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Integrated cost, quality, risk and schedule control through earned value management (EVM)

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Abstract

Purpose – The purpose of this paper is to propose an integrated earned value management (EVM) approach to control quality, cost, schedule and risk of projects.

Design/methodology/approach – This study represents a new EVM framework by considering a quality control index. Particularly, some control indices and cumulative buffers are defined by two proposed, methods, namely the linear- and Taguchi-based methods. These methods are implemented in three different projects in different industries.

Findings – According to the results, integration of the quality index creates a better control situation by providing more accurate information. Hence, project managers could comprehensively monitor the status of important factors to make more precise decisions while maintaining the simplicity of their analysis.

Originality/value – From the methodological and theoretical features, this paper offers new visions because, to the best of authors' knowledge, no comparable study has been conducted before.

Keywords Project management, Quality management, Risk management, Taguchi loss function, Earned value management

Paper type Research paper

1. Introduction

Today's competitive markets have forced project managers to consider many factors in managing the projects. With the advent of project management tools and techniques, concurrent consideration of cost, quality, schedule and risk can be considered as an advantage to finish the projects on time. Earned value management (EVM) is a managerial tool to control the projects with regard to different issues such as cost, schedule, etc. Although the EVM concept has been discussed by many authors, only a very few attempts have been made to propose EVM structures for concurrent investigation of cost, quality, schedule and risk. Therefore, proposing an approach to apply EVM to proficiently and effectually monitor and control the cost, quality, schedule and risk of projects is a challenge for many practitioners and researchers. While EVM variables are very important in real projects, they are less examined in previous studies. This is somewhat due to the intrinsic difficulties linked to these variables. Furthermore, many EVM variables are conventionally assessed at the end of a project or after the occurrence, considering all data as deterministic values.

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Therefore, proposing an EVM structure for quality, cost, schedule and risk control is the main objective of this study. In other words, this study aims to answer the following questions:

Q1. How linear- and Taguchi-based methods are applied to control quality, cost, schedule and risk?

Q2. How the proposed approach can be verified in real-world projects?

The scope of this research is limited to control quality, cost, schedule and risk. Though, the study context, methodology of research and outcomes can be valuable to practitioners and researchers who are interested in controlling quality, cost, schedule and risk in other projects. The research contribution is to provide a new awareness for integration of linear- and Taguchi-based methods to control quality, cost, schedule and risk. From the methodological and theoretical features, this research offers new visions because, to the best of authors' knowledge, no comparable study has been conducted before.

2. Literature review

This section discusses the related literature of this research. The section starts with some general definitions of project management and EVM and ends in the related studies of this research.

2.1 EVM

Different types of projects can be found in project management literature (Binder, 2016). The Project Management Book of Knowledge (®Guide, 2000) describes EVM as an approach that incorporates schedule, resources and scope to assess and measure the project performance. It associates the quantity of planned work with the spent quantity and what has been completed to control the schedule and cost performance. The EVM approach supplies ideals for performance and variances indices that could be applied to measure current project performance and status. Additionally, it forecasts the future according to the previous performance of the project and new information. This approach mixes cost, time management and scope in a single tool. EVM requires a periodic checking of the project.

Predicting a continuing project's actual cost and duration is a vital feature of project management. One of the common and best methods to predict projects is EVM. The reliability and utility of EVM as an approach to assess a project's existing cost performance and predicting its actual cost has been recognized from the initiation of the method in the 1960s. The EVM performance for the time dimension, though, merely acquired the essential improvement from the initiation of the spreading concept of earned schedule (ES) ((Batselier and Vanhoucke, 2017). According to the literature, ES is an advanced approach to extend the EVM concept.

2.2 Related studies

Vandevoorde and Vanhoucke (2006) compared different project duration forecasting methods using EVM. The purpose of this study is three-fold. First, this study compares the typical earned value performance indicators schedule variance (SV) and schedule performance index (SPI) with the newly developed ES performance indicators SV(t) and SPI(t). It is critical to consider the budget cost of work performed (BCWP) and budget cost of work scheduled (BCWS) in defining SV and SPI. Next, this study presents a generic schedule forecasting formula appropriate in diverse project conditions and associates the three approaches from literature to predict total project duration. Lastly, this research exemplifies the application of each approach on a simple project and real-life project data.

Henderson (2007) proposed a breakthrough development to EVM called ES. This examination is an advanced analytical approach that grows the measures of schedule performance in units of time, instead of cost. The similar simple EVM data are applied. Indicators, comparable to those of cost, are obtainable from the ES metrics. These indicators supply a predictive and status ability for schedule, analogous to cost. As these metrics apply time-based metrics, they enhance integrated schedule analysis and traditional EVM. Czarnigowska *et al.* (2011) focused on project performance prediction and reporting. This research has been done based on an EVM extension. The study summaries the fundamental philosophies of the technique and outlines its latest variations intended to improve reliability in describing the status of the project, growing the ability to predict projects and permitting for risk control. Batselier and Vanhoucke (2015) provided an evaluation of deterministic state-of-the-art predicting methods for project duration based on EVM. This study assesses the timeliness and accuracy of three promising deterministic approaches and their joint mixtures on a real-life project database. The outcomes specify that all three methods are relevant. In addition, two EVM extensions display accuracy-enhancing power for diverse applications, whereas earned duration management or EDM (t) accomplishes very comparable to the best EVM approaches and shows probability to progress them. According to this study, Khamooshi and Golafshani (2014) introduced EDM as schedule performance which is obtained from metrics expressed in time units instead of cost units.

Batselier and Vanhoucke (2017) improved the accuracy of the project forecast by mixing EVM with reference class forecasting and exponential smoothing. In this study, the EVM project control methodology is combined with the exponential smoothing forecasting method. These outputs are an extension of the recognized EVM, ES cost and time predicting formulas. A strong correspondence among the established methods and the newly presented approach – called the XSM – is recognized, which could ease future execution. More precisely, only one smoothing parameter is required to compute the enhanced performance factor of EVM. Furthermore, this parameter could be vigorously adjusted throughout the project progress according to the information of previous performance and/or estimated management actions. Furthermore, the reference class forecasting (RCF) method could be combined into the XSM. RCF predicts the future using the comparable previous circumstances and their results. According to this study, results from 23 real-life projects display that, for both cost and time forecasting, the XSM displays a significant overall performance enhancement with regard to the most precise project predicting approaches recognized by preceding study, particularly once integrating the RCF concept. Table I shows some related studies of this area.

