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An Earned Schedule-based regression model to improve cost estimate at completion

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Abstract

Traditional Earned Value Management (EVM) index-based methods for Cost Estimate at Completion (CEAC) of an ongoing project have been known for their limitations inherent with both the assumption that past EVM data is the best available information and early-stage unreliability.

In an attempt to overcome such limitations, a new CEAC methodology is proposed based on a modified index-based formula predicting expected cost for the remaining work with the Gompertz growth model via nonlinear regression curve fitting. Moreover, the proposed equation accounts for the schedule progress as a factor of cost performance. To this end, it integrates into its equation an Earned Schedule-based factor indicating expected duration at completion. The proposed model shows itself to be more accurate and precise in all early, middle, and late stage estimates than those of four compared traditional index-based formulae.

The developed methodology is a practical tool for Project Managers to better incorporate the progress status into the task of computing CEAC and is a contribution to extending EVM research to better capture the inherent relation between cost and schedule factors.

Keywords: Cost estimate at completion; Earned schedule; Earned Value Management; Regression analysis

1. Introduction

Forecasting project cost at completion is of great importance to project management success. It is a forward looking tool to assist Project Managers (PMs) with the task of making timely and appropriate decisions about cost outcome of their in-progress projects (Fleming and Koppelman, 2006).

For over four decades, Earned Value Management (EVM) has been used to forecast cost at completion. This objective methodology integrates project cost, schedule and scope metrics into a single measurement system. It is widely applied for measuring and analyzing project actual status against its baseline, and for providing estimates of project cost and duration at completion (De Marco and Narbaev, 2013). In particular, EVM is used to compute Cost Estimate at Completion (CEAC), a top-down estimate of the project total cost based on the project's status.

Within the EVM framework, several methods exist to compute CEAC, classified as either index-based (IB) or regression-based techniques (Christensen et al., 1995; Lipke, 2004).

In general, IB methods have an inherent limitation due to their only reliance on past information: they assume that remaining budget is adjusted by a performance index (Fleming and Koppelman, 2006; Kim and Reinschmidt, 2011). The second concern associated with the traditional approach is that it provides unreliable cost forecasts early into a project life because of few available EVM data (Fleming and Koppelman, 2006; Zwikael et al., 2000). In this regard, some studies (Anbari, 2003; Cioffi, 2006; Kim et al., 2003; Lipke, 2004) simplified practical implementation and/or extended applications of IB forecasting methods whereas other researches (e.g., Kim and Reinschmidt, 2011; Lipke et al., 2009; Marshall et al., 2008) employed

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statistics into EVM forecasting system to benefit from deeper analysis to support decision making. Caron et al. (2013), Naeni et al. (2011), and Pajares and Lopez-Paredes (2011) integrated risk management techniques to consider also uncertainty as a potential source of structural change in cost and schedule performance in the project dynamic environment.

With the purpose of overcoming the two mentioned weaknesses of the IB approach and produce more reliable CEAC, regression techniques have been regarded as an alternative to traditional IB methods. Through their curve fitting process, regression techniques improve accuracy of the CEAC, especially as they may use a combination of EVM data with Earned Schedule (ES) data and provide more reliable forecasts early into the project life.

However, reported literature reveals that little advancement has been made in the area of improving reliability of the IB approach via its refinement by regression techniques (Lipke et al., 2009; Marshall et al., 2008; Tracy, 2005). Most studies integrating regression concepts into IB approaches concern U.S. defense projects, which are complex in nature with large budgets and long durations (Christensen et al., 1995; Lipke et al., 2009). In addition, within the EVM framework, available regression-based methods to compute CEAC do not consider schedule progress in cost estimates (Lipke, 2003).

To fill these gaps, a new regression methodology is proposed to provide more reliable CEAC. The developed model overcomes the limitations inherent to traditional IB approaches. In addition, the model regards project schedule as a factor of cost performance and, hence, takes into account the schedule progress, measured via the ES concept, to calculate CEAC. The model equation is a classical IB formula modified with a Gompertz growth model function and it integrates an ES-based factor to indicate the expected completion time used into the model.

The paper is structured as follows. Section 2 frames commonly used IB formulae for CEAC, introduces a regression approach for cost S-curve fitting, and formulates a Gompertz growth model to implement it to the proposed methodology. Section 3 designs the methodology and establishes a framework for evaluating the model and comparing its estimated results with those of IB formulae. In Section 4, we apply the EVM data from nine projects to show application of the proposed model, derive the study results, and present the role of ES in the developed methodology. Section 5 explores the findings of the research and associated implications. Section 6 presents the work contributions in advancing the body of knowledge and draws conclusions and suggestions for future research.

2. Cost estimate at completion methods and framework

2.1. The index-based approach

In the EVM theory and practice, the calculation of CEAC entails summing up two factors (Eq. (1)), namely: the Actual Cost (AC) of performed work at Actual Time (AT) and the estimated cost of the remaining work. The second factor is a difference between the Budget at Completion (BAC) and the Earned Value (EV) adjusted by a Performance Index (PI—a measure of cost efficiency of budgeted resources) (PMI, 2011).

$$\mathrm{CEAC}(x) = \mathrm{AC}(x) + (\mathrm{BAC\text{-}EV}(x))/\mathrm{PI}(x) \tag{1}$$

The choice of a desirable PI depends on the project status and associated risks. Zwikael et al. (2000) relate this choice to premises set by PMs in selecting the PI, from the belief that all past cost deviations cancel into the future so that their projects can be accomplished within the BAC to a pessimistic argument that the deviations will continue at the rate observed so far. PMI (2011) provides four PIs to correct the remaining BAC (Table 1) with different assumptions associated with actual project performance. Among these indexes the most commonly used is the Cost Performance Index (CPI), which assumes that past cost performance is the best available indicator of future cost outcome as a reasonable floor estimate. Anbari (2003) states that an estimate obtained using a product of CPI and Schedule Performance Index (SPI) is an indicator of the overall project health and is a ceiling CEAC to reflect both cost deviation and schedule progress. Fig. 1 presents the EVM metrics addressed above and used in this research.

Since this IB approach only relies on past information, it requires stability of the PI to provide for reliable CEAC. In this regard, previous research carried out on defense projects found that a cumulative value of CPI stabilizes by the time the project is 20% complete and the forecast value does not vary by more than 10% from that point in time to completion. The EVM community received this finding as a rule of thumb and generalized it as being applicable for all types of projects. However, recent studies challenged this finding attributing it to large-scaled and long duration defense and energy projects only (Henderson and Zwikael, 2008; Lipke et al., 2009). They questioned whether the PI stability existed and found that most projects from other industries (e.g., construction, software) with relatively small budgets and short durations achieved the PI stability by the second half portion of the project life.

