Elsevier Editorial System(tm) for Expert Systems With Applications or its open access mirror
Manuscript Draft

Manuscript Number:

Title: Risk-based cost estimates at completion: Integrating cost contingency into earned value management cost forecasting

Article Type: Full length article

Keywords: aerospace project; cost contingency; earned value management; estimate at completion; project control

Corresponding Author: Dr. Timur Narbaev, Ph.D.

Corresponding Author's Institution: Kazakh-British Technical University

First Author: Timur Narbaev, Ph.D.

Order of Authors: Timur Narbaev, Ph.D.; Alberto De Marco, Ph.D.; Mario Vanhoucke, Ph.D.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

Timur Narbaev, PhD, PMP®
Business School, Kazakh-British Technical University
Tole bi 59, 050000 – Almaty, Kazakhstan
Phone: +7 705 181 75 85
E-mail: t.narbaev@kbtu.kz

December 31, 2019

Dear Editor,

Expert Systems with Applications

We would like to submit our manuscript "**Risk-based cost estimates at completion: Integrating cost contingency into earned value management cost forecasting**" for consideration for publication in *Expert Systems with Applications*.

We confirm that the content of this manuscript has not been published or accepted for publication, and is not under consideration for publication elsewhere.

The manuscript has been prepared in accordance with the journal guide for authors.

Sincerely,

Timur Narbaev, Ph.D. (Corresponding author)

Alberto De Marco, Ph.D.

Mario Vanhoucke, Ph.D.

Manuscript
Click here to download Manuscript: Manuscript_Final.docx Click here to view linked References

Risk-based cost estimates at completion: Integrating cost contingency into earned value management cost forecasting

Abstract

This paper proposes a novel cost forecasting method that integrates the Cost Contingency (CC) expenditure profile into the methodology of Cost Estimate at Completion (EAC(€)) in ongoing projects. Based on Earned Value Management (EVM) it provides three forecasting formulae that are able to model three alternate risk management strategies that could be activated by project managers to respond to risk in a project. The forward-looking method considers CC spending in a way that future risk is accounted with EVM-derived past performance embedded into the forecasts. The application of the proposed EAC(€) model to two complex case projects delivered by a large aerospace contractor demonstrates its construct and explores its validity to provide for more suitable and accurate forecasts.

Keywords: aerospace project; cost contingency; earned value management; estimate at completion; project control.

1. Introduction

As part of an effective project monitoring system, project cost and schedule forecasting is used by project managers to help control the performance of projects that deviate from original plans. No matter how perfect the plan and budget are, without systematic checks during the project delivery, neither the actual cost and schedule performance can be assessed nor control actions can be taken to reduce or eliminate deviations from the original plans (Cleland & Ireland, 2007). Therefore, project forecasting is a crucial management process to anticipate future project behavior, estimate final cost at completion and suggest control actions that would adjust the project final performance to protect the stakeholders' satisfaction.

Out of various methods available in both literature and practice, Earned Value Management (EVM) has been proving the most widely used tool to monitor the project status and calculate final estimates for time and cost (Anbari, 2003; Colin & Vanhoucke, 2015). Through the application of EVM, project managers track the project progress, calculate actual performance indices and estimate possible final cost and duration so that they can take informed corrective actions for either performance improvement or project plan revision throughout the project execution (Bryde, Unterhitzenberger, & Joby, 2017).

Most cost deviations in a project typically arise because of risk and uncertainties that materialize during the course of action and the EVM-based project monitoring process is effective to detect such cost variances in past performance. Similarly, the cost estimates at completion (EAC(€)) that are based on EVM measures predict final cost at completion by linearly, or nonlinearly, projecting past performance indicators into the future (Narbaev & De Marco, 2014a; Warburton & Cioffi, 2016). This means that future performance forecasts are made based on risk incurred in the past. Although the predictive power of project cost data is recognized as an indicator of the cost overrun probability in risk management (Kim & Pinto, 2019), EVM-based EAC(€)s do not consider the influence of past risk control actions on the future cost profile of the project. In fact, traditional EVM-based cost forecasting methods may not capture the additional positive or negative effect of past risk management actions.

In particular, the early or late expenditure of the Cost Contingency (CC) funds to respond to risk in a project may influence the final cost outcome. CC funds are typically estimated at the project planning phase (PMI, 2009), put aside as a reserve account (Xie, AbouRizk, & Zou, 2012) and used as an allowance to manage risk events (Uzzafer, 2013). In addition, the CC funds serve as a tool to protect the interests of various project stakeholders (owners, investors, creditors, community etc.) from unforeseen events and as potential opportunities

for improving stakeholder relationships (e.g. returning unspent CC to the client or using it to improve the project outcome) (De Marco, Rafele, & Thaheem, 2016).

Various risk management actions are used by project managers to preventing or responding to risks. These actions can be classified into proactive, neutral, and reactive risk management strategies (Kerzner, 2013; Pich, Loch, & Meyer, 2002; Repenning & Sterman, 2001). The proactive risk management implies the use of the CC funds from the project start with some flexibility such that risks can be prevented (Pich, Loch, & Meyer, 2002). The reactive risk management strategy suggests that project managers face risks rather than prevent them ahead of time assuming no expected risk will occur (Osipova & Eriksson, 2013). With the neutral risk management strategy, Kerzner (2013) noted that the utility which can be defined as a satisfaction from a payoff changes at a constant rate. De Marco, Rafele, & Thaheem (2016) stated that such risk management strategies applied by project managers define the way the CC is spent and influence the final cost outcome in projects.

Therefore, project managers need a forward looking tool to assist in the task of forecasting the final EAC(€) in integration with the projection of the effect of the CC consumption. For this purpose, as an integral component of the cost forecasting, project managers should develop a range of cost estimates considering the way the CC expenditures are going to impact to the final cost.

However, current EVM forecasting methodologies (e.g. reviewed in Hazır, Hazir, & Hazır, 2015; Willems & Vanhoucke, 2015) do not take into account the effect of past risk response actions in a way that the CC spending be reflected in the EAC(€) estimates. This means that any possible preventive or reactive risk attitude, and associated CC expenditure, are not mathematically incorporated into EAC(€) formulae to capture this influence. The EVM cost forecasting and CC management theories are barely studied together and their integration to address risk adjusted cost forecasts and CC management during project

execution, compared to its estimation during project planning, is nearly unavailable (Xie, AbouRizk, & Zou, 2012; Hammad, Abbasi, & Ryan, 2016).

The goal of this study is to propose a EAC(€) forecasting methodology which reflects the influence of past risk response actions on the final cost estimates represented by the CC consumption variable in the EAC(€) formula. In addition, the CC variable can take one of its three forms to capture the influence of either a proactive, a neutral or a reactive risk management strategy, respectively. This is represented by three different structures of the EAC(€) formula.

