}	Stakeholder satisfaction	γ_3	0.58974	0.282
			Others			
ω_4	0.24844	K_{13}	Design process	ρ_1	0.53846	0.225
		K_{14}	Land acquisition	ρ_2	0.58974	0.246
		K_{15}	Project management activities	ρ_3	0.64957	0.271
		K_{16}	Wastage	ρ_4	0.61538	0.257

Table 2. Complementary Weightings of Each Index

Index	Complementary weight
0–25% project completion	
Cost performance Index	0.4209
Schedule performance Index	0.3011
Risk performance Index	0.2780
26–50% project completion	
Cost performance Index	0.4200
Schedule performance Index	0.3209
Risk performance Index	0.2591
51–75% project completion	
Cost performance Index	0.4355
Schedule performance Index	0.3174
Risk performance Index	0.2471
76–100% project completion	
Cost performance Index	0.4365
Schedule performance Index	0.3027
Risk performance Index	0.2607

control becomes important during the middle of the project and the contingency amount must be spent to avoid any slippage. This is reinforced by observing the trend from this survey, showing that cumulatively around 64% complementary weight is given to SPI during the 2nd and 3rd quarters of the project. Finally, the RPI follows a U-shaped distribution with the maximum weight in the 1st quarter (0.2780). It then starts losing its significance until the 4th quarter where a marginal raise is observed in the last quarter (0.2607). This point regarding the importance of risk towards project performance indicats that projects suffer the most in the beginning and towards the end (Martin and Tate 2002). The RPI weightings remain close to those of SPI (average difference = 0.0492) throughout each quarter, indicating that the respondents have ranked risk at almost the same level as schedule, thus emphasizing its importance when incorporated in forecasting EAC.

Results obtained from the survey are incorporated in Eq. (12). Four equations are generated for the four quarters of project completion as shown in Eqs. (14)–(17), respectively. All these mathematical relationships are fed into Microsoft *Excel* to develop a user-friendly model for simulating various project scenarios

$$\mathrm{EAC} = \mathrm{AC} + \frac{\mathrm{BAC} - \mathrm{BCWP}}{0.4209\mathrm{CPI} + 0.3011\mathrm{SPI} + 0.278\mathrm{RPI}} \tag{14}$$

$$\mathrm{EAC} = \mathrm{AC} + \frac{\mathrm{BAC} - \mathrm{BCWP}}{0.42\mathrm{CPI} + 0.3209\mathrm{SPI} + 0.2591\mathrm{RPI}} \tag{15}$$

$$\mathrm{EAC} = \mathrm{AC} + \frac{\mathrm{BAC} - \mathrm{BCWP}}{0.4355\mathrm{CPI} + 0.3174\mathrm{SPI} + 0.2471\mathrm{RPI}} \tag{16}$$

$$\mathrm{EAC} = \mathrm{AC} + \frac{\mathrm{BAC} - \mathrm{BCWP}}{0.4365\mathrm{CPI} + 0.3027\mathrm{SPI} + 0.2607\mathrm{RPI}} \tag{17}$$

Along with the CPI and SPI, a major weighting of the developed EAC depends upon the RPI, which gets its input value from the CVs. To check the effect of all the CVs on RPI, which in turn affects EAC, a sensitivity analysis is performed using the *@Risk 5.5* add-on for *Excel*. A random project environment is created, data regarding the costs are entered, and the inputs related to the CVs are given to the model by defining their input ranges between 0 and 1. A total of 10,000 iterations are run.

The iterations resulted in the overall cumulative density function (CDF) as shown in Fig. 1. It shows that a project having planned cost of 100,000 units of currency at 10% of its physical completion having a CPI of 0.77 and SPI of 0.88 will have a minimum and maximum EAC of 128,696 and 157,654 units of currency, respectively. The variance between the minimum and maximum values shows the impact of risk in terms of cost that the project can face until its completion. If the risks related to quality, safety, and other aspects are not materialized, the project will finish near the minimum identified cost as the CPI of the project is low. However, if the risks trigger, the cost will increase and is likely to remain within the identified upper limit. The CDF also shows the probability of completing the project at a certain cost; for example, there is only 25% probability that the project having 100,000 BAC, CPI of 0.77, and