2.3 Identification of research gap

In summary, an operational and applicable EVM-based approach in concurrent controlling of quality, cost, schedule and risk has not been developed, particularly in real-world problems. In addition, only a very few attempts have been made to propose EVM structures for concurrent investigation of cost, quality, schedule and risk. Therefore, proposing an approach to apply EVM to proficiently and effectually monitor and control the cost, quality, schedule and risk of projects is a challenge for many practitioners and researchers. While EVM variables are very important in real projects, they are less examined in previous

Paper Year	ES	Estimate methods	Fuzzy	Quality	Risk
Lipke (2003)	✓				
Lipke *et al.* (2009)	✓				
Henderson (2003)	✓				
Henderson (2004)	✓				
Vandevoorde and Vanhoucke (2006)	✓	✓			
Elshaer (2013)	✓	✓			
Haji-Kazemi *et al.* (2013)		✓			
Narbaev and De Marco (2014)	✓	✓			
Lipke (2013)	✓				
Colin and Vanhoucke (2015)		✓			
Wauters and Vanhoucke (2016)[a]		✓			
Wauters and Vanhoucke (2017)[b]		✓			
Warburton and Cioffi (2016)		✓			
Batselier and Vanhoucke (2017)		✓			
Naeni *et al.* (2011)			✓		
Moslemi Naeni and Salehipour (2011)			✓		
Caron *et al.* (2013)		✓	✓		
Xu *et al.* (2010)			✓	✓	
Wang *et al.* (2011)				✓	
Gao and Ye (2011)				✓	
Vanhoucke (2012)[a]					✓
Pajares and Lopez-Paredes (2011)					✓
Vanhoucke (2012)[b]					✓
Colin and Vanhoucke (2014)					✓
Khodakarami and Abdi (2014)			✓		✓
Kim (2015)			✓		✓
Acebes *et al.* (2015)					✓
Babar *et al.* (2016)					✓
Kerkhove and Vanhoucke (2017)		✓			

Table I.
Literature summary

studies. Trying to fill the gap in the literature, this study is carried out to methodically control the quality, cost, schedule and risk using the EVM approach. Particularly, some control indices and cumulative buffers are defined by two proposed methods, namely, the linear- and Taguchi-based methods. These methods are implemented in three different projects in different industries, and the effects of the variables are assessed. This study seems to be the first application of linear- and Taguchi-based methods in the area of project management.

3. Research methodology

The main objective of this study is to control quality, cost, schedule and risk of projects using the EVM method. In other words, concurrent controlling of quality, cost, schedule and risk is the main output of this research. To do so, particularly, some control indices and cumulative buffers are proposed using two approaches, namely, linear- and Taguchi-based methods. These approaches are implemented in three different projects in different industries, and the effects of the variables are assessed. The following flowchart shows the summary of research steps. The research has been conducted in three linked phases as shown in Figure 1.

This research provides a new EVM framework by focusing on a quality control index. Quality should be considered and controlled in the same way as schedule and cost to

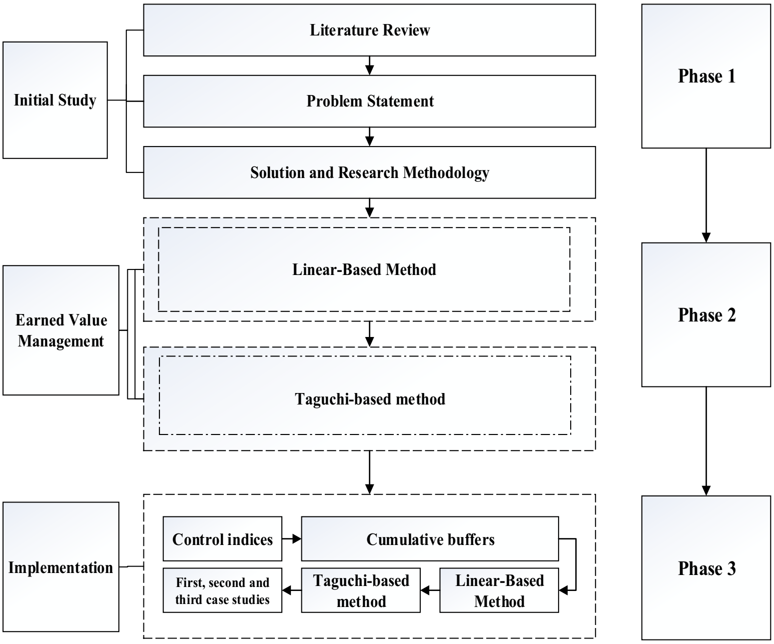

Figure 1. Different steps of the research

completely please the goals of projects. In addition to the following equations, there are some general definitions of EVM terms which are useful to be reminded for better understanding of this study. Previous sections have discussed some of these acronyms. However, we briefly tabulate them in Table II.