The paper is structured as follows. The next section provides an overview of the EVM index-based cost forecasting, regression-based cost forecasting and CC management during project execution; all is the framework upon which the proposed model is developed. Then the methodology presents the construct of the CC-based EAC(€) model with its three forms to reflect proactive, neutral and reactive risk management strategies of project managers in CC consumption, respectively. Next, the model is validated using data of two real life high-tech aerospace projects delivered by one of the EU aerospace agencies that asks for confidential anonymity and provide empirical evaluation about the robustness of our model. The projects are to design and prototype a pilot shuttle for autonomous hearth landing and a material shipping unit for the International Space Station (ISS). Afterward, the work elaborates on the results of the model application in the project-oriented organization and provides discussions regarding which of its forms provide more suitable and accurate estimates under given CC spending behavior. The study also maps the estimate results against the actual CC spending to corroborate the results with the actual risk management strategies undertaken by the project managers. Lessons learnt from the study are provided with both theoretical and practical implications. Finally, conclusions are drawn with future research directions.

2. Research background

2.1.The index-based cost forecasting (Linear)

The EVM practice relies on three key periodic metrics that are used to measure the project's cost and schedule performance: the Planned Value (PV) representing the budgeted cost of work scheduled at the Actual Time now (AT); the Earned Value (EV) – the budgeted cost of work performed to date; and the Actual Cost (AC) of work performed at AT. The Budget at Completion (BAC) represents the value of all the work scheduled for the project – the total of PV. The Earned Schedule (ES) is the time value at which the EV should have been earned according to the project baseline and defined by Eq.(1).

$$ES = t + \frac{EV - PV_t}{PV_{t+1} - PV_t} \tag{1}$$

where t is the integer time point representing schedule progress for which $EV \geq PV_t$ and $EV < PV_{t+1}$ (Lipke, 2003).

These metrics are used for deriving associated cost and schedule variances (actual versus budgeted performance) and indices (ratio expressions of the variances) as well as for estimating the project's cost and time at completion.

Based on these three metrics, the index-based EVM approach uses the Cost Performance Index (*CPI=EV/AC*), the schedule performance index (*SPI=ES/AT*) or their combinations to compute cost and time estimates at completion (Lipke, 2003; PMI, 2011). Therefore, with consideration of project past behavior and actual performance to date, the original BAC is revised by the corresponding performance index and the final cost estimate is defined by Eq.(2).

$$EAC(€) = AC + \frac{BAC - EV}{Cost\ performance\ factor} \quad (2)$$

Another metric is the Completion Factor (CF) which indicates the Expected Duration at Completion (EDAC) yielded to unity and is defined as *CF=EDAC/PD.* CF is an inverse of the time-based SPI. If the value of CF is greater than 1.00 then it indicates that a project is likely to be delivered late while less than 1.00 suggests an early finish.

Though widely accepted as a benchmark for EAC(€) this principal formula has been criticized with regard to the accuracy and stability of CPI value (Kim & Pinto, 2019). Thus various extensions and alternatives to this formula have been proposed, reviewed and summarized in Hazır, Hazir, & Hazır (2015) and Willems & Vanhoucke (2015).

2.2.The regression-based cost forecasting model (Nonlinear)

This paper proposes the CC-based cost forecasting model (hereafter named as the EAC(€)$_{risk}$) which is based on the methodology by (Narbaev & De Marco, 2014b) (the original EAC(€) model hereafter named as the EAC(€)$_{orig}$). This model was compared for its forecast accuracy, precision, and timeliness with conventional index-based methods and proved itself superior and applicable (Narbaev & De Marco, 2014a, 2014b).

The EAC(€)$_{orig}$ was built on the Gompertz growth model (GGM) developed by nonlinear regression modeling and integrates the ES concepts to account for schedule impact on cost forecasts. The GGM is defined by Eq.(3)

$$GGM(x) = \alpha e^{[-e^{(\beta - \gamma x)}]} \quad (3)$$

where the α-asymptote represents the value of the final cost as time tends to infinity; the β is the y-intercept (the initial value of a project cumulative cost) governing the cost curve's

location along the x-axis; and the γ-scale parameter accounts for the rate of the cost growth responsible for the curve's shape.

The mathematical properties of the GGM's three parameters are as follows. The maximum cost growth rate is MaxRate=$\alpha\gamma/e$ reached when the time $x=\beta/\gamma$ with the cumulative cost growth GGM(x)=α/e. The value of $x=\beta/\gamma$ defines the location of the cost curve along the x-axis and the γ-scale parameter builds its shape; both the location and shape are the function of its three parameters.

The GGM is often used to explore growth patterns in population where the growth curve is not symmetrical and whose growth rate monotonically picks to a maximum before it drops to zero (Seber & Wild, 1989). This growth function has found applications in the areas such as biology, economics, marketing where population growth can be well-shaped by an S-curve pattern. In Project Management, the GGM is used to study the cost spending profiles because its parameters reflect the patterns of physical progress which are S-shaped. The S-shaped pattern of such cost curves represents work progress which has a lower rate at the beginning and end (steady growth) and a higher rate in the middle (steeper growth) (Narbaev & De Marco, 2014b). In EVM, such curves are used to display AC, EV and PV of a project over time and to compute the final cost and duration estimates.

Following the approach by Narbaev & De Marco (2014b), the paper next briefs on the development of the EAC(€)$_{orig}$ methodology (Eq.4).

$$CEAC_{orig}(x) = AC(x) + \left[GGM\big(CF(x)\big) - GGM(x)\right] * BAC \tag{4}$$

In this model both GGM(CF(x)) and GGM(x) when normalized to unity represent the BAC consumption; the former shows its total value adjusted to the ES-based time estimate at completion while the latter presents its current spending at AT. Their difference estimates the

remaining portion of BAC, *i.e.*, from AT to project completion which is calculated by the nonlinear regression modeling using the GGM function.

The cost forecasting using the EAC(€)$_{orig}$ model above follows the three steps. Step 1 is the estimation of the values of the GGM's three parameters (Eq.3) through nonlinear regression. In Step 2 the EAC(€) is computed using the GGM parameters' values for Eq.(4). Step 3 integrates the ES-based CF to reflect schedule progress on cost performance and hence on the final cost estimates. Appendix A introduces the EAC(€)$_{orig}$ methodology and its three steps in more detail and a simple hypothetical data is used to demonstrate how to calculate the final cost forecast.

2.3.The CC management during project execution

Inaccuracies in estimation are inherent to the uncertain nature of a project, which is affected by various risks from project feasibility to cost, schedule, quality, financial performance and strategic objectives (Thamhain, 2013). For this, as part of the CC management system, project managers use risk response plans and contingency reserves are included into the original budget to manage risks that may take the project off from its predetermined time, cost and quality requirements. The CC reserves are added to BAC to manage unexpected events, decrease the probability of the project cost overrun and help in meeting the project agreed budget (Naeni & Salehipour, 2011). The CC management implies estimation and allocation of the contingency reserve during project planning and its control during project execution which, in turn, results from risk assessment. Such reserves are determined as a percentage of the project budget, a fixed value, or defined by quantitative approaches (PMI, 2009; Xie, AbouRizk, & Zou, 2012).

During project planning, contingencies are added to the project's budget to form the cost baseline. However, it is important that such contingency reserve accounts are not only defined during project planning, but also wisely spent and controlled during project execution

(Barraza & Bueno, 2007). The current study addresses the CC management during project execution and focuses on the CC spending, which can be integrated to the EVM system for EAC(€)$_{risk}$ forecasting of ongoing projects.

Table 1 presents an overview of the pieces of literature that propose methods and models integrating CC management into an EVM system. The added contribution to EVM is when the CC study adds value to project performance measurement, and/or duration or cost forecasting (i.e. to the EVM body of knowledge).