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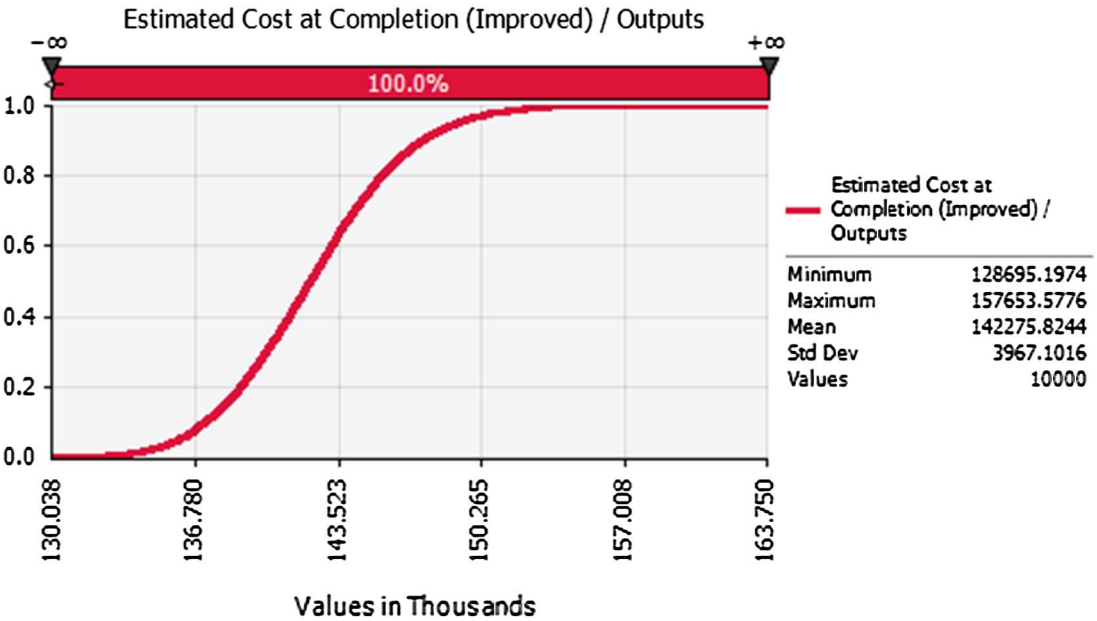

Fig. 1. Cummulative density function (CDF)