2.2. The regression-based approach and S-curve fitting

To overcome such limitations of conventional IB techniques, regression-based techniques have been gaining acceptance by practitioners. The main feature of these methods is that they describe a linear or nonlinear statistical relationship between a predictor (input) and response (output) variables through their parameters (Bates and Watts, 1988). Parameters of a regression model represent the behavior of project cost over the whole lifecycle.

Efforts put to apply regression models are greater than those needed for relatively simple IB cost forecasting methods. However, claims have been made that they yield better estimates early in the project life, while the IB approach is likely to be unreliable (Tracy, 2005).

In Project Management, S-curves are used to graphically display cumulative progress of work, expressed in units of costs, labor hours, progress percentage, etc., plotted against time (PMI, 2008). The S-like shape of this curve represents

Table 1
EVM performance indexes and assumptions (PMI, 2011).

Performance Index	PI formula	Assumption on future cost performance
Cost performance index, CPI	EV/AC	The same as past cost performance
Critical ratio, CR	CPI × SPI	Influenced additionally by past schedule performance
Composite index, CI	0.8CPI + 0.2SPI	Influenced jointly in some proportion by both cost and schedule performances
Moving average, MA	$\sum_{i=1}^{n=3} \mathrm{EV} \Big/ \sum_{i=1}^{n=3} \mathrm{AC}$	The same as of the last three time points. The averaged CPI is a ratio of sums through three periods beginning with the most recent period and going backwards

work progress which has a lower rate at the beginning and end (steady pattern) and a higher rate in the middle (steeper pattern). In EVM, such curves are used to display AC, EV, and Planned Value (PV) of a project over the time axis. Cioffi (2005) proposed a parameterized S-curve tool for managing the cost of an ongoing project: it is the derivation of a modified logistics equation with minor mathematical assumptions PMs can easily set. The model was validated using two projects and showed flexibility in generating a desired smooth cost profile by selecting the strength of the rise of the curve and the point at which half the total cost was spent.

Defining an equation for the S-curve model requires considering some issues relevant to nonlinear regression analysis. First, such models require defining initial values for their parameters and setting an algorithm for the least squares (LS) approximation (Bates and Watts, 1988). In nonlinear regression, there is no standard approach to specify initial values and one needs to know the initial information (e.g., prior historical data, EVM data, variables relationship) in dealing with this task. This is because a model's predictor and response variables have a nonlinear relationship.

Second, the most common assumption in nonlinear regression is that the observed data points around the S-shaped curve follow a Gaussian distribution. With these concerns, nonlinear curve fitting approximates values of the model parameters with the LS method minimizing the sum of squared errors of estimated and actual values. The proposed methodology applies the Gauss–Newton algorithm for this iterative approximation, which converges not heavily depending on the initial values (Bates and Watts, 1988) of a nonlinear model within specified tolerance thresholds.

2.3. The Gompertz growth model formulation

A Gompertz growth model (GGM) has found wide application in many fields associated with population growth studies, such as biology, economics, marketing, etc. The model describes phenomena inherent to data with a growth pattern. It is extensively used in curve fitting and forecasting and belongs to a family of sigmoidal models.

The GGM generic function is given in Eq. (2). The α is a future value asymptote of the model that represents the final cost (which is never attained) as time (x) tends to infinity (Seber and Wild, 1989). The β parameter is the y-intercept indicating an initial budget size and the γ is a scale parameter that governs the cost growth rate (GR).

$$\mathrm{GGM}(x) = \alpha e^{\left[-e^{(\beta-\gamma x)}\right]} \tag{2}$$

This model features with the position of the inflection point at approximately 1/3 of the total growth ($\mathrm{GGM}(x) = \alpha/e$) at time ($x = \beta/\gamma$) when its GR ($\alpha\gamma/e$) is the greatest. The GR monotonically increases to a maximum before steadily declining to zero (Seber and Wild, 1989). Fig. 2 illustrates the S-shaped curve of the GGM.

With regard to the project cost growth, the GGM shapes such growth considering the cost behavior as follows. During the project initial stage, work progress is typically slow, it speeds up close to the middle stage increasing the cumulated cost accrual associated with the progress and accelerating the GR. Finally, as the project reaches its completion, there is less work remaining decreasing the GR to zero.

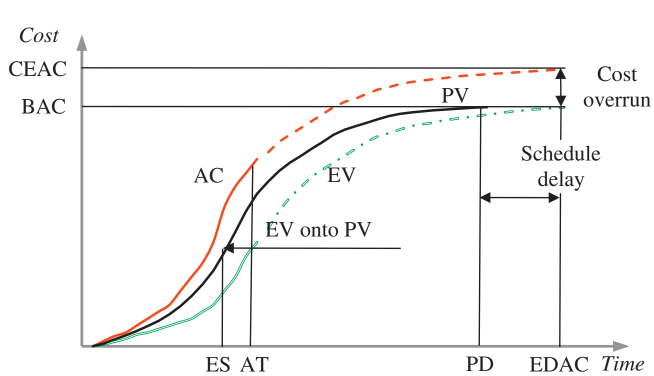

Fig. 1. EVM measures and forecasts.

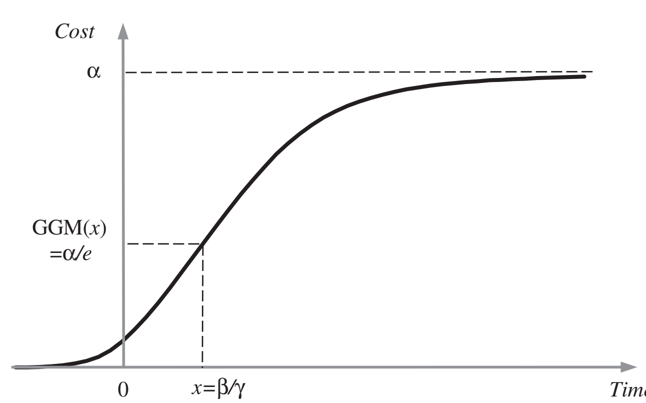

Fig. 2. The S-curve of the Gompertz growth model.

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Recently, Trahan (2009) proposed to use the GGM as an industry proxy for future projects. S-curves were developed using EVM data from a number of U.S. defense contracts. The parameters of the S-curve model for complete projects were found by regressing normalized AC values of the entire project life against respective time points. The majority of the sample projects experienced cost overrun. Therefore, the normalization of AC and actual time values to BAC and planned duration, respectively, produced the values for the S-curve model parameters best suitable for overrun projects. Hence, the major finding was that the model is accurate to compute CEAC of either overrun or overrun-close projects.

Trahan's work is one of the inspiring references of this proposed GGM. However, in contrast with Trahan's work, the method proposed in this paper presents a comprehensive methodological approach, greater validity, increased practicability for ongoing projects, and extended applicability to various stages of a project life cycle.