The study by Barraza & Bueno (2007) proposed a simple approach to allocate CC reserves to project activities using Monte Carlo simulation with normal distribution. All activities have the same probability for the CC distribution with respect to the project BAC. With each time step, the CC allocation can be updated based on past project performance and CC spending. The primary contribution of this paper is to the EVM performance measurement but no specific application to duration or cost forecasting is proposed. Xie, AbouRizk, & Zou (2012) focused on estimating the remaining CC reserves during project execution. Based on the Value at Risk technique with a given confidence interval and past periodic data, namely daily, weekly, and monthly, their model is able to generate various CC forecasts over different time horizons for the remaining life of an ongoing project. They showed that the model generates more accurate CC forecasts when the prediction horizon increases. De Marco, Rosso, & Narbaev (2016) proposed a nonlinear regression-based EVM cost forecasting model which equation has the CC variable dependent on the BAC spending progress. They compared the results of EAC(€) of their model with the ones of the index-based models at the early, middle and late stages of the project life. In addition, they tested the stability of their model changing the CC variable from 2.5% to 12.5% of BAC with a 2.5% increment. On average, in 5 out of 8 case projects their model proved superior over the index-based cost forecasting models.

Table 1.

A summary of studies on integration of CC and EVM.

Study	Purpose	Method/model	Validation on projects	Contribution to EVM
Barraza & Bueno (2007)	To control total CC as part of project's BAC during project execution	The probabilistic model with Monte Carlo simulation allocating total CC among project activities	Not validated; Demonstrated on a hypothetical industrial project	Performance measurement: BAC, PV and AC are updated to include CC
Xie, AbouRizk, & Zou (2012)	To forecast the remaining CC fund during project execution	The method is based on the Value at Risk approach which estimates the future CC by updating the remaining reserves considering project risks	One ongoing tunnel construction project	Performance measurement: the CC fund is part of AC
De Marco, Rosso & Narbaev (2016)	To calculate adjusted EAC(€) under the influence of risk	The nonlinear-regression based model which has the CC variable as part of project's BAC	Eight projects from various industries	Cost forecasting: Remaining BAC is updated by the CC variable
Babar, Thaheem, & Ayub (2017)	To calculate adjusted EAC(€) under the influence of risk	The modified index-based EVM model whose formula has the risk performance index dependent on project variables (quality, safety, stakeholder etc.)	Two construction projects: administrative and school buildings	Cost forecasting: the classical EVM forecasting formula has, in addition to CPI and SPI, the new risk performance index
Kim & Pinto (2019)	To assess the CPI as an indicator of EAC(€) distribution	The probabilistic EAC(€) model is built on the index-based formula with the CPI adjusted by the CC factor which consider risks generated by the Monte Carlo simulation	One construction project	Performance measurement: CPI values are updated considering risks
This study	To calculate EAC(€) influenced by past risk management actions	The nonlinear S-shaped model which captures three risk management strategies, respectively, reflected by the three forms of the CC factor in the EAC(€) formula	On two aerospace projects	Cost forecasting: the nonlinear EAC(€) formula is modified to include the CC factor in addition to BAC

Babar, Thaheem, & Ayub (2017) developed a framework that incorporated project's 16 key performance indicators (grouped into quality, safety, stakeholder satisfaction, and others) into the risk performance index to predict risk adjusted cost forecasts. They refined the conventional deterministic EAC(€) formula (Eq.2) which had the remaining BAC adjusted by the complementary weights of CPI and SPI and modified this equation by adding the risk

performance index. The risk performance index is an aggregate indicator of the above 16 indicators which values were found based on the results of the survey of 101 respondents. Kim & Pinto (2019) proposed an extension to the conventional index-based cost forecasting by replacing CPI with a new cost overrun index. This probabilistically built indicator takes into account a range of possible costs and the relative likelihood within the range which can be used as an alternative to deterministic CPI in calculating EAC(€).

In summary to Table 1, this work is different from the previous studies as follows. First, the model does not require project managers to have prior knowledge in the Bayesian, Monte Carlo, or other simulations and inputs from field interviews, surveys and historical data. All what is needed are the CC and EVM planned and reported data of a project being delivered. Second, unlike the previous works, this study is able to mathematically represent the influence of risk management strategies in EAC(€) through the CC consumption pattern. For this, the model can take one of its three forms with a factor in its formula reflecting an outcome of a particular CC management strategy.

The CC spending measures can be grouped into proactive, neutral, and reactive risk management strategies (Kerzner, 2013; Pich, Loch, & Meyer, 2002; Repenning & Sterman, 2001). According to Pich, Loch, & Meyer (2002) the proactive CC management is an instructionist strategy where project managers use the CC from the project start date combined with some flexibility to adapt and learn from future unforeseen events. Osipova and Eriksson (2013) claim that the risk proactive (preventive) approach can help achieve a balance between managing occurred risks and enough CC budget flexibility for dealing with later risks. Under this aggressive risk management policy, a project manager is risk averse and she is willing to spend money ahead since the beginning of the project to reduce the probability of later risk and its impact on the project objectives.

On the contrary, a risk reactive project manager is a risk loving individual who prefers reacting to occurred risks than preventing them ahead of time by thinking optimistically that no risk would happen. With a risk loving manager, more CC is available by the project end, which is consumed with a higher rate compared to the contingency spending at the project beginning as under the proactive strategy. In his work, Ford (2002) studied the risk management behaviors of different project managers and grouped them into aggressive (proactive) and passive (reactive) CC management strategies. His simulation model proved that a project manager with a proactive approach reallocates contingency budget as early as possible into the project life, utilizes it to control project schedule and works towards resolving unexpected problems ahead. With the reactive risk management policy, he showed that CC is redistributed slower and put off until it is spent for meeting crucial objectives later by the project end. In their work, De Marco, Rafele, & Thaheem (2016) tested proactive and reactive CC management strategies on a complex construction project using the system dynamics modeling. They simulated the influences of main stakeholders over the CC management process and investigated project managers' behaviors in responding to risk. They revealed that with a reactive risk management strategy, risk was ignored at the project beginning and reactively dealt with later into the project life. They corroborated their simulation results by the findings from the interviews with a panel of experts in understanding the managerial impacts and interests of various project stakeholders. They suggest that a proactive risk management practice might be an effective policy for managing the CC in complex engineering, procurement, and construction projects.

3. Methodology

The CC-based EAC(€)$_{risk}$ model proposed in this paper considers the influence of risk response actions through the CC consumption profile, which is part of its equation. The risk response actions are grouped into three CC management strategies, namely: proactive, neutral

and reactive. They are in turn represented by three respective CC consumption profiles in the forecast formula, which are based on the given risk management strategies. The model presents the estimates of both project's final cost and contingency budget, separately. In addition, the present study adds the managerial influences of project managers represented by the CC factor into the EAC(€)$_{orig}$ model and in doing so it investigates the behavior of project managers in responding to risk. This all is a refinement and extension of the model by Narbaev & De Marco (2014b).