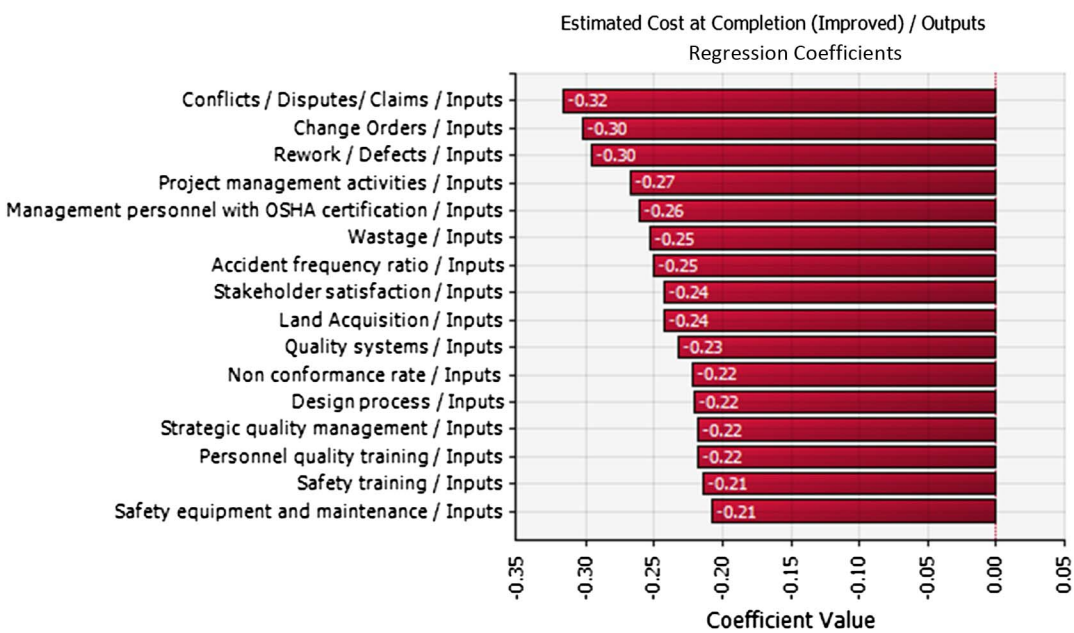

Fig. 2. Regression coefficients

SPI of 0.88 will complete at 139,500 units of currency in a random risk environment. Similarly, the probability of the project to be completed under 144,190 is 40%, while there is a 90% chance of it being completed under 147,460 units of currency. So, the actual cost at completion (CAC) follows an incremental trend with an increase in the confidence. Further, the individual effect of any CV can also be observed from the coefficient values obtained from sensitivity analysis as shown in Fig. 2.

The coefficient values show that the CV of conflicts/disputes/claims has the largest impact on the RPI value, which increases the forecasted EAC amount. It is evident from a number of studies that poor contract management both in developed (Semple et al. 1994) and developing (Okpala and Aniekwu 1988) countries have been a major risk affecting cost (Rosenfeld 2013). Similarly, CVs of rework and change orders have the second highest impact on the output results, followed by project management activities and certified safety personnel on site.

Case Studies

To validate the proposed model, the developed equation is applied to data obtained from the completed construction projects from two different countries: Pakistan and Qatar. The project managers are asked various questions regarding the input variables (CVs) of the modeled equation. As stated in the methodology, different

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Table 3. Financial Details of Case Studies in USD

Case study	Value type	Completion percentage 20%	40%	70%	90%	100%
1	Planned value (PV)	45,373.35	80,066	147,761	188,269	212,514
	Actual cost (AC)	44,775.77	81,599	141,188	191,576	211,654
	Earned value (EV)	45,714.20	82,538	145,878	198,776	214,938
2	Planned value (PV)	47,306	101,103	170,463	237,902	243,518
	Actual cost (AC)	51,555	112,301	179,391	230,918	257,510
	Earned value (EV)	50,014	107,420	163,312	224,384	246,005
3	Planned value (PV)	—	—	—	151,446,563	164,946,563
	Actual cost (AC)	—	—	—	162,407,789	199,458,958
	Earned value (EV)	—	—	—	135,794,210	189,211,851

weightings are assigned to CPI, SPI, and RPI for four quarters of the project, so the data of the project re obtained at four data points of project completion. As the actual CAC is already known, it is compared with the results obtained from the developed model, as well as with the PMI standard equations. The case studies allow checking the behavior of the proposed model when applied on a real construction project. Due to the confidential nature of the data, the project descriptions are not disclosed; however, the financial details are given in Table 3.

The project of Case Study 1 is an administrative building. With a duration of 10 months and contract amount of US$224,780, the budgeted planned cost of the project was US$212,514. The project was completed in time and within the planned budget. Further, the project of Case Study 2 is a school building and was due to be completed in 12 months. The contract amount of the project was US$261,580 with the budgeted planned cost of US$243,518. The project was completed 1 month late and suffered some losses in terms of profit. Finally, the project of Case Study 3 is an oil and gas facility. The baseline cost of the project was US$164,946,563 and the planned duration was 27 months. The project faced delays and was completed in 33 months. This project was completed way above the planned value, so the contractor faced major losses, which were later claimed after project closure. The data of Case Study 3 were only received at 85% physical completion along with its actual CAC.

The inputs regarding the CVs are taken as per the project manager's perspective, which is a mix of subjective and objective assessment of various performance metrics on their projects. It must be noted that the entire estimation process is built upon careful and accurate assessment of CVs and KPIs. Thus, in order to ensure maximum accuracy, three project managers were consulted a number of times for their valuable inputs. Further, to incorporate academic vision, three professors were asked to participate. The data points were systematically reviewed in accordance to Tranfield et al. (2003). The inclusion of academic experts helped in analyzing CVs with subjective input where the influence from multiple CVs was normalized for assessment. For example, the effectiveness of quality training is estimated using 33.3% each of *personnel quality training* value, *nonconformance rate*, and *rework/defects*. These weights were validated by the projects managers according to their experience.