The quality control index is defined based on two proposed methods of linear approach and Taguchi loss function. However, the Taguchi method treats the cost of quality more aggressively. Three new control indices, namely, CCoI, SCoI and QCoI, have been defined to integrate EVM with quality and risk management. According to PM (2010), the following equations are applied in EVM:

$$\text{(PV) Planned Value} = \text{(BCWS) Budgeted Cost of Work Performed} \tag{1}$$

$$\text{(EV) Earned Value} = \text{(BCWP) Budgeted Cost of Work Performed} \tag{2}$$

$$\text{(AC) Actual Cost} = \text{(ACWP) Actual Cost of Work Performed} \tag{3}$$

$$\text{(SV) Schedule Variance} = \text{EV} - \text{PV} \tag{4}$$

$$\text{(CV) Cost Variance} = \text{EV} - \text{AC} \tag{5}$$

$$\text{(SPI) Schedule Performance Index} = \text{EV}/\text{PV} \tag{6}$$

Table II.
Glossary of EVM terms

No.	Term	Acronym	Definition
1	Cost variance	CV	CV is the difference among the actual incurred cost and the earned value
2	Schedule variance	SV	SV is equal to the difference between the planned value and earned value
3	Schedule performance index	SPI	SPI is equal to the earned value over the planned value
4	Cost performance index	CPI	CPI is calculated by dividing the earned value to the actual costs
5	Budget cost of work scheduled	BCWS	BCWS is the budget summation of all scheduled works to be completed in a predetermined time
6	Budget cost of work performed	BCWP	BCWP is the planned cost of the work value which is completed up to the present time
7	Actual cost of work performed	ACWP	ACWP is the recorded cost of completed works within a predetermined time
8	Earned schedule	ES	ES is an advanced approach to extend the EVM concept
9	Quality variance	QV	QV is the difference of the actual consumption of a factor and its planned consumption
10	Actual quality cost of work performed	AQCWP	AQCWP is the portion of ACWP which is related to quality issues
11	Earned duration management	EDM	EDM is a schedule performance which is obtained from metrics expressed in time units instead of cost units

$$\text{(CPI) Cost Performance Index} = \text{EV}/\text{AC} \tag{7}$$

This study has integrated new quality control indices with EVM. The following equations show the results of this integration:

$$\text{(QEV) Quality Earned Value} = \text{(BQCWP) Budgeted Quality Cost of Work Performed.} \tag{8}$$

$$\text{(QAC) Quality Actual Cost} = \text{(AQCWP) Actual Quality Cost of Work Performed.} \tag{9}$$

$$\text{(QV) Quality Variance} = \text{QEV} - \text{QAC} \tag{10}$$

$$\text{(QPI) Quality Performance Index} = \text{QEV}/\text{QAC} \tag{11}$$

$$\text{BQ} = \sum \text{Budget Quality Score of the Finished Projects} \times \text{Corresponding weights} \tag{12}$$

$$\text{AQ} = \sum \text{Actual Quality Score of the Finished Projects} \times \text{Corresponding weights} \tag{13}$$

$$\text{BQCWP} = \text{Amount of Work Performed} \times \text{Budgeted Cost per Basic Unit Performed Work} \tag{14}$$

$$\text{AQCWP} = \text{Amount of Work Performed} \times \text{Actual Cost per Basic Unit Performed Work} \tag{15}$$

To achieve the QAC based on QEV, two new methods are used. The first proposed technique revises previous methods and calculates QAC based on a linear relationship with QEV as follows:

$$\text{QAC} = \text{QEV} \times \text{Qi} \tag{16}$$

$$\text{Qi (Quality Control Index)} = (\text{BQ} + |\text{AQ} - \text{BQ}|)/\text{BQ} \tag{17}$$

In the second method, the Taguchi method and its definition of quality are used. According to Taguchi, quality is defined as the loss imparted to society. Thus, the loss amount determines the desirability level. In addition, less quality loss ends to more product desirability. Taguchi attributes this loss to any quality characteristic variability around its ideal point. This loss might include any dissatisfaction, trouble, financial and physical damage. Consequently, focusing on the quality characteristic around its ideal point ends to product quality improvement. According to Taguchi, the loss is proportional to the square deviation from the target (Taguchi *et al.*, 1989). The Taguchi loss function plays an important role in achieving quality actual cost (QAC) in the second method. $X = |AQ - BQ|$ is the deviation from the target. The Taguchi loss function is considered as the loss function of quality cost in projects:

$$L(x) = k(x^2) \rightarrow C(x) = k \times (AQ - BQ)^2 \tag{18}$$

$$\text{QAC} = \text{QEV} + C(x) \tag{19}$$

4. Results and discussion

As mentioned before, the major output of this study is the control indices of cost, schedule and quality. New metrics and indices are prepared to compare cost, schedule and quality variances with a maximum control deviation per time unit. Three buffers of cost buffer (CPB_f), schedule buffer (SPB_f) and quality buffer (QPB_f) are determined using statistical methods. QPB_f is the difference between the maximum quality amount at a confidence level of (per cent), and the mean quality value (per cent) is the probability that the project quality value will be less than the maximum quality amount. Similarly, CPB_f and SPB_f are defined as the confidence level of cclper cent and sclper cent. Project managers are responsible for the decisions of required cclper cent, sclper cent and qclper cent. Afterward, these buffers are divided into different time intervals. Variant weights (wc, ws, wq) are assigned to these time intervals. The weights are the difference between two adjacent points on risk baseline curves and are proportional to the risk decline per all-time intervals. All of the indices, except the quality indices, are taken from Pajares and Lopez-Paredes (2011). The weights are defined as follows:

$$\mathrm{wq_t} = \mathrm{QRB_{t-1}} - \mathrm{QRB_t} \tag{20}$$

$$\mathrm{ws_t} = \mathrm{SRB_{t-1}} - \mathrm{SRB_t} \tag{21}$$

$$\mathrm{wc_t} = \mathrm{CRB_{t-1}} - \mathrm{CRB_t} \tag{22}$$

QRB_t, SRB_t, and CRB_t are quality, schedule, and cost risk baseline at time t, respectively:

$$\sum_{t=1}^{T} wq_t = \sum_{t=1}^{T} QRB_{t-1} - \sum_{t=1}^{T} QRB_t = QRB_0 - QRB_T = \sigma^2_{pq} \tag{23}$$

$$\sum_{t=1}^{T} ws_t = \sum_{t=1}^{T} SRB_{t-1} - \sum_{t=1}^{T} SRB_t = SRB_0 - SRB_T = \sigma^2_{ps} \tag{24}$$

$$\sum_{t=1}^{T} wc_t = \sum_{t=1}^{T} CRB_{t-1} - \sum_{t=1}^{T} CRB_t = CRB_0 - CRB_T = \sigma^2_{pc} \tag{25}$$