To introduce the CC factor which is *k*-percent of BAC (i.e. CC=BAC**k*) the study refines the EAC(€)$_{orig}$ formula. The assumption of taking CC as a predetermined percentage of BAC is a common practice and has been reported in both academia (e.g., Table 1) and practice PMI (2009). To simplify the refinement process towards deriving the EAC(€)$_{risk}$ model, the paper presents the portion GGM(CF(*x*))-GGM(*x*) of the original model (Eq.4) with a new notation Ω(*x*) as Ω(*x*)=GGM(CF(*x*))-GGM(*x*).

The transformation into the proposed risk adjusted EAC(€) model is given Eq.(5).

$$CEAC_{risk}(x) = AC(x) + \left[GGM\big(CF(x)\big) - GGM(x)\right] * BAC * (1+k) = AC(x) + \left[GGM\big(CF(x)\big) - GGM(x)\right] * BAC + \left[GGM\big(CF(x)\big) - GGM(x)\right] * BAC * k = AC(x) + \Omega(x) * BAC + \Omega(x) * BAC * k = AC(x) + \Omega(x) * BAC + \Omega(x) * CC \quad (5)$$

In the above formula, AC represents the sum of to date values of cost of work performed and of CC which is the performance measurement baseline, an approved integrated scope-schedule-cost baseline. Hence, this theoretically built EAC(€)$_{risk}$ reflects the CC spending in the cost forecasts.

Finally, the new model is able to give the estimates of both project's cost and contingency budget separately. To this end, the Ω(*x*) value accounts for the remaining portion of both

BAC and CC. This makes possible for the model to show the way project managers consume the CC budget for taking risk response actions until this budget is consumed (Ford, 2002).

To align the model to suitably reflect the proactive, neutral and reactive risk management strategies, the methodology proposes three forms for the model, respectively. The three forms are able to exemplify the profile of the CC spending that progresses throughout the project life cycle. It is noted that BAC is cumulatively spent according to an S-shaped curve that is well fitted by the GGM. This is also true for the contingency budget consumption, but utilized as per a reversed S-shaped curve depending on BAC consumption profile as a function of the GGM.

The model defines the behavior of a project manager in spending CC (proactively, neutrally or reactively) by the CC spending rate (CCR) which is ruled by the Ω factor. For this it introduces a *constant* CCR ruled by Ω (to represent the neutral CC management strategy), *decreasing* CCR ruled by Ω^2 (to represent the proactive CC management strategy), and *increasing* CCR ruled by $\sqrt{\Omega}$ (to represent the reactive CC management strategy).

Table 2 presents the three forms of EAC(€)$_{risk}$ model and their characteristics which, respectively, consider the three CC consumption strategies. Fig. 1 depicts these three CC spending patterns by the EAC(€)$_{risk}$ model.

Table 2.

The three forms of the proposed EAC(€)$_{risk}$ model.

The CC management strategies	$f'(x)$ – CCR	$f''(x)$ – change in CCR	The model's forms
Neutral: Constant CCR, Ω	1	0	Form 1: $CEAC_{risk}(x) = AC(x) + \Omega(x) * BAC + \Omega(x) * CC$
Proactive: Decreasing CCR, Ω^2	$2\,\Omega$	2	Form 2: $CEAC_{risk}(x) = AC(x) + \Omega(x) * BAC + \Omega(x)^2 * CC$
Reactive: Increasing CCR, $\sqrt{\Omega}$	$1/(2\sqrt{\Omega})$	$-1/(4\sqrt{\Omega}$	Form 3: $CEAC_{risk}(x) = AC(x) + \Omega(x) * BAC + \sqrt{\Omega(x)} * CC$

The neutral CC consumption: a constant CCR. This type of contingency spending is ruled by CCR represented by 1 (by the first derivative of Ω) and linear to the progress of the BAC spending. This provides for the CC spending proportional to the progress of the budget expenditure with the CCR equal to 0 (by the second derivative of Ω). This type of consumption means that project managers spend their CC budget along with the same S-curve behavior as the project's BAC.

The proactive CC consumption: a decreasing CCR. With this type of contingency consumption, the CCR diminishes nonlinearly against the progress of BAC (by the first derivative of Ω^2) and its change overtime is constant (by the second derivative of Ω^2). Project managers who are proactive prefer to prevent future risks rather than work on corrective measures when risks occur. This type implies that project managers tend to consume most of their CC budget with the highest rate at early stage of the project's life cycle (exemplified in Fig. 1) and the CCR decreases as the project approaches its completion.

The reactive CC consumption: an increasing CCR. When project managers are reactive to risks, they tend to spend their contingency reserves passively; they prefer to react to occurred risk rather than prevent them. With this type of the CC consumption, risk averse behavior is represented and modeled by the CCR, which is increasing overtime by the first derivative of $\sqrt{\Omega}$. The second derivative of the factor models the change in the rate as a project develops. This implies that a back-loaded consumption of the contingency budget is preferred by project managers with less consumption at the beginning then followed by its accelerated utilization as the project approaches its completion.

Insert Fig. 1.

The three CC spending profiles by the $EAC(€)_{risk}$ model.

4. Validation

4.1.Case projects

The proposed model is developed and demonstrated using data collected from two case aerospace projects. These projects are picked because they are examples of complex projects in large organizations where available project management regulations, standards, and best practices call for the need to collect project data and in particular to carefully and separately monitor the CC consumption. The case projects are developed by the same aerospace company that here calls for anonymity. This is a large organization that works as a contractor for national and international space programs to develop prototypes and systems for space missions. The objective of this research is to develop a method and the case projects serve the purpose of illustrating its construct and exploring its validity via using real case data of past projects rather than explaining the specific CC management practices of the select case company and case projects.

The two select case projects are the following. The first project is about the design and development of a rocket-powered autonomous vehicle to refill the International Space Station (ISS) with no ability to re-enter the atmosphere. The shuttle was effectively used in space operations: two days after launch the shuttle reached the ISS where the crew could pick up new materials from the pressurized unit and discard all accumulated waste. The vehicle was then returned and got destroyed at contact with terrestrial atmosphere. Project 1 had the BAC of €150,033 thousands and the planned duration (PD) of 41 months. The CC budget was defined as a fixed percentage of the BAC and is 10% of the budget (€15,003 thousands). The actual cost at completion (CAC) of the project was €148,195 thousands with the CC spent of €6,567 thousands. The total cost for the project incurred was €154,762 thousands and it completed on time.

The second project is about the design and prototyping of an experimental autonomous space vehicle with high aerodynamics for effective atmospheric re-entry ability. The project experienced slight time delay and minimum cost overrun. The shuttle was successfully tested on a full orbit journey with its final water landing in the ocean. Project 2 had the BAC of €21,800 thousands, PD of 38 months, the planned CC of €2,180 thousands, CAC is €21,900 thousands, the CC spent is €2,800 thousands and AD is 40 months.

The data for this research were collected from the case company's project control department. After collection data were cleaned up, classified, and integrated so as to get a complete monthly EVM dataset. This included reports of all the EVM metrics, forecasts, and CC consumption with necessary data for this research presented in Table 3.

Table 3.

The cost data of the case projects (thousands of euro).