Table 4 shows the CV values as simulated using the developed model at four distinct points: 20, 40, 70, and 90% for Case Studies 1 and 2. For Case Study 3, only one data point is available; hence, it is only simulated at 85% completion. Owing to the varying significance of KPIs during the project lifecycle, the data are simulated

Table 4. CV Input Values of Case Studies

KPI	CV	Percent complete: Case Study 1 20%	40%	70%	90%	Case Study 2 20%	40%	70%	90%	Case Study 3 85%
Quality	Nonconformance rate	0.9	0.8	0.75	0.7	0.9	0.85	0.75	0.65	0.6
	Personnel quality training	1	1	1	1	1	1	1	1	1
	Quality systems	0.9	0.9	0.9	0.9	0.7	0.7	0.7	0.7	0.9
	Rework/defects	0.95	0.9	0.9	0.75	0.95	0.9	0.8	0.8	0.79
	Strategic quality management	0.9	0.9	0.9	0.8	0.7	0.7	0.7	0.7	0.8
Safety	Accident frequency ratio	1	0.95	0.85	0.8	0.97	0.9	0.85	0.8	0.94
	Management personnel with standard certification	1	1	1	1	1	1	1	1	1
	Safety equipment and maintenance	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.8
	Safety training	1	1	1	1	1	1	1	1	1
Stakeholder satisfaction	Change orders	1	1	1	0.8	1	1	0.9	0.8	0.65
	Conflicts/disputes/claims	1	1	1	1	1	0.9	0.6	0.6	0.5
	Stakeholder satisfaction	1	1	0.85	0.85	0.85	0.85	0.5	0.5	0.5
Others	Design process	0.95	0.95	0.85	0.75	0.6	0.6	0.6	0.6	0.5
	Land acquisition	1	1	1	1	0.6	0.7	0.7	0.9	1
	Project management activities	1	1	1	1	0.7	0.7	0.7	0.7	0.8
	Wastage	0.9	0.9	0.7	0.5	0.8	0.7	0.7	0.7	0.5

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Table 5. Indices Values of Case Studies

	Percent complete								
	Case Study 1				Case Study 2				Case Study 3
Performance matric	20%	40%	70%	90%	20%	40%	70%	90%	85%
Cost performance index	1.021	1.012	1.033	1.038	0.944	0.957	0.965	0.972	0.836
Schedule performance index	1.008	1.031	0.987	1.056	1.029	1.042	1.015	0.943	0.897
Quality performance index	0.922	0.881	0.869	0.792	0.846	0.818	0.762	0.737	0.779
Safety performance index	0.955	0.936	0.898	0.857	0.922	0.895	0.876	0.857	0.932
Stakeholder satisfaction performance index	1.000	1.000	0.986	0.897	0.986	0.940	0.724	0.679	0.567
Risk performance index	0.960	0.943	0.918	0.850	0.861	0.840	0.768	0.756	0.765

Table 6. Forecasted EAC Values (USD) of Case Studies

	Percent complete								
	Case Study 1				Case Study 2				Case Study 3
Estimation method	20%	40%	70%	90%	20%	40%	70%	90%	85%
EAC (PMBOK) [Eq. (3)]	206,933	206,248	206,515	204,117	251,955	248,863	251,189	251,795	201,292,367
EAC (PMBOK) [Eq. (2)]	208,152	210,097	205,683	204,817	257,830	254,581	252,296	250,609	197,273,556
EAC (PMBOK) [Eq. (1)]	211,576	211,575	207,825	205,314	246,380	248,398	249,711	250,052	191,560,142
EAC (developed equations) [Eqs. (14)–(17)]	211,586	211,587	208,480	205,394	257,339	255,013	254,917	252,015	197,287,221

at random points within each quarter to capture maximum forecast scenarios. The points are carefully selected to avoid transitional biases from one quarter to another.

It must be noted that revealing the profit margin is always a challenge for contractors and usually such financial data are not provided as it directly affects the privacy and repute of organization. Thus, collecting such data becomes even more challenging. However, owing to the convenient availability of data, this process can be simulated for almost all construction projects except for where the accuracy of the costing system is unreliable (Gershon 2013).

After using the inputs regarding the CVs and the financial data, CPI, SPI, and RPI for the respective data points are calculated using the modeled equation and are shown in Table 5. The forecasted EAC values using the standard and the developed equations are shown in Table 6.

The trend of CPI and SPI of Project 1 somehow has remained same; it is maintained at above 1.0 except once, when the SPI dropped to 0.98 at 70% completion. Due to near-perfect performance of the project, the cost and schedule have remained close to the planned value. Thus, the actual CAC shows a saving of about US$860. Taking into consideration the CPI and SPI of the project at various stages, the EAC equations of PMI show that there could have been more savings. For example; considering the project statistics at 20% completion (CPI = 1.02 and SPI = 1.00), as per the three standard PMI formulae, the EAC would be US$206,900, 208,100, and 211,600 respectively. When compared with the actual CAC, an average variance of US$2,100 is obtained.

This cost difference can be easily explained by the methodology proposed in this research that a project having no schedule issues and being executed under the planned budget may be exposed to some risks related to quality, safety, and stakeholder satisfaction. The RPI value in Case Study 1 dropped from 0.96 at 20% completion to 0.85 at 90% completion. This decrease in RPI describes the increase in probability of risk exposure. which this project actually faced during its course. As the CPI and SPI of the project somehow remained near 1.0 up until 90% completion. PMI's EAC formulae forecast the project completion cost between US$204,117 to 211,576 throughout the project. When EAC is calculated using the modeled equation incorporating the RPI, the forecasted amount is more realistic and closer to the actual CAC of the project. The ranges were found out to be in between US$205,394 and 211,587. Table 6 shows the comparison of EAC values by PMI formulae and the proposed model.

In Case Study 2, the CPI is 0.94 at 20% completion and by 90% completion it has climbed to 0.97, depicting the cost control after the first quarter of the project. Similarly, the project seems on schedule until 40% completion with SPI of 1.04 but at 90% it has dropped to 0.94. The varied SPI in the later stage of the project indicates incoherence with the project baseline schedule. The project exceeded the planned cost by US$13,992 and hence reduced the contractor's profit. If the RPI of the project at 20% is taken into account, the risk performance is worse than that of cost and schedule. The deteriorating trend of risk performance continues throughout the project, which points to inadequate risk management. The project has suffered losses in its last quarter due to some major rework, an accidental death at site, and land acquisition issues resulting in delay and cost overruns. The delay due to land acquisition was later claimed by the contractor, leading to a dispute between stakeholders and resulting in negative feeding of relevant CVs.

Using standard formulae at 20% completion (CPI = 0.94 and SPI = 1.02), the anticipated EAC amount is calculated as US$251,955, 257,830, and 246,380, respectively. This forecasted amount is lower than the actual CAC by an average of US$5,284. On the other hand, the modeled equation, including the risk factors, gives an EAC of US$257,339, which is lower by only US$171 from the actual CAC. Similarly, at 70% project completion, the CPI has improved to 0.965 and SPI is at 1.01, amd the anticipated EAC is US$251,189, 252,296, and 249,711, respectively, by using PMI standard formulae. The modeled equation shows a value of US$254,917. This is because even though the CPI and SPI are not alarming, the RPI of the project has dropped to 0.76, which is fairly

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Table 7. One-Way ANOVA Analysis for Significance of Differences

Completion (%)	p value
20	0.051987
40	0.032548
70	0.005949
85	0.835585
90	0.022569

low and indicates the potential risk exposure of the project. As the modeled equation incorporates this risk perception while calculating EAC, it shows a relatively higher amount than the standard PMI formulae.

In Case Study 3, the CPI of the project is 0.836 and SPI is 0.89 at 85% completion, reflecting substantial losses in both cost and time. The RPI at this data point is 0.765, relecting the fact that the project was facing quality, safety, and other issues. The project exceeded the planned cost by US$32,340,658. The three PMI formulae, when used to forecast the EAC at the data point, anticipated a value of US$201,292,367, 197,273,556, and 191,560,142, respectively. The forecasted amount calculated by one of the formulae is closer to the EAC, but the other two formulae forecast lower values. The proposed equation forecasts an EAC cost of US$197,287,221, which is also lower than the actual CAC. This variance can be explained by the availability of limited data; it is anticipated that the missing data from the first three quarters could have already been alarming in terms of quality, safety, and other risks, resulting in a badly quantified RPI. Since the proposed model is extensively based on high-quality data, any degree of personal bias in ranking of variables may compromise the quality of results.