3. Methodology

3.1. The Earned Schedule method

The CEAC methodology proposed in this paper integrates ES concepts into its equation to take into account the project work progress. The ES technique overcomes limitations inherent to the EVM method when it comes to computing Expected Duration at Completion (EDAC) of a project (Lipke, 2003). It measures the schedule progress in time units and eliminates a deficiency of EVM-based SPI, which tends to unity as the project approaches its completion, regardless of any early or late finish. As far as the accuracy of the ES method in computing EDAC is concerned, comparative studies with EVM methods show that the ES technique provides more accurate estimates than SPI-based calculations (e.g., Vandevoorde and Vanhoucke, 2006).

The value of ES is obtained by projecting to the actual date the EV curve onto PV curve assuming that the current EV should actually have been earned at that projected time (Fig. 1). Therefore, the ES is defined as per Eq. (3).

$$\mathrm{ES}(x) = \mathrm{C}(x) + \mathrm{I}(x) \tag{3}$$

where C and the subscript c denote the number of total time units for which EV exceeds PV and the incremental portion $\mathrm{I}(x) = (\mathrm{EV}(x) - \mathrm{PVc})/(\mathrm{PVc}_{+1} - \mathrm{PVc})$ which is more or equal to 0 and less than 1.00.

As a consequence, a time-based $\mathrm{SPI_t}$ can be defined as per Eq. (4).

$$\mathrm{SPI_t}(x) = \mathrm{ES}(x)/\mathrm{AT} \tag{4}$$

Thus, the resulting EDAC when the project is at time (x) is the ratio of Planned Duration (PD) to $\mathrm{SPI_t}(x)$. As the proposed approach utilizes the ES concept to consider schedule impact in CEAC, the model uses the inverse of $\mathrm{SPI_t}(x)$, which is the ratio of EDAC to PD.

For the purpose of better understanding the proposed equation, this inverse ratio is referred to as Completion Factor (CF). The CF indicates EDAC yielded to unity and it can also be defined as inversely related to $\mathrm{SPI_t}(x)$ (Eq. (5)).

$$\mathrm{CF}(x) = \mathrm{EDAC}(x)/\mathrm{PD} = \mathrm{SPI_t}(x)^{-1} \tag{5}$$

If the value of the CF, based on work progress to date, is greater than 1.00 it indicates that a project is likely to be delivered late, while less than 1.00 shows an early finish.

3.2. The proposed CEAC model

This section develops the new methodology following three steps. First, the values of the three parameters of the GGM (Eq. (2)) are found through nonlinear regression analysis.

Then, the new CEAC formula is introduced with integration of the GGM parameters to calculate CEAC.

Finally, we further modify the CEAC formula with the purpose of reflecting schedule progress on cost performance. To this end, the ES-based CF is integrated into the formula. Here, the CEAC equation has two variants: a base one without integration of the CF, and an ES-based one that interpolates the value of the defined CF.

Recently, Narbaev and De Marco (2014) provided comparative study on this CEAC methodology integrating four growth models (Bass, Gompertz, Logistic, and Weibull) into its equation. They found that GGM is the best statistically valid model converging to approximate values of its parameters in nonlinear regression curve fitting. In addition, the GGM generated more accurate CEAC for the early and middle stages of the project life. This work provides further extended applicability and reliability of the previous model by providing accurate late estimates, analysis of forecast precision, model timeliness, and integration of the influence of schedule progress on the CEAC computation.

In particular, the proposed GGM is compared with four different index-based performance indexes, is applied when the project is in its late stage, is tested for the narrowness of the forecast error, and has proven its reliability over time, which refers to as generating more accurate and precise cost estimates in the early, middle and late completion stages of a project.

The first step in developing the methodology is to find the values for the three GGM parameters through nonlinear regression curve fitting. For this, both time (a predictor variable) and cost (a response variable) units are normalized to input into the GGM equation. The normalization of all the values of time points to unity (1.00) assumes that a project is 100% time complete (i.e., PD = 1.00). Each next time point is a cumulated portion of this unity with the final time point representing PD (1.00) of a project. These values represent a predictor variable (x) of the GGM. Each time point (x), a value of the predictor variable, has a corresponding cost point, a value of the response variable. These corresponding cost points are formed as follows. The values of AC from time zero (x = 0) to AT are normalized to unity (i.e., BAC = 1.00) while the values of PV from AT onto project completion with the final value of the normalization representing BAC (1.00, i.e., 100% complete). Then, the normalized values of to date AC and PV are combined to form the values of the response variable (y) in the GGM.

Finally, each time point (x) of the GGM equation (Eq. (2)) has its corresponding cost value (y) to run the nonlinear regression with the GGM. This allows finding the values for the three fitting parameters. Both time and cost units have final values equaling 1.00 (PD = 1.00 for time and BAC = 1.00 for cost).

The initial values of the three parameters are set as 1.00 with the confidence level of 95%. This choice is made considering issues related to defining initial values of the GGM parameters and the Gauss–Newton approximation algorithm addressed in Subsection 2.2 and the point that the values of predictor and response variables are normalized to unity. Then, via running this regression procedure, the values of the three parameters are obtained: the α asymptote, the y-intercept β, and γ-scale. The Minitab® software tool is used for this task.

The second step requires computing CEAC by using Eq. (6). This equation is the refined version of a classical IB formula as previously given in Eq. (1). The difference is that Eq. (6) calculates the remaining expected cost by regression analysis, while the IB formula adjusts it with a PI. The second summand is an estimate to complete a project. It is equal to the product of BAC times the difference of the two values of GGM (Eq. (2)): when a project is 100% time complete (the result of the GGM function when time (x) is 1.00) and at AT (the result of the GGM function when time (x) is at AT).

$$\mathrm{CEAC}(x) = \mathrm{AC}(x) + [\mathrm{GGM}(1.00)\text{-}\mathrm{GGM}(x)]\mathrm{BAC} \tag{6}$$

Finally, the GGM is modified to consider the possible influence of work progress on CEAC. The main assumption of this refinement is that favorable schedule efficiency tends to improve the final cost, while a poor schedule progress may increase the final cost. To this end, in Eq. (6), the value of x = 1.00 (which implies that a project finishes on time) is replaced by the CF (the ratio of EDAC to PD). This is less than1.00 if a project is ahead of schedule and greater than 1.00 if a project is behind schedule. This modification represents a cost–schedule integrated approach because the cost estimate considers the schedule impact as a determinant factor of cost behavior. The refined CEAC formula is given in Eq. (7).

$$\mathrm{CEAC}(x) = \mathrm{AC}(x) + [\mathrm{GGM}(\mathrm{CF}(x))\text{-}\mathrm{GGM}(x)]\mathrm{BAC} \tag{7}$$

3.3. Evaluation of the model

This section provides the framework for assessing the quality of the proposed methodology and analyzing the influence of schedule progress through ES-based CF on CEAC. The evaluation of the forecast is based on two criteria: accuracy and precision.