Months	Project 1				Project 2			
	PV	EV	AC	CC	PV	EV	AC	CC
1	87,547	87,855	87,547	0	719	719	722	0
2	92,733	93,794	92,733	0	1,744	1,438	1,445	0
3	93,837	94,000	93,837	1,437	2,616	2,158	2,168	0
4	97,342	99,370	97,342	1,437	3,335	2,877	2,890	0
5	103,937	101,113	100,196	3,012	3,924	3,597	3,613	0
6	105,635	103,386	102,453	3,012	4,643	4,316	4,336	0
7	106,780	104,634	103,694	3,012	5,232	5,035	5,058	0
8	108,163	106,379	105,414	3,012	5,951	5,755	5,781	0
9	110,694	109,689	107,892	3,012	6,758	6,561	6,591	0
10	112,641	109,999	109,537	4,742	7,194	7,085	7,117	0
11	114,945	112,480	112,007	4,742	7,673	7,673	7,708	0
-	-	-	-	-	-	-	-	-
34	147,745	145,866	144,042	6,567	20,056	19,838	19,929	2,800
35	148,253	146,630	144,800	6,567	20,165	20,099	20,191	2,800
36	148,697	147,160	145,323	6,567	20,557	20,557	20,651	2,800
37	148,998	147,698	145,876	6,567	20,928	20,710	20,805	2,800
38	149,215	147,924	146,099	6,567	21,800	21,364	21,462	2,800
39	149,500	147,961	146,135	6,567	-	21,582	21,681	2,800
40	149,680	148,528	146,695	6,567	-	21,800	21,900	2,800
41	150,033	150,033	148,195	6,567	-	-	-	-

4.2.Application

The data provided are enough to apply the model and show its distinctive feature on integration of the CC management with the EVM concepts (emphasized in Table 1).

As an example to show the risk-based EAC(€) computation the paper demonstrates its calculation for the early stage of Project 1. The proposed model's three alternate forms (Table 2) are used to show the forecast under constant, decreasing, and increasing CC spending rates to respectively explore the neutral, proactive and reactive CC management strategies in responding to risk. Hence, the model allows project managers to show the influence of various managerial behaviors in the CC consumption which in turn is reflected in $EAC(€)_{risk}$.

What needs to be computed first is the value of the $\Omega(x)$ factor which accounts for the remaining portion of the BAC. This is found by the nonlinear regression with an estimation of the three parameters of the GGM (Eq.(3)) using the EVM data of the case. To estimate the three parameters of the GGM the study applies the nonlinear regression modeling with its procedure provided in Appendix A.

The GGM parameter estimation results in α=0.977, β=0.358 and γ=5.160. Using them in GGM(CF(x)) and GGM(x) for the early stage estimation (the month of 10 taken as an example) gives the values of 0.973 and 0.651, respectively. Then AC is the sum of to date project cost (€109,537 thousands) and the CC (€4,742 thousands) spent by AT and is equal to €114,279 thousands.

The model's three forms introduced in Table 2 produce the cost forecasts of €167,499, €164,221, and €171,181 thousands, respectively. As mentioned above in this section, the total cost for the project incurred is €154,762 thousands. To determine which form represents the estimate more accurately the research will use the Percentage Error (PE) which is the difference between $EAC(€)_{risk}$ and CAC including total CC spent as CAC+CC and expressed

as a percentage of CAC+CC. Its negative value means underestimation while positive suggests overestimation in the forecast. The PE is defined with Eq.(6).

$$PE\% = \frac{CEAC_{risk} - (CAC+CC)}{(CAC+CC)} 100\% \quad (6)$$

The PE is 8.23% (by Form 1), 6.11% (by Form 2) and 10.61% (by Form 3) for Project 1 in the early stage estimation. The model with Form 1 assumes that the rate of the CC spending is constant and proportionally consumed as BAC (Fig. 1). Form 2 implies CCR is decreasing with an assumption that the CC budget is spent more intensively at the beginning of the project life and gradually decreasing towards the end. And Form 3 intends to capture the CC management strategy in responding to risk when Project managers use the contingency less intense at the project outset and increasing its CCR over time with the highest rate by the end.

5. Results and discussion

The section discusses the results and findings of the forecast results of the GGM nonlinear regression (Table 4), the pattern of the real CC spent (Fig. 2), the cost forecast results of the proposed model (Table 5) with lessons learnt and implications.

5.1.GGM results

Table 4 presents the results of the GGM nonlinear regression (Eq.3). As per Project 1 at the early stage estimation, the parameters α is 0.977 (normalized to unity) which implies the project final cost as it approaches infinity (Bates & Watts, 1988). Its value is less than one (ideally representing the BAC of 1.00) which indicates cost savings on the project budget. For Project 2 this value is 1.136 implying a cost overrun. The same conclusion can be made for middle and late stages forecasts that reveal the real cost outcomes of both projects: Project 1 was delivered under budget while Project 2 overrun its budget. The β with its value of

0.358 presents the S-curve's location along x-axis. The last parameter γ=5.160 governs the cost growth rate accountable for the shape of the cost curve. Its higher value implies the higher rate of cost growth that is a sharper cost increase. It is noted that according to the properties of the GGM the highest cost growth rate is when $x=\beta/\gamma$ and GGM$(x)=\alpha/e$ and in this case it is 1.855.

Table 4.

The Gompertz growth model parameter values and properties.

The GGM outputs	Project 1			Project 2		
	Early	Middle	Late	Early	Middle	Late
α	0.977	0.983	0.964	1.136	1.089	1.097
β	0.358	0.973	1.351	0.942	1.392	0.963
γ	5.160	4.719	5.048	2.798	3.034	3.101
$x=\beta/\gamma$	0.069	0.206	0.268	0.337	0.459	0.311
GGM(x)=α/e	0.359	0.362	0.355	0.418	0.401	0.404
MaxRate=$\alpha\gamma/e$	1.855	1.707	1.790	1.169	1.216	1.252
GGM(x)	0.651	0.815	0.915	0.333	0.573	0.944
GGM(CF(x))	0.973	0.957	0.947	0.982	0.909	0.981

5.2.CC spending in case projects

Fig. 2 presents the real contingency expenditure for the two cases shown in bold lines. The dashed curve lines are for demonstration purposes only to depict a similarity with the curves in Fig. 1. The consumption patterns reasonably present the two forms of the CC consumption proposed by the methodology: proactive and reactive. Project 1 has the most of the consumption in the first half of the project life which diminishes and fully consumes by the second half. Hence this resembles the proactive CC management strategy when a PM aggressively spends the most of the contingency budget for risk preventive actions, mostly during the first stages of a project. In this project the CC was spent in six months: 3, 5, 10, 15, 18 and 24. The CC spending pattern of Project 2 depicts the reactive contingency management strategy according to which most of the budget is spent in the second half of the project to correct the negative effects of occurred risky events. With such a strategy, a risk

averse project manager decides to react to risks occurred rather than preventing them by thinking more optimistically that risks would not happen. This project spent the contingency budget in months 13, 20, 24, 28, 29 and 30.