Where σ^2_{pc}, σ^2_{ps} and σ^2_{pc} are total project quality, schedule and cost variances, respectively. It is assumed that the risk baselines at t = T are 0 (the project has been completed), while at t = 0, it equals to total project variability. Thus, maximum quality, schedule and cost buffers at $(t-1, t)$ time interval are determined according to the following equations:

$$\mathrm{QBf_t} = \mathrm{wq_t} * \mathrm{QPB_f} / \ \sigma^2_{\mathrm{pq}} \tag{26}$$

$$\mathrm{SBf_t} = \mathrm{ws_t} * \mathrm{SPB_f} / \ \sigma^2_{\mathrm{ps}} \tag{27}$$

$$\mathrm{CBf_t} = \mathrm{wc_t} * \mathrm{CPB_f} / \ \sigma^2_{\mathrm{pc}} \tag{28}$$

Additionally, the cumulative quality, schedule and cost buffers are as follows:

$$\mathrm{AQBf}_t = \mathrm{QBf_t} + \mathrm{AQBf}_{t-1} \tag{29}$$

$$\mathrm{ASBf}_t = \mathrm{SBf_t} + \mathrm{ASBf}_{t-1} \tag{30}$$

$$\mathrm{ACBf}_t = \mathrm{CBf_t} + \mathrm{ACBf}_{t-1} \tag{31}$$

The resulting cumulative values should be compared with the EV variances. The schedule control index (SCoI) is defined based on equation (32):

$$\mathrm{SCoI_t} = \mathrm{ASBf_t} + \mathrm{SV\,(t)} = \mathrm{ASBf_t} + \mathrm{ES} - \mathrm{AT} \tag{32}$$

SV (t) is the ES variance. It should be mentioned that, in delay cases, the variance of schedule is negative. Thus, in practice, the cumulative buffer is compared with the delay in the actual time (AT). When the cumulative delay (−SV(t)) is greater than the cumulative buffer, SCoI would be negative. It means that the schedule deviations are above the "normal" warning about structural and systemic changes in the project. Similarly, a cost control index (CCoI) could compare the cost buffers with cost variances. However, more factors are required. The cost variance should be compared with the cumulative cost buffer (ACBf) in the time of the ES (t = ES). Thus, the CCoI is defined according to equation (33):

$$\mathrm{CCoI}_t = \mathrm{ACBf}_{(t=\mathrm{ES})} + \mathrm{CV}_t = \mathrm{ACBf}_{(t=\mathrm{ES})} + \mathrm{EV} - \mathrm{AC} \tag{33}$$

For a second time, a negative CCoI warns of the possibility of going beyond the expected variability. A similar equation is proposed for quality. The quality control index is integrated with conventional EVM indices by two new linear- and Taguchi-based approaches. The quality control index is introduced as follows:

$$\mathrm{QCoI}_t = \mathrm{AQBf}_t + \mathrm{QV}_t = \mathrm{AQBf}_t + \mathrm{QEV} - \mathrm{QAC} \tag{34}$$

In addition, in this case, QCoI < 0 shows that poor quality is higher than the expected variability. Hence, some drastic measures should be considered to meet the quality requirements and to prevent serious problems in the project. When the project is performing better than the expected schedule, the QV, SV (t), or CV are positive. Therefore, no corrective actions are needed.

5. Implementation of proposed model

This section discusses the implementation of the proposed model. Three case studies are selected, and the proposed methods are applied to investigate them with regard to cost, quality, schedule and risk.

5.1 First case study

A simple project is used to show the applicability of the proposed methods. Figure 2 depicts the project's activities on network (AON) diagram. It is assumed that the duration of the activities follows the uniform probabilistic distribution. The total planned cost of the project is a 6,400 monetary units, the total planned duration is 12.8 weeks and the budgeted quality cost is 900 monetary units. The project is accomplished within 14.8 weeks with a quality control index of Qi = 1.12 and a total cost of 7,140 monetary units. The mean planned, actual duration, actual cost, minimum and maximum budgeted quality costs are shown in Table III.

The historical project data and the associated forecasts are entered into the Monte Carlo simulation software to get the probabilistic distribution and project variability during the planning phase. As a consequence, there exists an expected variability at any time of the project. The Monte Carlo simulation is run by Primavera risk analysis software, which only provides cost and schedule risk analysis. In addition, the quality Monte Carlo simulation is

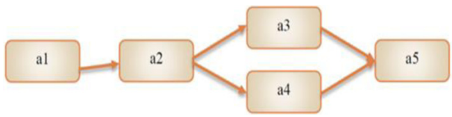

Figure 2.
Project AON diagram

executed by Microsoft Excel. The obtained histogram is drawn using Minitab17. The obtained results are depicted in Figure 3.

It is assumed that the costs (EV, actual costs and quality costs) are uniformly distributed. As shown in Figure 4, cost and schedule variances are always negative. In addition, the values of cost and schedule performance indices are less than 1. Hence, the project status is always over budget and behind schedule. However, there is no information whether they are within the accepted thresholds or not.

Calculation of the EVM quality control indices is conducted by the Taguchi quality loss function. This is defined as L(x) = 0.03 × (x)^2. The quality cost variance and quality performance indices are illustrated in Figure 5. As shown, QV is always negative, and QPI value is less than 1 in both methods. Therefore, the expected quality level is not met, and there is a loss cost caused by poor quality. Having known the maximum and mean amounts and using Monte Carlo simulation results, the project buffers are obtained as follows:

- Project cost buffer at ccl% = 90%: $CPB_f = 7067.43 - 6101.03 = 966.4$.
- Project schedule buffer at scl% = 90%: $SPB_f = 25 - 19 = 6$ week.
- Project quality buffer at qcl% = 90%: $QPB_f = 993.723 - 899.082 = 94.641$.

EVM new quality control indices by both methods applied to the first case study are shown in Figure 5. Cost, schedule, risk and the quality risk baseline diagrams are shown in Figure 6. As it is clear, all these three curves are decreasing. However, the slopes provide information on how the project risk is declining during the project horizon. As shown, the risk is decreasing from its maximum value at the beginning of the project to zero at the end. Subsequently, cumulative buffers and variances are calculated and applied in equations (29), (30) and (31) to obtain schedule, cost and quality control indices. The control indices are illustrated in Figures 8 and 9. As it is evident in Figure 8, SCoI and CCoI are positive in many cases. In other words, delays and overrun costs associated with Figure 4 are in the expected range. When the control indices are negative, the project goes ahead of the acceptable variability range. Thus, corrective or preventive actions should be taken to avoid more losses and deviations. If CV and SV are positive, the control indices are also positive.