Among the two criteria to assess the quality of a cost forecasting method, accuracy is regarded as the most often used and important one (Yokum and Armstrong, 1995). This study measures CEAC accuracy by a percentage error (PE) and the mean absolute percentage error (MAPE) for early, middle, and late stages. PE is the difference between CEAC and Cost at Completion (CAC) expressed as a percentage of CAC with a negative value suggesting underestimation and a positive value suggesting overestimation. MAPE is referred to as the average of the absolute values of differences between CEAC and CAC over the number of projects tested (Bates and Watts, 1988). Eqs. (8) and (9) are used to compute these measures:

$$\mathrm{PE}\% = \frac{\mathrm{CEAC\text{-}CAC}}{\mathrm{CAC}} 100\% \tag{8}$$

$$\mathrm{MAPE}\% = \frac{100\%}{n} \sum_{i=1}^{n} \frac{|\mathrm{CEAC}_i\text{-}\mathrm{CAC}_i|}{\mathrm{CAC}_i} = \frac{1}{n} \sum_{i=1}^{n} |\mathrm{PE}_i|\% \tag{9}$$

where CAC—Cost at Completion; n—number of projects.

The second criterion of the model is precision, defined as the narrowness of a forecast error. It is measured by the Standard Deviation (SD), which is an indicator of a statistical dispersion of the values of prediction errors from the average forecast within the population (Seber and Wild, 1989). SD is computed by Eq. (10), which takes the square root of the variance (the average of the squared differences between the PE of an individual project and mean of the PEs). A smaller value of SD indicates that cost estimates calculated by a particular model are closer to its Mean Percentage Error (MPE) and, hence, produce more precise CEACs.

$$\mathrm{SD}\% = \sqrt{\frac{\sum_{i=1}^{n} (\mathrm{PE}_i - \mathrm{MPE})^2}{n}\%} \tag{10}$$

The accuracy of EVM cost forecasting methods should also be reliable over a certain period or the entire project life. This property of cost forecast is defined as timeliness and shows reliability in the accuracy of cost forecasting (Kim, 2007). From a practical perspective, PMs may be more concerned about timeliness in cost forecasting as it implies reliability in cost forecasting and provides a project team with warning signals about the final cost outcome (Kim, 2007; Kim and Reinschmidt, 2011). Teicholz (1993) defines it as accuracy of estimates during the first half of project duration. Vandevoorde and Vanhoucke (2006) evaluate it correlating to changes in EDAC accuracy over the project's final stage. These works report timeliness analysis with regard to accuracy of estimates. This paper adds also the analysis of the precision timeliness. In this regard, this paper defines the timeliness of the proposed CEAC methodology as a property describing more accurate and precise CEAC over the three forecast stages. From a practical perspective, this may be of great importance to PMs as it suggests reliability of the cost forecast process.

Finally, based on these two criteria, estimates using the proposed model are compared with the four IB methods according to the PI values and assumptions given in Table 1.

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As discussed earlier in the paper, another important advantage of the proposed methodology is the ability to appropriately capture the influence of the schedule progress into CEAC. The EVM approach is known as an objective method that assists PMs in the task of monitoring and controlling projects through an integrated cost–schedule–scope measurement system (PMI, 2008). This implies that changes in one element of this triangle may cause changes in the other/others. One of basic prerequisites of the EVM approach is that work scope remains as it is throughout the project life. On the contrary, the scope of work is revised when complimentary activities are added into a project upon approval of change orders from a project owner. Such scope change is subject to a project's rescheduling leading to potential changes in all components of the measurement system including a work breakdown structure, the performance measurement baseline and so forth. In such a case, the EVM system is revised according to these changes.

In line with these considerations, the proposed CEAC model considers the possible influence of work progress on CEAC. This relation is reflected through the integration of ES-based CF which is related to SPI_t and, hence, a measure of time-based schedule efficiency (PMI, 2011). For this, at some time (x) if the project schedule efficiency is favorable (CF < 1.00) this shows that the final cost tends to improve, while a poor efficiency (CF > 1.00) would influence increase of the final cost. However, it is noted that this cannot be generalized for those ongoing projects that are subject to adjustments and corrective actions as measures to speed up the work progress, such as in the case of activity crashing or fast tracking. This usually results in cost increase or significant changes to the original scope and schedule network (e.g., re-baselining), which in turn needs the EVM system to be reset.

The model considers this relationship by replacing the 100% time completion value with the value of the CF in its equation (Eq. (7)). In other words, the model generates more accurate and precise estimates when it takes into account the schedule progress.

4. Application and results

4.1. Sample application

This study uses the EVM data of nine construction projects selected from qualified reported literature. Five out of nine projects are delivered with cost overruns and six report schedule delays. They all are small to medium-scale projects with average BAC close to 8 million US dollars and PD varying from 6 to 27 months.

As the number of time points and values of reported EVM data differs from project to project, a percent value for the budget completion at early, middle, and late stages cannot be a predetermined percentage. As a consequence, we define the range for these stages as 10–25%, 45–65%, and 70–95%, respectively (Narbaev and De Marco, 2014). Below we demonstrate the stepped procedure using the EVM data of Project 1 to forecast CEAC when the project is in its early stage.

Table 2
Normalized predictor and response values for Step1 (Project 1).

Time point[a] (months)	*Predictor* (time points normalized to PD)	PV (×€000)	AC (×€000)	*Response* (AC–PV normalized to BAC)[b]	BAC% complete
0	0.000	0	0	0.000	0.00
1	0.067	2.9	2.4	0.001	0.08
2	0.133	318	340	0.091	8.54
3	0.200	680	789.6	0.212	16.49
4	0.267	822	965.1	0.259	20.90
5	0.333	1217		0.327	27.97
6	0.400	1656		0.445	39.74
7	0.467	1908		0.512	46.66
8	0.533	2116		0.568	54.02
9	0.600	2314		0.621	60.35
10	0.667	2428		0.652	63.73
11	0.733	2720		0.730	70.51
12	0.800	2983		0.801	77.02
13	0.867	3345		0.898	85.62
14	0.933	3607		0.968	90.32
15	1.000	3725		1.000	96.71
16	–			–	100.00

[a] AT = 4, PD = 15, and AD = 16.
[b] AC—from time point 0 to 4; PV—from 5 to 15; BAC = 3,725,000€.

The first step is to determine the values of the three GGM parameters through the nonlinear regression curve fitting. Table 2 provides initial absolute values for time (column Time point) and cost data (columns PV and AC). Then these time points are normalized to unity (assuming PD = 15 is 1.00) and PV and AC values are normalized to unity (assuming BAC = 3,725,000 euro is 1.00). These normalized time (variable x) and cost (variable y) points are reported down on the columns Predictor and Response in Table 2 and are input data for the GGM equation to run the fitting process. The AC–PV values are combined values of AC from time zero (x = 0) to AT and of PV from AT to BAC = 15. To compute the early stage CEAC for Project 1, month 4 is chosen as the time for the early stage estimation time when 20.90% of the BAC is earned. The requirements one should take into account when running the nonlinear regression are introduced in Subsection 3.2.