Overall under the reactive CC management strategy a project manager intends to use the contingency less intensely at the project outset and increasing its CCR over time with the highest rates by the end. Hence a project manager reactively responds to emerging risks rather than acts more proactively and takes preventive measures as under the proactive strategy. The proposed methodology is able to model such nonlinear patterns of the contingency spending by the Ω^2 factor (for decreasing consumption to reflect the proactive strategy) and the $\sqrt{\Omega}$ to accommodate the increasing rate of the CC (to represent the reactive strategy). It is noted that the spending patterns are not smooth and uneven over time, i.e. nonlinear, and this influences the EAC(€) forecasts. Such characteristics of the contingency utilization are resolved by the GGM's ability to govern the nonlinear behavior of the CC spending pattern. In the model this is managed by the part of the formula which is GGM(CF(x))-GGM(x) presented with the Ω factor in Eq.(5).

Insert Fig. 2.

Actual CC spending in the case projects (thousands of euro).

5.3.EAC(€) results

Table 5 presents the forecast errors of the proposed model. In Project 1 the model depicting the proactive approach in responding to risk shows more accurate estimates than the models with the neutral and reactive forms in all the estimation stages. The CC consumption pattern in this form is represented by the Ω^2 factor. It suggests that the CCR is higher at the project's first half compared to the rates of the neutral and reactive approaches. This CCR accelerates as per its 2nd derivative and diminishes as the project approaches its

completion. The estimates using the reactive approach with the increasing CCR shows the least accurate EAC(€)s.

The results for Project 2 show opposite findings. In all the three forecast stages, namely early, middle, and late stage forecasts, the model with reactive approach to manage risks, represented by the $\sqrt{\Omega}$ factor produces the most accurate EAC(€)s. Interesting to note that the form with the proactive approach shows the least accurate estimates. Note that PEs with positive signs mean overestimation while with negative signs suggests underestimation in the cost forecasts.

Table 5.

The forecast accuracy results by the model's three forms (PE, %).

Forecast stages	Project 1			Project 2		
	Neutral	Proactive	Reactive	Neutral	Proactive	Reactive
Early	8.23	6.11	10.61	-8.12	-10.13	-6.74
Middle	5.81	4.63	8.09	-6.98	-8.95	-4.83
Late	1.21	0.91	2.63	-3.28	-3.60	-1.90

5.4.Lessons learnt and implications

This study shows that the accuracy of the EAC(€)s could depend on a project's CC consumption behavior which may be modeled using the nonlinear method proposed. Based on the two real case complex projects the lessons learnt and implications can be summarized as next.

The results of this study revealed that EAC(€) can be more accurately computed using Model Form 2 (in Table 2) when the project risk is proactively prevented at the project outset as demonstrated by the actual CC consumption of Project 1. Also in such project types project managers would assume that the greatest part of risk is shouldered at the beginning of the project. Accordingly project managers would tend to spend most of the CC budget during the project's early phases and the CC expenditure will be decreasing as far as few activities

remain. Also this work shows that in such projects the cost accrual rate and the CC peak spending are also the greatest at the early stage which is found by the nonlinear fit of the GGM.

On the contrary, Model Form 3 provides more accurate EAC(€)s for cases when the project risk is accepted and reactively corrected late into the project as demonstrated by the actual CC consumption of Project 2. In such projects most of the work may be planned by the end of the project and project managers may expect that most of the risk burden will fall at this stage. The work done rushes after the projects' mid time and the CCR increases and reaches its top value as the project closes to completion.

As a final important note when compared to the other two forms Form 1 generates the least accurate risk adjusted cost forecasts. The hypothesis for this form is that the CCR is constant and proportional to the BAC expenditure governed by the GGM. This consideration reaffirms the finding that the CC consumption profile is not solely dependent on the S-curve pattern of a project base budget but on the risk management strategies used by project managers.

The study offers both theoretical and practical implications.

For scholars, the study closes the gap between the CC management and EVM-based cost forecasting. The two theories are traditionally considered as two separate components and have seldom been addressed together. Also, little study is available to mathematically represents both theories into a combined model to help forecast CC-adjusted EAC(€). This work develops them together into a unique cost forecasting framework model.

For practitioners, the model is a useful tool that can apply either Form 2 or Form 3 to derive accurate risk adjusted EAC(€)s for better and more informed project control decisions. The model is able to reflect project managers' behaviors in responding to risk and the choice of a particular form depends on project scheduled work and their risk attitude. In other terms

project managers and teams managing large projects for governments and main contractors can use the model to test ex-ante the effects of different risk policies, namely, to figure out possible EAC(€)s resulting from application of either a risk preventive, risk neutral, or risk reactive attitude.

6. Conclusion

Project managers widely use EVM-based cost forecasting models for the task of estimating final cost of on-going projects. These methods look backwards to past progress data. In parallel, project managers utilize CC reserve accounts to respond to risks that may occur and affect the project outcome. This is part of an effective risk management practice and hence forward looking. However, the EVM and CC management theories have been rarely integrated towards proposing cost forecasting models which mathematically consider the impact of risk on the cost forecasts.

This paper offers a novel EVM-integrated cost forecasting method able to capture the consumption of the CC reserve account into the final cost forecasts. The tool is risk-adjusted as it reflects the influence of managerial behavior in responding to risks which is modeled using three alternate formulae. The three formulae are designed to reflect the proactive, neutral, or reactive risk response strategy, respectively. The methodology considers the CC spending in a way that future risk (forward looking) is accounted with past performance (backward looking) embedded into cost forecasts calculations. The application of the model to two major complex case projects in the aerospace sector is an opportunity to present the construct and explore the validity of the proposed formulae under the conditions of a proactive and a reactive risk management policy. The developed method is a contribution to the research community as it elaborates an integrated approach to the EVM and CC management theories and for practitioners as a practical application to complex risky projects delivered by large project-oriented organizations.

Future research is suggested towards extending the applicability of the proposed methodology for duration forecasting and in program management. First, the methodology can further be developed for duration forecasting with time contingency adjusted to project schedule. This area should take the advantages of the earned schedule concepts with extending its current potential into the proposed methodology. Second, with the purpose of understanding the model behavior in multiple projects environment, a possible avenue for future research can be its development into the context of program management with consolidation of EVM and CC reporting from multiple projects within a risky program.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. The EAC(€)$_{orig}$ modeling steps and forecasting

The EAC(€)$_{orig}$ modeling process by Narbaev & De Marco (2014b)

Table A-1 presents the EAC(€)$_{orig}$ modeling process to calculate the final expected cost in three steps. The EAC(€)$_{orig}$ model without consideration of the schedule progress (without the CF integration) is given in Eq.(4).

Table A-1.

The EAC(€)$_{orig}$ modeling steps.

Steps	Action
1. Develop the Growth Model Equation (Eq.3)	• Normalize all values of time points to unity (*i.e.*, PD=1.00). Each next time point (starting from 0 date to PD=1.00) is a cumulated portion of this unity. These values represent a predictor variable (x). • Normalize the values of ACs (from beginning onto AT) to unity (*i.e.*, BAC=1.00). • Normalize the values of PVs from AT onto PD to unity (i.e., BAC=1.00). • Combine the normalized values of ACs and PVs. Each time increment represents a cumulated portion of this unity. These values represent a response variable (y). • Load the normalized predictor and response values into the nonlinear regression platform and select a GGM function (Eq.3). Perform the parameter estimation. • Find the values of the three parameters (α, β, γ) of the GGM.