Furthermore, adding new quality control indices, more information could be obtained about the project process. A negative value for QV and less than one value of QPI, demonstrates that the project quality requirements are not met. In addition, a negative value for the new quality control index is a sign that the project is out of the accepted normal range, while the positive value shows the acceptable range. The zero value of QV and 1 value of QPI demonstrate that the project is progressed according to the expected quality obligations.

The costs of poor quality are calculated by two proposed methods. As depicted in Figure 7, the Taguchi loss function presents the costs of poor quality more aggressively

Table III.
Activities duration, cost, and quality of case study 1

Max Cq	Mean Cq	Min Cq	Real cost	Planned cost	Real duration	Mean duration	Max D	Most likely D	Min D	Precedent relations	Activity
200	175	150	60	900	7	3	7	4	2	–	*a1*
300	275	250	19,900	1,800	7	4	8	5	3	a1	*a2*
135	127.5	120	1,840	1,600	8	2	8	3	1	a2	*a3*
210	190	170	1,590	1,400	8	4	8	6	2	a2	*a4*
155	132.5	110	850	700	3	2	3	2	1	a3, a4	*a5*
1,000	*900*	*800*	*7,140*	*6,400*	*14.8*	*12.8*			*Project*		

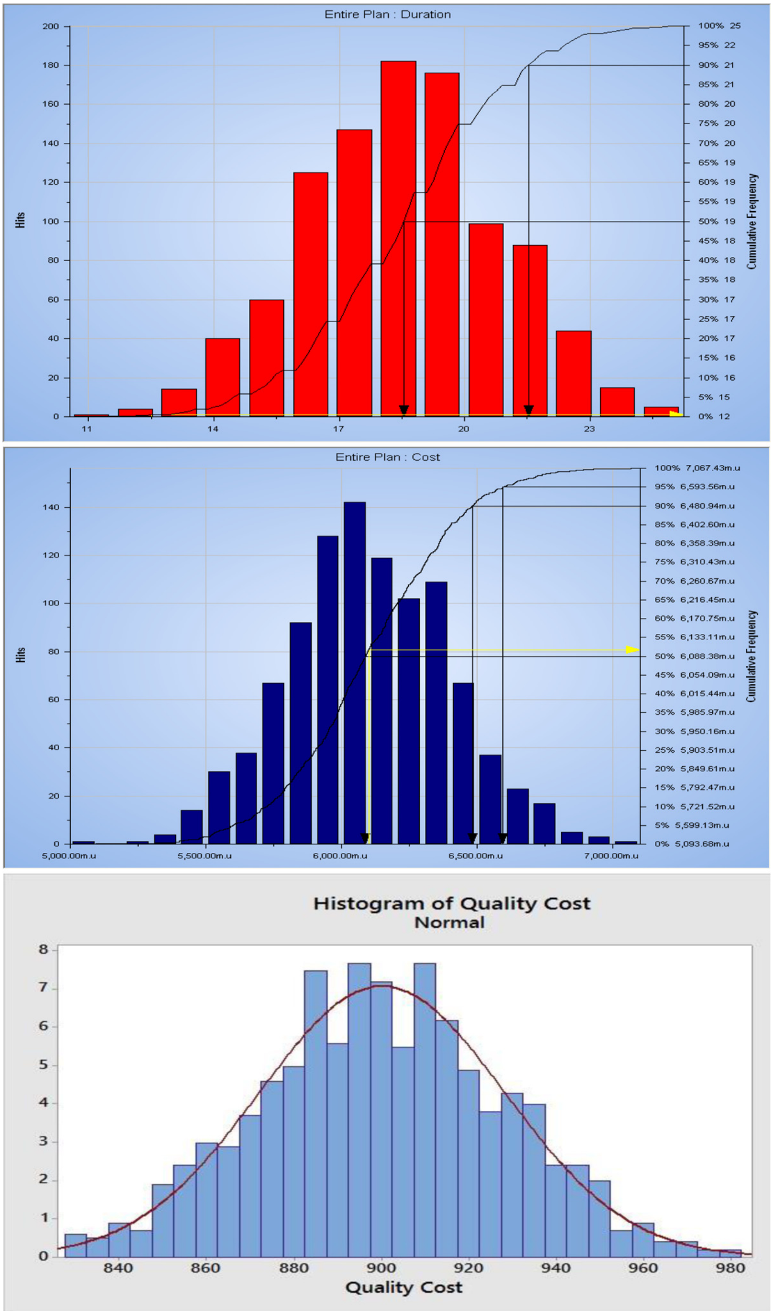

Figure 3.
Histogram outputs of Monte Carlo simulation software for the duration, cost and quality (first case study)

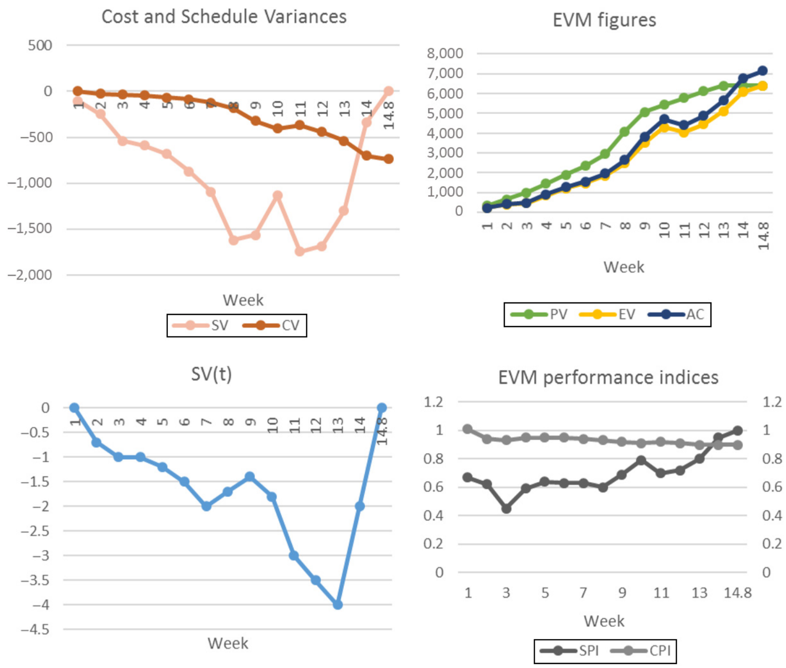

Figure 4.
EVM indices obtained from the first case study

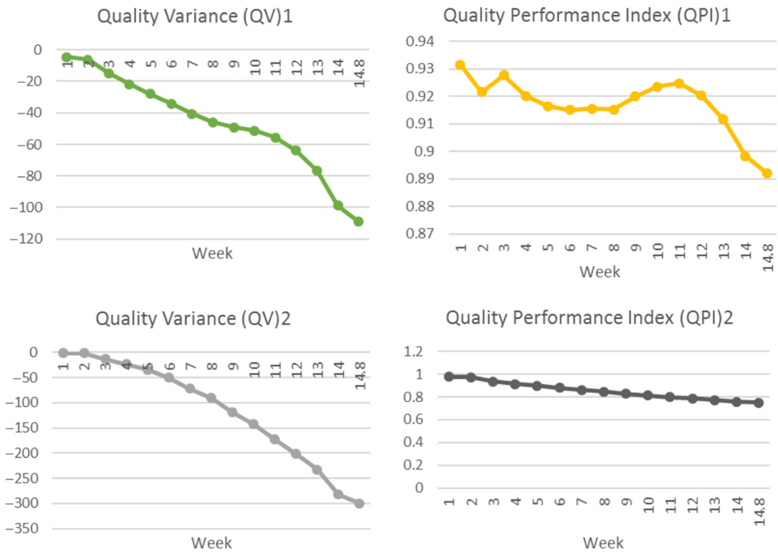

Figure 5.
EVM new quality control indices by methods 1 and 2 applied to the first case study

Figure 6.
Diagrams of cost, schedule and quality risk baseline from the first case study

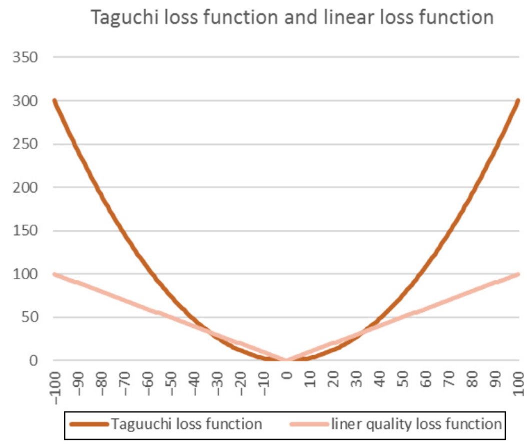

Figure 7.
Comparison of Taguchi loss function with a linear quality loss function (cost of poor quality)

than the linear loss function. In other words, the curve slope of the quality loss function in the Taguchi method is significantly higher than the linear loss function. Figure 8 shows the schedule and cost control indices obtained from the first case study. As illustrated in Figure 9, the probability of negative values for the quality control index (out of expected loss range) of the second method is greater than the first one.

5.1.1 Evaluation of variables influence on each other in the first case study. As the quality control index is incorporated into conventional EVM indices, the impact of the three indices of schedule, cost and quality on each other should be assessed. Commonly, Pearson's and Spearman's correlation factors are used for two schedule and cost variables. In addition, the partial correlation coefficient is used for three variables using the SPSS software. Table IV shows the output of SPSS 24 software for all variables of the first case study. The zero-order correlation is significant for the quality, cost and duration variables. In addition, all variables are strongly correlated two-by-two with a positive zero-order correlation coefficient. $r_{12} = 0.999$, $r_{13} = 0.980$ and $r_{23} = 0.982$ where variable 1 = quality, variable 2 = duration and variable 3 = cost.

On the other hand, partial correlation coefficients are not significant ($r_{12,\,3} = 0.322$, $r_{13,\,2} = 0.322$). This means that the effect of two variables on each other could not be evaluated by keeping the third variable constant. In other words, the third variable is effective. For instance, it is known that the project costs rise with the increment in project duration. This issue might be due to incurred costs from poor quality.

5.2 Second case study

Another project named Re-vamp check-in is selected from Vandevoorde and Vanhoucke (2006) to reassess the control indices in another industry. It is a real project for an airport luggage handling system at Fabricom Airport Systems in Brussels (Belgium) and concerns a revamping of different check-in islands. The project was performed with a four-month delay. It should be mentioned that the actual cost was less than the budgeted cost. Figure 10 represents the EVM indices. According to Figure 11, half of the project delay was more than the acceptable limit. However, with CPI > 1 and CV > 0, it was not distinguishable whether

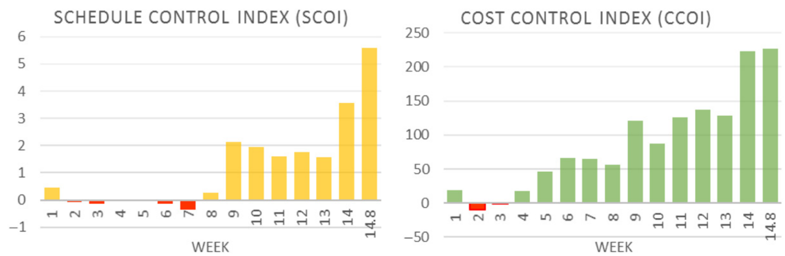

Figure 8.
Schedule and cost control indices obtained from the first case study

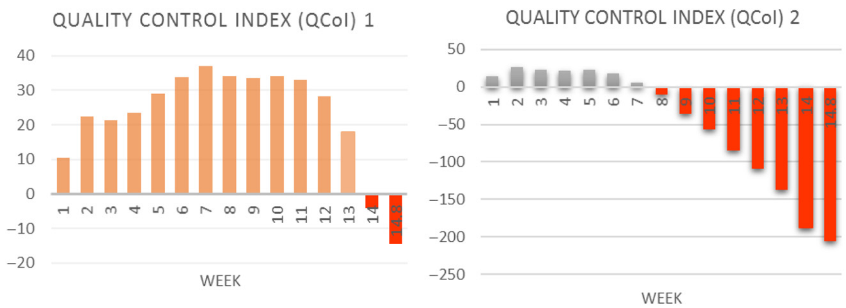

Figure 9.
New quality control index using both methods (out of expected loss range)

Control variables	*Duration*	*Cost*	*Quality*
-None-[a]			
Duration			
Correlation	*1*	*0.982*	*0.999*
Significance (two-tailed)		0	0
df	0	13	13
Cost			
Correlation	*0.982*	*1*	*0.98*
Significance (two-tailed)	0		0
df	13	0	13
Quality			
Correlation	*0.999*	*0.98*	*1*
Significance (two-tailed)	0	0	
df	13	13	0
Quality			
Duration			
Correlation	*1*	*0.322*	
Significance (two-tailed)		0.261	
df	0	12	
Cost			
Correlation	*0.322*	*1*	
Significance (two-tailed)	0.261		
df	12	0	

Note: [a] Cells contain zero-order (Pearson) correlations

Table IV. SPSS 24 Output for correlation coefficients in the first case study correlations

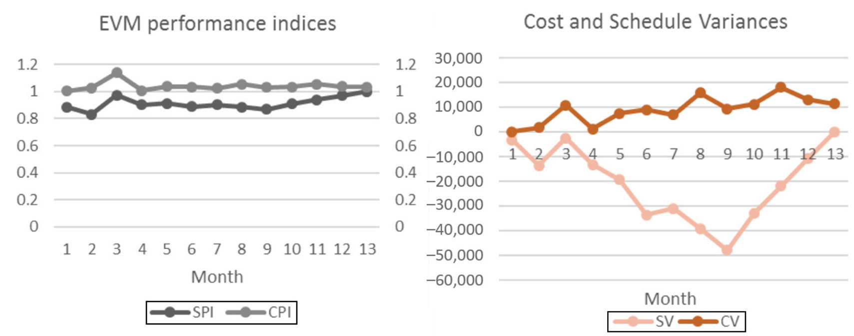

Figure 10. EVM indices obtained from the second case study

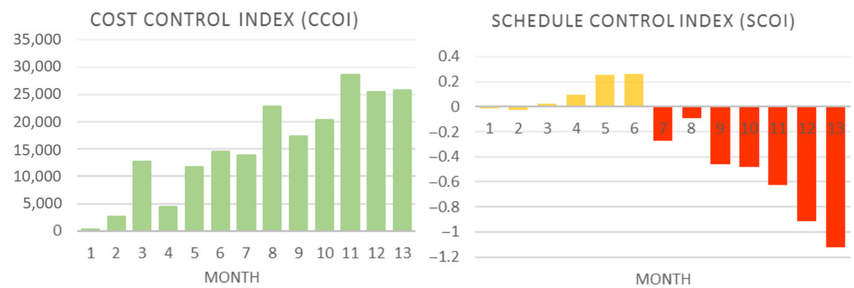

Figure 11. Cost and schedule indices for the second case study (half of the project delays were more than the acceptable limit)

the forecasts were wrong or the work quality was damaged. Quality control indices shown in Figure 12 illustrate that the poor quality is greater than the expected amount. Additionally, Figure 13 clearly depicts the poor quality of the project. The maximum and mean measures of simulation results with 1,000 iterations are summarized as follows:

- Duration: maximum = 14 and mean = 10.938 months.
- Cost: maximum = 374,965 and mean = 356,979.661 monetary units.
- Quality: maximum = 10,159 and mean = 9,241 monetary units.

5.3 Third case study

The third case study is an industrial construction project for the renovation of an industrial unit in Italy, which is taken from De Marco and Narbaev (2013). It is noteworthy that quality data are added to these real project data. The project was

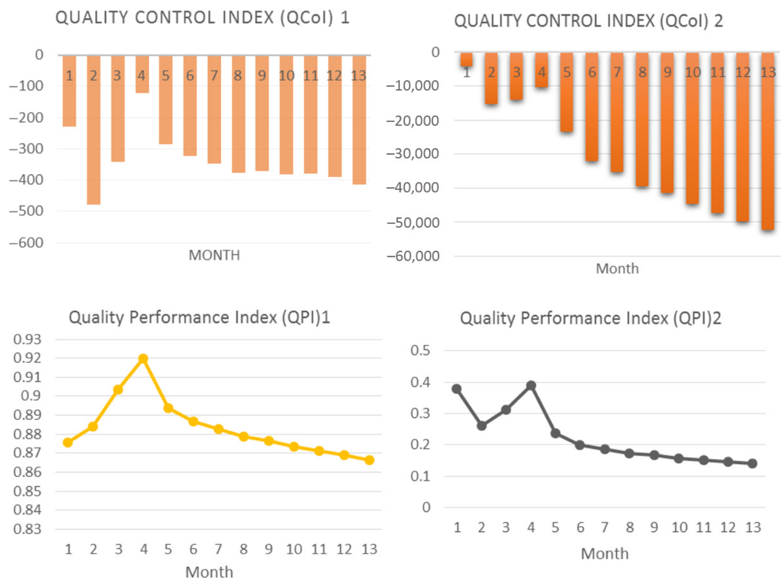

Figure 12.
New quality control indices by method 1 and 2 for the second case study (poor quality is greater than the expected amount)

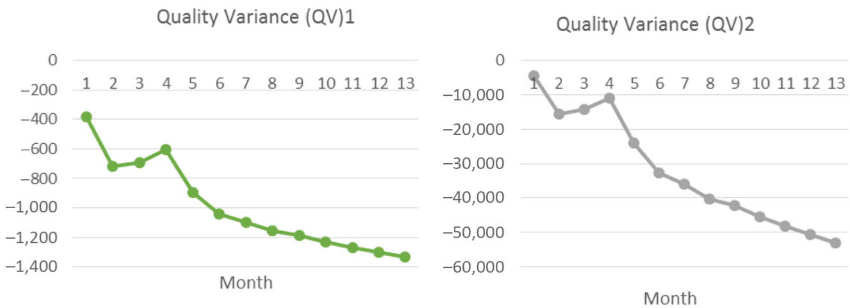

Figure 13.
EVM new quality control indices by methods 1 and 2 obtained from the second case study (poor quality of the project)

finished with a 23-day delay. It should be mentioned that the actual cost was greater than its budgeted amount. The EVM diagram indices shown in Figure 14 represents the increment of time and cost. The cost and schedule control indices of Figure 15 show that the delays and over-budget costs were not within the expected variability limit, and early corrective actions should be taken.

The quality control indices in Figure 16 present different outcomes with two methods. The first method indicates that the poor quality is within the acceptable threshold, but the second method assesses the poor quality more aggressively, as it indicates that the poor quality exceeded the expected threshold, and thus locates a critical situation. The quality control indices shown in Figure 17 illustrates that the project quality requirements were not met. The maximum and mean amounts of the simulation results with 1,000 iterations are summarized as follows:

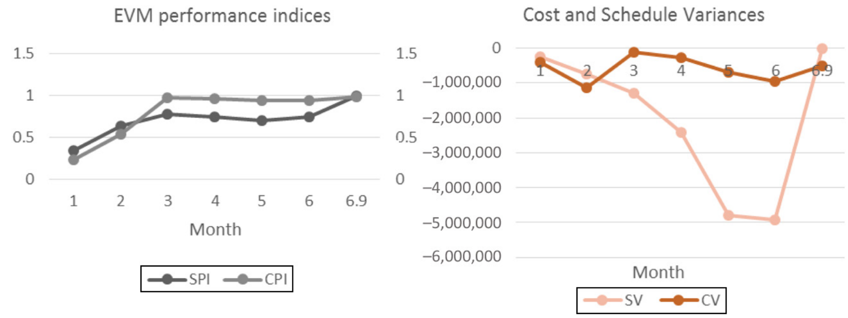

Figure 14.
EVM indices obtained from the third case study

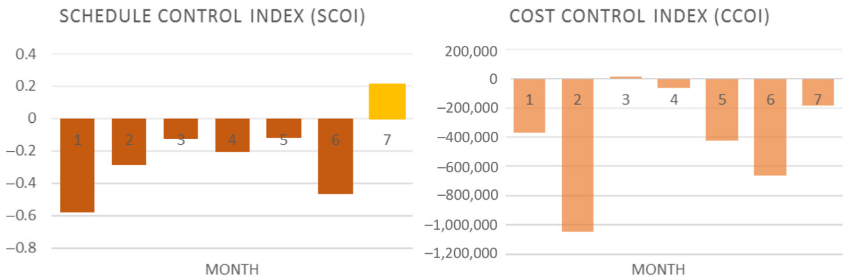

Figure 15.
Cost and schedule control indices for the third case study (delays and over-budget costs were not within the expected variability limit)

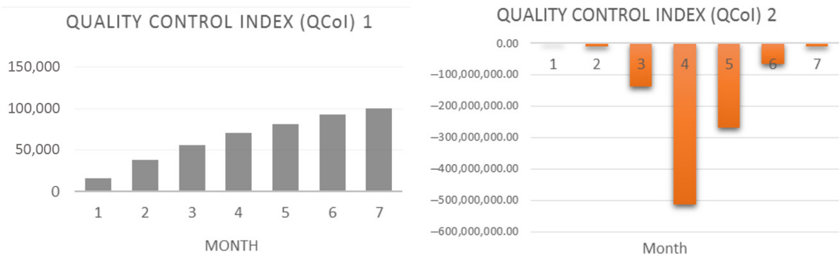

Figure 16.
New quality control indices by method 1 and 2 obtained from the third case study (different outcomes with two methods)

Figure 17.
EVM new quality control indices by methods 1 and 2 obtained from the third case study (project quality requirements were not met)

- Duration: maximum = 8 and mean = 7/047 months.
- Cost: maximum = 21,987,957 and mean = 21,600,121 monetary units.
- Quality: maximum = 1,899,085 and mean = 1,797,794/1 monetary units.

6. Conclusion

This study developed a new EVM framework by considering a quality control index. Quality, as the third angle of the golden project triangle, should be considered and controlled as same as schedule and cost to fully satisfy the goals and objectives of projects. The quality control index has been defined according to two proposed methods. The first method is linear and the second one is based on the Taguchi loss function, which more aggressively treats the cost of quality. Three new control indices, namely, CCoI, SCoI and QCoI, are defined to integrate EVM with quality and risk management. These indices alert project managers about critical situations and undesirable changes at every time of the project horizon. The control indices compare EVM variances with some new cumulative buffers, which are derived from the Monte Carlo simulation results of 1,000 iterations at determined confidence levels of cclper cent, sclper cent and qclper cent. If CCoI, SCoI and QCoI are negative, early drastic measures should be taken. The partial correlation analysis illustrated that the duration, cost and quality variables strongly affect each other, and the effect of two variables could not be assessed without considering the third one. This issue underlines the importance of the quality variable, which has been incorporated into basic EVM to have accurate and precise analysis and forecasting at any time of the project duraton. In this study, variant actual projects from different countries are considered to evaluate the new proposed EVM indices.

As the main advantage of the proposed approach, the new proposed indices do not need complicated calculations and additional data. Consequently, keeping the simplicity of the basic EVM, they can be easily used in large-sized projects and give useful information to all stakeholders. On the other hand, there was a limitation in gathering quality data from the projects to calculate EVM quality control indices. The results of this study complement previous studies on EVM. For further study on this topic, future studies can be conducted in other real-world projects to further test and verify the proposed model. Moreover, other methods of risk analysis could be applied and compared in various projects in different industries and countries. Furthermore, other practical approaches to quality control can be introduced to calculate the quality control index of EVM.

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