In order to statistically signify difference between the results obtained from standard PMI equations and the proposed model, one-way ANOVA analysis is conducted. The values obtained through standard equations are subtracted from those of the developed model as evident by the p value in Table 7. The detailed calculations are shown in Appendix S1 of the Supplemental Data. The first point is taken at 20% completion where the p value is slightly larger than 0.05, which is the significance condition. The marginal difference is negligible and ascertains the significance of proposed model at 20% project completion. Similarly, at 40, 70, and 90% completion, the p value is less than 0.05 and signifies that EAC calculated using the proposed methodology is consistent throughout the project phases. However, at 85% completion, the p value is outside the significant range. This is mainly due to limited data at this point, which cannot be generalized. Thus, in comparison to the PMI models that show variations among their results, making their reliability questionable and complicated to interpret for management, the proposed methodology offers significantly different and better EAC.

Conclusions

The construction industry is lagging in developing modern methods that integrate relevant information and uncertainties for performance forecasting. This paper aims at assisting project managers to forecast better EAC by integrating risk in the conventional EVM index-based formula. In doing so, a RPI is developed that is based on the significant project KPIs. These KPIs are based on pertinent CVs, which are identified from the relevant literature. A total of 16 CVs are incorporated in the forecasting equation from the total pool of 55 CVs after conducting a survey. The filtered constituent variables feed to four indicators of quality (QPI), safety (SFPI), stakeholder satisfaction (SSPI). and other performance (OPI). The new indices will allow project managers to quantitatively measure issues pertaining to quality, safety, and stakeholder satisfaction that pose risk to the overall project.

The results of the case studies reveal that the developed equation shows a variance of 0–3% (average = 1.08%) from the actual CAC, whereas the standard PMI formulae show variation of about 2.15% on average. Although the improvement upon existing methods of estimating CAC seems marginal, the production and construction industries around the world are aiming at highest possible precision such as Six Sigma (99.997% probability) and Seven Sigma (almost 100% probability), for which the variations need to be minimized (Siddiqui et al. 2016). This process embodies the philosophy of substantial improvements with the help of marginal gains in valuation and estimating accuracy (Sunder and Waymire 1983).

Despite such endeavors, the majority of construction projects experience variations from 3 to 18% in the form of cost contingencies (Mak and Picken 2000). Therefore, the construction industry needs to follow the lead of its counterpart in manufacturing to increase its level of precision in estimation methods. In this regard, the current study is a modest step toward minimizing the gap between values obtained through different formulae for estimating EAC. Further, it also reduces the project manager's dilemma of selecting the most appropriate method for estimating EAC by providing a standard uniform formula. It is evident from the case studies and statistical analysis of the significance of differences between the proposed methodology and existing techniques that the established equation for forecasting EAC gives better results except for where enough data are not available. The weightings of CPI, SPI, and RPI can be manually adjusted by the project manager as per the project scenario and relative importance of indices.

The proposed model is practical and forecasts reliable figures throughout the project construction life, helping stakeholders to make better and timely decisions. The improvement is a substantial contribution to the body of knowledge aimed at enhancing the estimation confidence, and is statistically validated with the help of one-way ANOVA. This is due to explicit efforts and does not occur by chance, unlike PMI standard equations, which show inconsistency when applied to different project scenarios. In the same scenarios, the proposed equation shows more promising results. The developed equation shows fairly low variation from the actual CAC during early stages of the project until completion, which is a major limitation of traditional EVM practices. The model used 16 CVs for measuring quality, safety, stakeholder satisfaction, and other performance measurements. Other CVs and KPIs can be incorporated in the model to address more complexity and diversity in construction projects. The model will benefit from a technological underpinning if it is incorporated as a standalone feature in project monitoring software.

Supplementary Data

Appendix S1 includes the one-way ANOVA analysis used for statistical assessment of differences between the values of proposed methodology and existing techniques, and is available online in the ASCE Library (www.ascelibrary.org).

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