Output	The values of the GGM's three parameters
2. Calculate EAC(€) (Eq.4)	• Insert the values of the three parameters into the GGM (Eq.3) for cases when x=AT and x=1.00. • Find the values of GGM for cases when x=AT and x=1.00. • Compute EAC(€) by including the above two values of the GGM into Eq.(4).
Output	The EAC(€) value.
3. Integrate ES into EAC(€) equation (Eq.4)	• Refine the EAC(€) model (Eq.4) by replacing x=PD=1.00 with the value of CF. • This refined EAC(€) model considers the impact of the schedule progress.
Output	The refined EAC(€) value considering the schedule progress.

The EAC(€)$_{orig}$ model demonstration

As part of Step 1 of the EAC(€)$_{orig}$ modeling process, Table A-2 presents the results of the normalization of time and cost points of simple hypothetical EVM data. Both time and cost points are normalized to unity assuming PD=15 is 1.00 (for the time points) and BAC=3,725,000 euro is 1.00 (for PVs and ACs), respectively. 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 EAC(€) for Project 1, month 4 is when 20.90% of the BAC is earned (the last column). Then, the predictor and response values in the table are loaded to the nonlinear regression platform with the pre-defined GGM equation (Eq.3). The Minitab® is used for this task.

Before running the nonlinear regression, there are some requirements one needs to take into account. First, it is necessary to define starting values for a parameter under estimation (Bates & Watts, 1988). Since the predictor and response variables are normalized to unity, starting values for the three parameters are 1.00 as well. The Gauss-Newton algorithm is used with the confidence level of 95% which will converge with the minimum sum of squared errors. Then, the regression modeling produced the estimates of its three parameters: the α-asymptote, the y-intercept β and γ-scale, which are 1.202, 1.212 and 2.772, respectively.

In Step 2, for the month 4 when x=0.267 the GGM(0.267)=0.241 and when x=1.00 the GGM(1.00)=0.974. The remaining of portion of the BAC is adjusted by the difference of

these two values of the GGM. The model (Eq.4) calculates a EAC(€) with PE=-6.96, which means that it is underestimating its actual cost at completion. PE is a measure of forecast accuracy which is the difference between EAC(€) and CAC expressed as a percentage of CAC with a negative value suggesting underestimation and a positive value – overestimation.

Table A-2.

The Step1 normalization results of the EAC(€)$_{orig}$ model.

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 actual completion is 16.25 months.
[b]AC - from time point 0 to 4; PV - from 5 to 15; BAC=3,725,000€.

In Step 3 the schedule progress is taken into account with the assumption that it is a determinant factor for EAC(€)s. For this, CF which is equal to 1.083 at AT=4 replaces x=1.00 in Eq.(4) to appear as in Eq.(2). The refined EAC(€)$_{orig}$ estimate which now considers the schedule impact is closer to the CAC value with PE=-2.91.

References

Anbari, F. T. (2003). Earned value project management method and extensions. *Project Management Journal*, *34*(4), 12–23. https://doi.org/10.1109/EMR.2004.25113

Babar, S., Thaheem, M. J., & Ayub, B. (2017). Estimated Cost at Completion: Integrating Risk into Earned Value Management. *Journal of Construction Engineering and Management*, *143*(3), 04016104. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001245

Barraza, G. A., & Bueno, R. A. (2007). Cost Contingency Management. *Journal of Management in Engineering*, *23*(3), 140–146. https://doi.org/doi:10.1061/(ASCE)0742-597X(2007)23:3(140)

Bates, D. M., & Watts, D. G. (1988). *Nonlinear Regression Analysis and Its Applications*. *New York: Wiley* (Vol. 85). https://doi.org/10.1002/9780470316757

Bryde, D., Unterhitzenberger, C., & Joby, R. (2017). Conditions of success for earned value analysis in projects. *International Journal of Project Management*. https://doi.org/10.1016/j.ijproman.2017.12.002

Cleland, D. I., & Ireland, L. (2007). *Project management: Strategic design and implementation* (5th ed.). New York: McGraw-Hill. Retrieved from https://www.mendeley.com/research-papers/project-management-strategic-design-implementation-16/?utm_source=desktop&utm_medium=1.17.13&utm_campaign=open_catalog&userDocumentId=%7Bbb9cbceb-b944-49df-9923-b0aa483a4470%7D

Colin, J., & Vanhoucke, M. (2015). A comparison of the performance of various project control methods using earned value management systems. *Expert Systems with Applications*, *42*(6), 3159–3175. https://doi.org/10.1016/j.eswa.2014.12.007

De Marco, A., Rafele, C., & Thaheem, M. J. (2016). Dynamic Management of Risk Contingency in Complex Design-Build Projects. *Journal of Construction Engineering and Management*, *142*(2), 04015080. https://doi.org/10.1061/(ASCE)CO.1943-

7862.0001052

De Marco, A., Rosso, M., & Narbaev, T. (2016). Nonlinear cost estimates at completion adjusted with risk contingency. *Journal of Modern Project Management*, *4*(2). https://doi.org/10.19255/JMPM01102

Ford, D. N. (2002). Achieving Multiple Project Objectives through Contingency Management. *Journal of Construction Engineering and Management*, *128*(1), 30–39. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:1(30)

Hammad, M. W., Abbasi, A., & Ryan, M. J. (2016). Allocation and Management of Cost Contingency in Projects. *Journal of Management in Engineering*, *32*(6), 04016014. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000447

Hazır, Ö., Hazir, T., & Hazır, Ö. (2015). A review of analytical models, approaches and decision support tools in project monitoring and control. *International Journal of Project Management*, *33*(4), 808–815. https://doi.org/http://dx.doi.org/10.1016/j.ijproman.2014.09.005

Kerzner, H. (2013). *Project management: A systems approach to planning, scheduling, and controlling*. Hoboken, NJ: Wiley. https://doi.org/10.1016/0377-2217(82)90164-3

Kim, B. C., & Pinto, J. K. (2019). What CPI = 0.85 Really Means: A Probabilistic Extension of the Estimate at Completion. *Journal of Management in Engineering*, *35*(2). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000671

Lipke, W. H. (2003). Schedule is Different. *The Measurable News*, *2*, 31–34. Retrieved from http://www.pmi-cpm.org/members/library/Schedule Is Different.lipke.pdf

Naeni, L. M., & Salehipour, A. (2011). Evaluating fuzzy earned value indices and estimates by applying alpha cuts. *Expert Systems with Applications*. https://doi.org/10.1016/j.eswa.2010.12.165

Narbaev, T., & De Marco, A. (2014a). An Earned Schedule-based regression model to improve cost estimate at completion. *International Journal of Project Management*, *32*(6). https://doi.org/10.1016/j.ijproman.2013.12.005

Narbaev, T., & De Marco, A. (2014b). Combination of growth model and earned schedule to forecast project cost at completion. *Journal of Construction Engineering and Management*, *140*(1). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000783

Osipova, E., & Eriksson, P. E. (2013). Balancing control and flexibility in joint risk management: Lessons learned from two construction projects. *International Journal of Project Management*, *31*(3), 391–399. https://doi.org/10.1016/j.ijproman.2012.09.007

Pich, M. T., Loch, C. H., & Meyer, A. De. (2002). On Uncertainty, Ambiguity, and Complexity in Project Management. *Management Science*, *48*(8), 1008–1023. https://doi.org/10.1287/mnsc.48.8.1008.163

PMI. (2009). *Practice Standard for Project Risk Management*. Newtown Square, PA: Project Management Institute.