The GGM equation generated by Minitab® for the EVM data of Project 1 (Table 2) is given in Eq. (11). To calculate CEAC for the early stage, four months into the project execution when x is 0.267 (Table 2), this GGM equation result is 0.241 (or 24.10% of the project BAC). The interpretation of the values of the three parameters (addressed in Subsection 2.3) is as follows. The ratio of the β parameter to the γ parameter gives time percent complete point ($x = \beta/\gamma$) when the cost growth rate is maximum which is 43.70% for Project 1with resulting cumulative cost of 44.20% ($GGM(x) = \alpha/e$) of the BAC. Finally, the α asymptote value of 1.202 implies that, as Project 1 tends to infinity, it will experience a 20.20% cost overrun.

$$GMM(x) = 1.202e^{\left[-e^{(1.212-2.773x)}\right]} \tag{11}$$

Step 2 computes the project CEAC for its base case using Eq. (6). For this purpose, we additionally compute the value of GGM equation when x = 1.00 (100% time complete). As previously explained, the remaining of the project BAC must be adjusted by the difference of the two values of GGM: when a project is 100% time complete and at AT. From this, GGM(1.00) = 0.974 and we use the refined version (Eq. (6)) to calculate the CEAC of Project 1. The methodology finds the project CEAC with PE = −6.96, which means that it is underestimating its CAC.

Step 3 is about taking into account schedule progress based on the assumption that the schedule is a factor of cost performance and, hence, it has its impact on the estimate. Therefore, we include the projects CF into Eq. (6). It is noted that the project has PD = 15 months, EDAC = 16 months at AT = 4, and Actual Duration (AD) of 16.25 months. At month four, CF equals 1.083 and it replaces x = 1.00, as given in Eq. (7). It produces a new CEAC that considers work progress: it is closer to the CAC value with PE = −2.91 (4.05% of improvement over PE = −6.96 of the base case).

4.2. Accuracy and precision

This section presents the CEAC computations for the nine sample projects and provides an analysis of accuracy and precision of the estimates together with an assessment of the role of the ES influence in the early, middle, and late stages.

Table 3 allows an evaluation of the projects' CEAC accuracy in PE for the early stage computed by applying the proposed method (Eqs. (6) and (7) for base and ES-based cases, respectively) in comparison with the IB method (Eq. (1)). It adjusts the remaining portion of BAC by the four PIs (CPI, CR, CI, and MA) introduced in Table 1. Accordingly, the IB method produces four different CEACs, which vary in assumptions associated with future cost performance (Anbari, 2003; PMI, 2011). The detailed information on how these PEs are computed is provided in Appendix A for a sample case. In the five cases (Projects 1, 2, 4, 7, and 8) CEAC results calculated by GGM (either the base or ES-based cases) are more accurate than those computed by the four IB formulae. When comparing the cost estimates of the ES-based case with the base case it appears that the integration of CF into the model improves the model's forecasting capability (Projects 1, 2, 3, 5, 7, 8, and 9). Overall, GGM allows overcoming the critical limitation of the traditional IB formulae to accurately determine early CEAC. The IB methods generate mixed results that are difficult to interpret. However, the following can be concluded: all of the traditional formulae provide PE above 10.00 for Projects 2 and 7 and above 5.00 for most of the cases.

Table 3
CEAC accuracy results for the early stage (in PE, %).

Project	Base	ES	CPI	CR	CI	MA
1	−6.96-	−2.91	16.26	21.44	13.18	15.14
2	11.08	−0.19	0.29	23.34	3.67	19.96
3	−5.74	−4.37	−1.01	0.63	−0.85	0.21
4	1.55	5.21	−9.31	−7.36	−7.25	−5.25
5	−14.57	−9.77	−4.11	7.06	−3.19	−4.92
6	−5.18	−5.59	−2.02	−7.68	−3.71	−2.75
7	−4.03	−0.48	−28.51	−11.00	−22.52	−28.09
8	−6.68	0.54	−1.58	57.05	10.78	−1.46
9	9.72	8.74	12.24	10.40	10.20	6.22

Table 4 provides results of the estimates' accuracy (computed by Eq. (9)) and precision (computed by Eq. (10)). Overall, the results show that the proposed model's estimates are more accurate (in MAPE) and precise (in SD) than those of the index-based formulae. Also, the integration of the schedule progress into the model equation leads to improving the CEAC accuracy. Therefore, the ES-based GGM appears to be the most accurate and precise model in all the execution stages. This allows concluding that schedule is a factor of cost behavior and delay/advance in the work progress has its respective influence on the project cost outcome.

With regard to the model timeliness, as addressed in Subsection 3.3, it implies providing for more accurate and precise CEAC in early, middle, and late completion stages. The results of both accuracy and precision suggest that the ES-based GGM meets this criterion producing more accurate (Fig. 3A) and precise (Fig. 3B) estimates in all of the stages. Finally, another pattern noticed is that all the compared models (except the GGM base case) improve both CEAC accuracy and precision as projects tend to completion.

4.3. The role of ES in the cost forecasting

This section aims to test the effect of the schedule impact on the CEAC accuracy and to find out if there is a relation between the work progress and the estimate accuracy. To accomplish this analysis, we calculate CEAC for both cases (both without and with the CF). Then, the study analyzes the possible existence of a relationship between CEAC and project cost outcome (underrun, on budget, overrun). Table 5 reports the results of the analysis: values of CF computed at the forecast time, PE of CEAC for the two cases, and the projects' cost outcome. A CF greater than 1.00 indicates that the project is experiencing a schedule delay at the time of estimation and warns that this poor schedule efficiency may be influencing increase in the final cost.

Overall, the ES-based case appears to be more accurate in all three stages than the case when the work progress is not considered. From this table it can be drawn that the integration of the CF into the forecasting model results in more accurate cost estimates. In particular, this improves the estimates accuracy of the seven projects in the early, five projects in the middle, and six projects in the late stages.

Table 4
CEAC accuracy and precision.

Completion stage	Base	ES	CPI	CR	CI	MA
Accuracy (MAPE, %)						
Early (10–25%)	7.28	4.20	8.37	16.22	8.37	9.33
Middle (45–65%)	5.11	3.47	4.87	10.19	4.63	4.89
Late (70–95%)	5.48	3.22	4.44	5.72	4.32	4.43
Precision (SD, %)						
Early	6.63	5.27	12.03	20.20	10.50	12.98
Middle	5.76	3.42	6.72	10.19	6.24	6.59
Late	5.77	3.17	5.95	7.86	5.92	5.92

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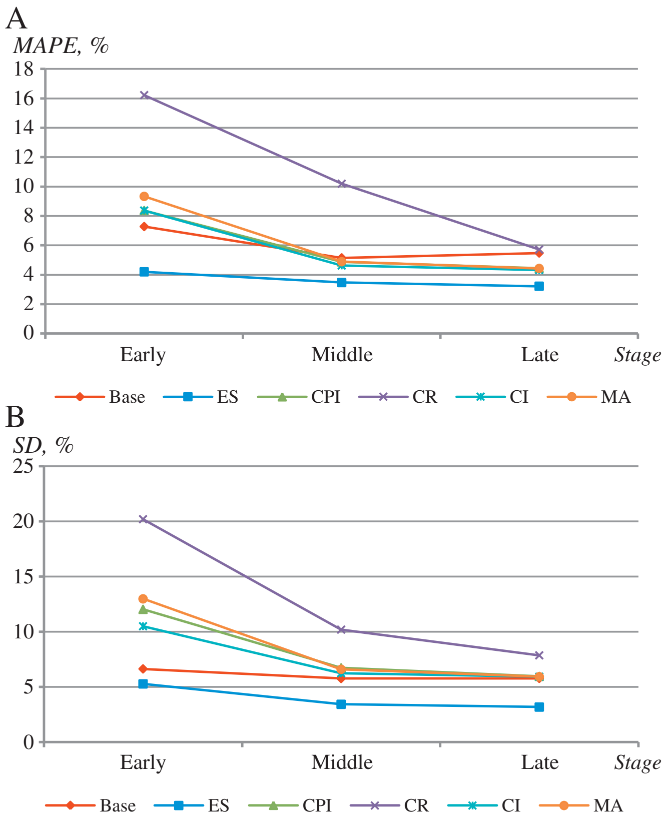

Fig. 3. The CEAC timeliness by different formulae. A) Accuracy. B) Precision.

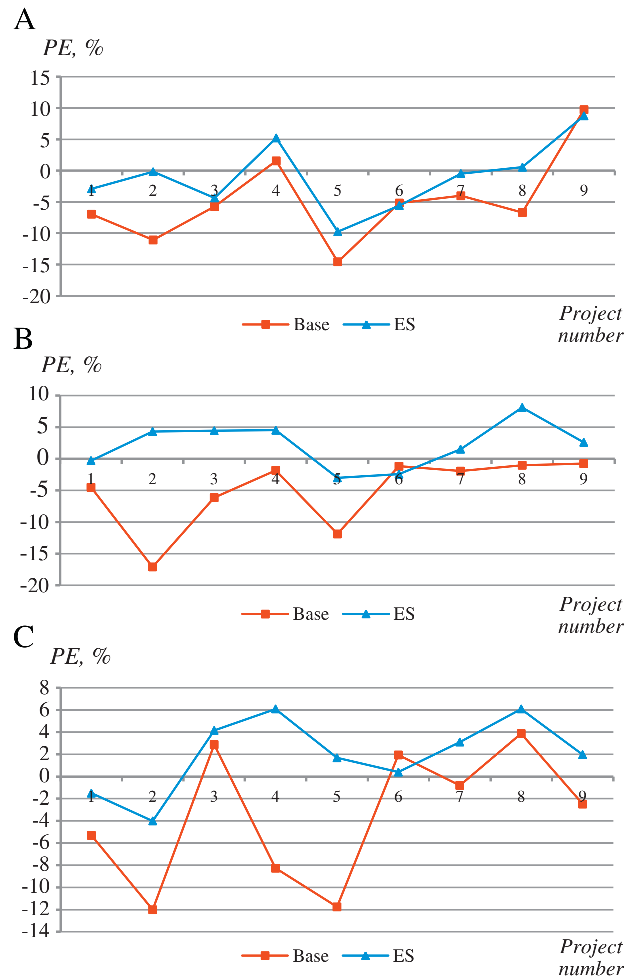

Fig. 4. Influence of ES method on the CEAC model. A) Early stage (10–35% BAC). B) Middle stage (45–65% BAC). C) Late stage (70–95% BAC).

Additionally, the valuable contribution of the ES method to enhance the accuracy of the proposed CEAC methodology for the early, middle, and late stages is provided in Fig. 4A, B, and C, respectively. Closer to zero line values of PE in the chart imply more accurate estimates. On average, integration of CF into the GGM (Eq. (7) against Eq. (6)) improves the cost estimates from MAPE = 7.28 to 4.20, 5.11 to 3.47, and 5.48 to 3.22 in the early, middle, and late execution phases, respectively (Table 4).

5. Discussion

Three main findings of the proposed CEAC model can be highlighted with regard to its accuracy, precision, and the influence of schedule progress on CEAC.

Table 5
Schedule influence on CEAC for Base and ES-based GGM cases (PE, %).

Project	Early			Middle			Late		
	CF	Base	ES	CF	Base	ES	CF	Base	ES
1	1.08	−6.96	−2.91	1.11	−4.51	−0.28	1.11	−5.31	−1.51
2	1.13	−11.08	−0.19	1.18	−17.09	4.31	1.25	−12.02	−4.31
3	1.02	−5.74	−4.37	1.17	−6.14	4.44	1.02	2.87	4.15
4	1.09	1.55	5.21	1.05	1.81	4.52	1.29	−8.27	6.09
5	1.13	−14.57	−9.77	1.18	−11.88	−3.01	1.22	−11.76	1.68
6	0.98	−5.18	−5.59	0.93	−1.17	−2.44	0.88	1.94	0.39
7	1.15	−4.03	−0.48	1.09	−1.94	1.52	1.04	−0.80	3.10
8	1.85	−6.68	0.54	1.18	−1.01	8.12	1.03	3.86	6.09
9	0.99	9.72	8.74	1.01	−0.76	2.61	1.01	−2.49	1.97

First, the comparative analysis (Subsection 4.2) of CEAC found by the proposed nonlinear GGM and the four simple IB formulae proves that the proposed model generates more accurate CEAC (Table 3). The cost estimates provided by the ES-based GGM are the most accurate: 4.20, 3.47, and 3.22 for the early, middle, and late stages, respectively. CEAC generated by Base GGM and the traditional approach with CPI, CI, and MA produced the same results between these four cases (Table 4). Lastly, the estimates computed by the CR-based method are the worst among the methods (MAPE = 16.22, 10.19, and 5.72 for the three stages, respectively). Overall, with regard to the accuracy of CEAC the following concerns are worthwhile to note. The test results show that a pure and simple traditional IB approach to forecast the expected project final cost might be inadequate. CEAC comprises a sum of two components: to date actual cost and the remaining portion of cost to complete. The first limitation is associated with the assumption that a traditional IB technique is backward looking and relies on past EVM information only. Therefore, the index-based approach adjusts the remaining BAC by PI proposing that a project will continue in its current progress until its completion. This forces PMs to accept the belief that cost performance is stable for the rest of the

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project life. However, the project implementation environment has uncertainty and changes in project cost outcome that decrease as a project tends to completion. This change is reflected in the cumulative value of CPI, which gets stabilized as a project progresses. This indicates stability in project execution and, subsequently, ensures for more stable values of CEAC by the end of a project. This leads to integrate the interpretation of the first finding with the second limitation of traditional IB approaches. For a project in its early life, when few EVM data are at hand, this technique is unreliable as it makes extrapolations from few time points for the rest of the project: this is risky and provides inaccurate estimates.

Second, the proposed model provides more precise estimates. Precision refers to the narrowness of the forecasting error. On average, the cost estimates provided by the ES-based GGM are the most precise: MAPE = 5.27, 3.42, and 3.17 while the worst estimates are produced by the CR-based method as MAPE = 11.82, 5.41, and 4.77 for the early, middle, and late stages, respectively (Table 4). Overall, unlike the IB approach, the developed CEAC model gives more accurate and precise estimates as it adjusts the remaining portion of CEAC (second summand of Eq. (6)) by the GGM via nonlinear curve fitting, whereas the IB method achieves this adjustment by PI (Eq. (1)). It is a refinement of the IB approach via nonlinear regression. The new technique interpolates intrinsic properties inherent to growth models into its formula (Eq. (6)) and takes into account a combination of AC (from a project start to AT) and PV (from AT onto completion) reflected in the three GGM parameters.

Another point to remark is about the GGM property to maintain more accurate and precise estimates in all the three stages compared to the traditional approach, as it means reliability in the forecasting. We defined this property of the model as timeliness, referred to as the ability to give warning signals about the final cost outcome of a project. The timeliness of accuracy and precision means reliability in CEAC forecasting. Moreover, in the ES-based GGM case, accuracy (Fig. 3A) and precision (Fig. 3B) appeared to improve over time from early to late stage estimation, with decreasing values of MAPE (4.20, 3.47, and 3.22) for accuracy and SD (5.27, 3.42, and 3.17) for precision (Table 4). The characteristic of this decrease in the estimates' errors proves the model to be considered as viable. This feature of the model suggests that the observations in MAPE and SD tend to converge to the actual result at completion. In addition, the explanation of this tendency lies in the nature of the ES approach suggesting improvement of duration estimates as SPI_t stabilizes and a project approaches its completion. In addition to this, it makes use of nonlinear regression. The growth model via the regression combines to date AC data with future PV for which its three parameters show the relationship between past, current and future project performance and progress. This second finding collaborates with the previous research (Christensen et al., 1995; Marshall et al., 2008; Tracy, 2005) which reported the advantage of the nonlinear regression modeling over the conventional IB methods in the EVM system. Our comparative analysis shows that CEAC computed by the four IB formulae produce abrupt and, hence, unstable estimates. The values of MAPE of these four formulae vary from as small as 4.32 to as large as 16.22 and SD ranging from 5.92 to 20.2. Therefore, the proposed model's timeliness property is another practical advantage over the IB approach. We remark that, in most projects regardless of their nature, budget, and duration, estimates by a traditional approach stabilize by the second half of the project life or at late stage. The results of the timeliness of accuracy and precision are in accordance with the findings of previous research in the field. For example Henderson and Zwikael (2008) showed that the PI values (CPI and SPI_t) converged to their respective final values as projects approached completion.

A third finding of this study is that asserting schedule progress as a factor of future cost improves both accuracy and precision of the developed model. EVM is a system that integrates project cost, schedule, and scope. In this regard, schedule is known as a factor of project cost performance. Advance/delay in work progress has its relative influence on cost behavior. The majority of projects experience the impact of schedule progress on their final cost. Therefore, our methodology makes explicit use of ES concepts in calculation of CEAC. This practical contribution of the ES method into the forecasting formula reflects schedule impact and, hence, provides more reliable CEAC (Fig. 4 and Table 5).

In addition, this research provides a novel and extended contribution to previous research on the development of the GGM. In particular, the research conducted by Narbaev and De Marco (2014) provided for information about adapting the GGM to EVM, comparing it with other growth models in the field, constructing the best fit S-curve for CEAC with the integration of ES concepts for early and middle stage estimates, and, finally, applying the model to compute CEAC of a set of construction projects. This paper continues that work as part of its future research and provides a comparison with the four IB methods, the calculation of CEAC for a late stage, the analysis of precision of CEAC, and finds the model timeliness property as being reliable in providing most accurate and precise estimates throughout project life.

Finally, this study aims at the diffusion of the GGM for a variety of projects and various industries.

6. Conclusion

Reliability in forecasting CEAC has long been a focus of many comprehensive research and comparative studies. This is because accurate and precise CEAC forecasts throughout the project life equip the project team with essential information in taking prompt preventive actions and assisting on timely completion within available budget. The traditional approach using PI in EVM has been in use to assist in this task for over four decades with little change. However, this technique relies on EVM data only and merely calculating CEAC by adjusting the remaining BAC by a PI (Kim and Reinschmidt, 2011; Lipke et al., 2009). In addition, the IB method may produce inaccurate and unreliable CEAC in the early stages of projects due to little EVM data available.

This paper proposes a new CEAC methodology to forecast the final cost of ongoing projects. It is a combined index–

regression approach. The method is based on an ES-based IB equation modified by integration of the GGM via a nonlinear regression analysis. This combined approach produces more accurate and precise CEAC effective for all stages of the project life because it meets the property of timeliness. The proposed methodology overcomes the reported limitations inherent with the traditional linear IB methods.

Practical implications arise from the proposed CEAC model as a tool for PMs to better incorporate the progress status into the task of forecasting the final cost of an ongoing project. In particular, the inclusion of the ES-based CF, which indicates the expected completion time, takes into account any schedule advance or delay into the estimate. This implies that schedule is a factor of cost performance and has a large influence on CEAC. The results of comparative analysis without (the base case) and with (the ES-based case) CF in the model equation show that the second case generates more accurate and precise forecasts in all the three completion stages of a project. This cost–schedule relationship represented in the model equation is a contribution to extending the EVM research and practice to better capture the inherent relation between cost and schedule forecasts.

In addition, the field literature reports that application of traditional IB methods (originally developed as a tool to manage complex and large projects) is questionable when it comes to CEAC of small-sized and short-duration projects. On the contrary, the proposed forecasting tool demonstrates applicability to small and medium-sized projects, such as those used for the sample test.

Moreover, it is an effective and practicable method for early CEAC when as few as three time points are available. Thus, it is effective for short lifespan projects with small-sized budgets.

To pursuit the advantages of this methodology, future research is directed toward evolving the theoretical framework and providing for extended applicability. On the one hand, with the purpose of understanding the model behavior in a dynamic project environment, it might be opportune to integrate the given CEAC calculation method with uncertainty and risk analysis able to capture major exceptional risk events into CEAC formulation, as well as include expert managerial belief as a potential source of corrective actions affecting future project performance and CEACs. With this regard, it should also be comprised within the framework of the system behavior theory.

Another prospective research direction drives toward understanding the impact of reducing the number of the parameters for the GGM, as it will ease understanding the time–cost/schedule relationship being described by the model, as well as it will make the model easier-to-adopt by field practitioners.

Finally, the method is proposed to practitioners for application to a larger variety of projects at different progress stages and for diffusion in various industries.

Appendix A. Calculation of CEAC for a sample project

This section provides the detailed information on how CEAC is calculated with the two GGM cases (Base and ES-based) and four IB methods (CPI-, CR-, CI-, and MA-based) for Project 2 for the early stage. With BAC =21,400,000 euro and PD = 6.2 months, the project's BAC percent complete after three months from the start is 20.76%, hence, the computation of CEAC is done at AT = 3 with CF =1.33. Table 6 provides EVM data (in euro) of the project whereas Table 7 presents the values of the four performance indexes. The formulae to find the values of these performance indexes are given in Table 1. Table 8 presents results of CEAC for six cases with corresponding PEs.

Table 6
EVM data.

Time points	Months	PV	EV	AC	SPI
1	1	370,220	124,120	535,000	0.335
2	2	2,080,080	1,333,220	2,461,000	0.641
3	3	5,730,920	4,442,640	4,562,480	0.775
4	4	9,625,720	7,201,100	7,468,600	0.748
5	5	16,050,000	11,249,980	11,936,920	0.701
6	6	19,688,000	14,768,140	15,729,000	0.750
7	6.2	21,400,000	21,400,000	21,913,600	1.000

Table 7
Four performance indexes of the index-based method.

Time points	Months	CPI	CR	CI	MA
1	1	0.232	0.078	0.253	–
2	2	0.542	0.347	0.562	–
3	3	0.974	0.755	0.934	0.781
4	4	0.964	0.721	0.921	0.895
5	5	0.942	0.661	0.894	0.955
6	6	0.939	0.704	0.901	0.945
7	6.2	0.977	0.977	0.981	0.956

Glossary

Actual Cost (AC). The realized cost incurred for a project during a specific time period.

Actual Time (AT). The number of time periods from the start of a project to a project status date.

Budget at Completion (BAC). The sum of all the budgets established for the work to be performed on a project. The total Planned Value for the project.

Completion Factor (CF). The Earned Schedule (ES)-based factor which is the ratio of Expected Duration at Completion to Planned Duration (PD). It is inversely related to the time-based Schedule Performance Index (SPI_t). The value of CF less than 1.00 indicates a project is ahead of schedule (favorable condition), more than 1.00—behind schedule (unfavorable condition), and equal to 1.00—according to schedule.

Composite Index (CI). A Performance Index (PI) expressed as the sum of the portions of Cost Performance Index (0.8*CPI) and Schedule Performance Index (0.2*SPI).

Cost at Completion (CAC). The realized cost incurred for a whole project. Actual Cost (AC) of a finished project.

Cost Estimate at Completion (CEAC). The expected total cost of completing a project. It is expressed as the sum of the Actual Cost (AC) to date and the remaining portion of Budget

Table 8
CEAC calculation by the two GGMs and four IB methods.

By GGM	Result	By IB method	Result
CF by Eqs. (3)–(5)	1.33	CEAC by Eq. (1) (CPI-based)	21,977,264
GGM(x = 0.484)	0.489	PE for CPI-based	0.29%
GGM(x = 1.00)	1.187		
		CEAC by Eq. (1) (CR-based)	27,027,216
CEAC by Eq. (6) (Base)	19,486,285	PE for CR-based by Eq. (8)	23.34%
PE (Base) by Eq. (8)	−11.08%		
		CEAC by Eq. (1) (CI-based)	22,717,569
GGM(CF = 1.33)	1.298	PE for CI-based by Eq. (8)	3.67%
CEAC by Eq. (7) (ES-based)	21,871,224		
PE (ES-based) by Eq. (8)	−0.19%	CEAC by Eq. (1) (MA-based)	26,286,599
		PE for MA-based by Eq. (8)	19.96%

at Completion (BAC minus AC) adjusted by a Performance Index (PI) or Gompertz Growth Model (GGM).

Cost Performance Index (CPI). A Performance Index (PI) expressed as the ratio of Earned Value (EV) to Actual Cost (AC).

Critical Ratio (CR). A Performance Index (PI) expressed as the product of Cost Performance Index (CPI) and Schedule Performance Index (SPI).

Earned Value (EV). The cumulative to date measure of the work performed, expressed in terms of the budget authorized for that work.

Expected Duration at Completion (EDAC). The expected total time for completing a project. It is expressed as the ratio of Planned Duration (PD) to the time-based Schedule Performance Index (SPI_t).

Gompertz Growth Model (GGM). An S-shaped model represented by a sigmoid function which accounts for the slow initial growth of cost accrual, accelerating the growth rate on the middle stage, and slowing down again by the end of a project.

Index-Based (IB) method. A method to compute Cost Estimate at Completion (CEAC) that adjusts the remaining portion of Budget at Completion (BAC) by a performance index.

Least Squares (LS) method. A method that determines the best fit of the observed values in the data fitting. The method minimizes the sum of the squared forecast errors; the error which is the difference between an observed value and the fitted value generated by the Gompertz Growth Model (GGM).

Mean Absolute Percentage Error (MAPE). The average of the absolute values of Percentage Errors (PE) on the number of projects tested.

Moving Average (MA). A Performance Index (PI) expressed as the averaged CPI which is the ratio of sums through three periods beginning with the most recent period and going backwards.

Percentage Error (PE). A measure of forecast accuracy which is the difference between Cost Estimate at Completion (CEAC) and Cost at Completion (CAC) expressed as a percentage of CAC with a negative value suggesting underestimation and a positive value—overestimation.

Performance Index (PI). A measure of cost efficiency of budgeted resources. Four types of PI are used in the research.

Planned Duration (PD). The planned duration for a project.

Planned Value (PV). The authorized budget assigned to scheduled work.

Standard Deviation (SD). A measure of a statistical dispersion of the values of Percentage Errors (PE) from the Mean Absolute Percentage Error (MAPE) which is computed by taking the square root of the variance (the average of the squared differences between PE of an individual project and mean of PE). A smaller value of SD indicates that cost estimates calculated by a particular model are closer to its mean forecast error and suggest more precise estimates.

The α parameter. A parameter of the Gompertz Growth Model (GGM) that represents the never attained final cost as time (x) tends to infinity.

The β parameter. A parameter of the Gompertz Growth Model (GGM) that is the y-intercept which indicates an initial budget size of a project.

The γ parameter. A parameter of the Gompertz Growth Model (GGM) that governs the cost growth rate.

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