PMI. (2011). *Practice Standard for Earned Value Management* (2nd ed.). Newtown Square, PA: Newtown Square, PA. https://doi.org/1-930699-42-5

Repenning, N. P., & Sterman, J. D. (2001). Nobody Ever Gets Credit for Fixing Problems That Never Happened: Creating and Sustaining Process Improvement. *California Management Review*, *43*(4), 64–88. https://doi.org/10.2307/41166101

Seber, G. a. F., & Wild, C. J. (1989). *Nonlinear regression (Wiley Series in Probability and Statistics)*. Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/0471725315

Thamhain, H. (2013). Managing risks in complex projects. *Project Management Journal*, *44*(2), 20–35. https://doi.org/10.1002/pmj.21325

Uzzafer, M. (2013). A contingency estimation model for software projects. *International Journal of Project Management*, *31*(7), 981–993. https://doi.org/10.1016/j.ijproman.2012.12.002

Warburton, R. D. H., & Cioffi, D. F. (2016). Estimating a project's earned and final duration. *International Journal of Project Management*, *34*(8), 1493–1504. https://doi.org/10.1016/j.ijproman.2016.08.007

Willems, L. L., & Vanhoucke, M. (2015). Classification of articles and journals on project control and earned value management. *International Journal of Project Management*, *33*(7), 1610–1634. https://doi.org/10.1016/j.ijproman.2015.06.003

Xie, H., AbouRizk, S., & Zou, J. (2012). Quantitative Method for Updating Cost Contingency throughout Project Execution. *Journal of Construction Engineering and Management*, *138*(6), 759–766. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000457

*Highlights (for review)

Highlights

- A new Cost Estimate at Completion (EAC(€)) model is developed considering cost risk
- A Cost Contingency (CC) variable is mathematically presented in the EAC(€) equation
- Three CC spending patterns in the model depend on three risk management strategies
- An application to two aerospace projects proves the model's construct and validity

Fig.1.

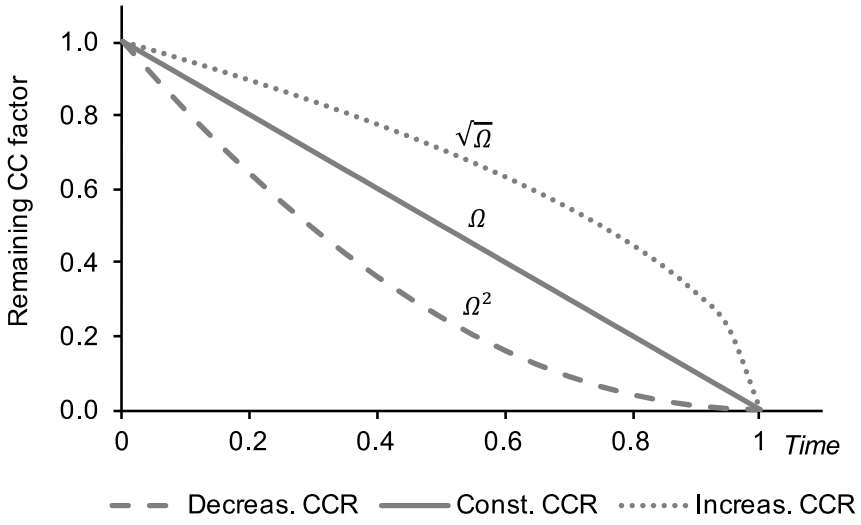

Fig. 1. The three CC spending profiles by the EAC(€)$_{risk}$ model.

Fig.2.

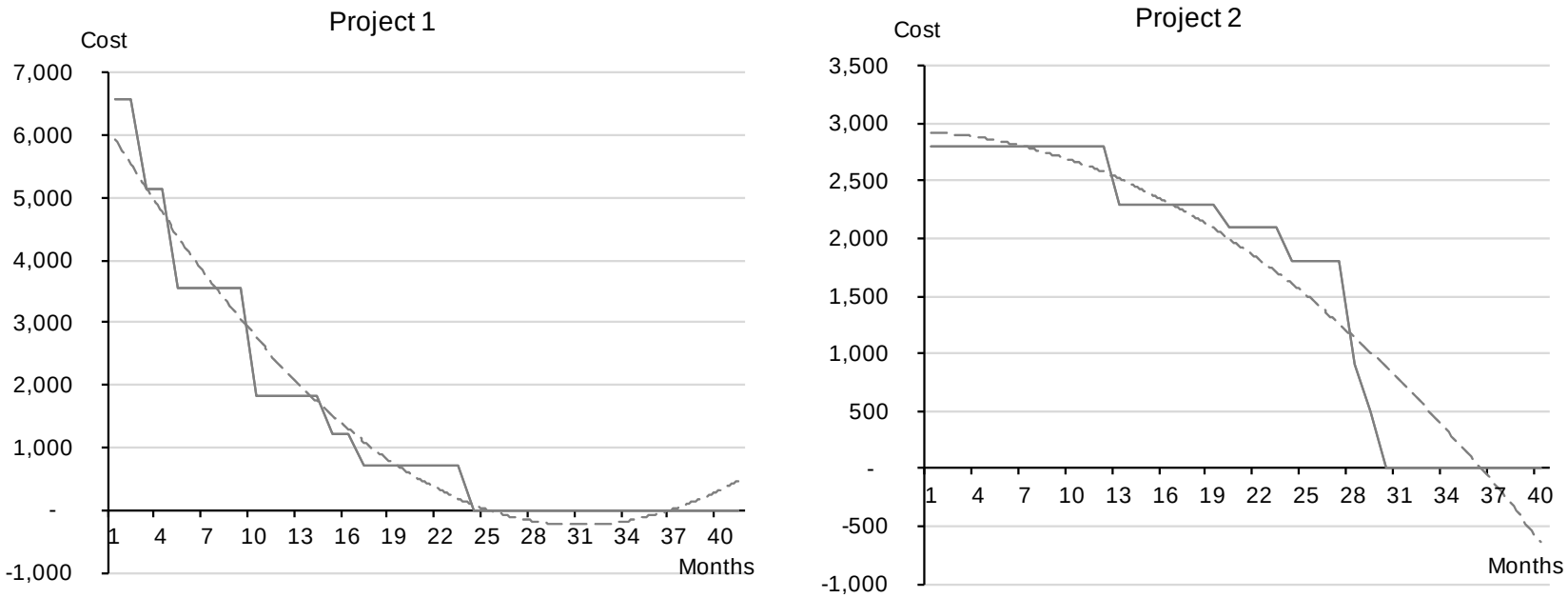

Fig. 2. Actual CC spending in the case projects (thousands of euro).

Captions

Click here to download Supplementary Material: Captions.docx

Title page

Click here to download Supplementary Material: Titile page.docx

Credit authorship contribution statement

Timur Narbaev: Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Visualization, Project administration. **Alberto De Marco:** Conceptualization, Methodology, Validation, Investigation, Data Curation, Writing - Review & Editing, Supervision. **Mario Vanhoucke:** Conceptualization, Methodology, Validation, Data Curation, Writing - Review & Editing, Supervision.

***Conflict of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: