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Comparative analysis of earned value management techniques in construction projects

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Several earned value techniques are used to monitor progress and forecast the cost and time performance of construction projects. However, their forecasting accuracy, particularly across different project types and progress stages, remains understudied. This study evaluates the predictive accuracy of three earned value techniques: Earned Duration, Earned Schedule, and Planned Value—across a diverse dataset of 30 construction projects. The overarching objective is to evaluate the accuracy of these techniques in predicting project completion dates and to discern the most effective method based on project duration percentages. The findings reveal that Earned Schedule provides the most accurate predictions during early project stages, while Earned Duration is more reliable at later stages. The results emphasize the importance of considering project type and progress level when selecting a forecasting method. Practical guidelines are proposed to assist project managers in choosing the most effective technique at different stages of project development. By refining forecasting accuracy and providing strategic guidelines, this research serves as a valuable resource for achieving enhanced project outcomes across diverse construction projects.

Earned Value Management (EVM) is a widely recognized project management technique that integrates cost, schedule, and scope to provide an objective assessment of project performance. It enables project managers to detect deviations early, facilitating proactive decision-making and risk mitigation[1]. Despite its widespread adoption, traditional EVM techniques have faced scrutiny regarding their forecasting reliability. Studies indicate that while EVM is effective in tracking cost and schedule performance, its predictive accuracy remains questionable, particularly at different stages of project progress[2]. Traditional EVM methods primarily rely on cost-based progress tracking, which may not accurately reflect schedule deviations. Emerging research suggests that incorporating alternative earned value techniques—such as Earned Duration (ED) and Earned Schedule (ES)—can improve forecasting accuracy, particularly for schedule estimates[3,4]. These methods offer better alignment with time-related project performance, addressing some of the limitations of conventional EVM.

Nevertheless, EVM has been scrutinized for its reliability, with studies emphasizing the effectiveness of time schedules as a crucial factor in project success[5,6]. Conceptual problems and implementation difficulties have surfaced, as explored by Cândido et al.[7,8], revealing shortcomings in lean construction applications and a narrow focus on physical and financial advances over time. Moreover, the inherent limitations of EVM in measuring 'amount of work performed' rather than time deviations have been underscored[9]. Fleming and Koppelman[10] further highlight the challenges of applying EVM to dynamic construction projects. This study aims to address these controversies and gaps by conducting a comprehensive comparison of three earned value techniques—Earned Duration, Earned Schedule, and Planned Value—across diverse construction projects, offering valuable insights for project managers and enhancing project management practices in this evolving sector.

Several relevant studies have been explored to provide a broader perspective on earned value management in construction projects. For example, Bhosekar and Vyas[11,12] concentrated on cost control in construction projects within the real estate sector, emphasizing the significance of the EVM tool and comparing its analysis with other project management tools. Virle et al.[13] discussed the implementation of both EVM and Earned Schedule (ES) in construction projects, exploring their elements and parameters impacting their significance. Gaddam and Landage[14,15] reviewed the utilization of earned schedule and earned value management, highlighting their efficiency in control-ling and evaluating construction projects. Their study applied these concepts to a flyover

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infrastructure construction project in India. Suresh and Ganapathy[16,17] studied the implementation of earned value analysis for evaluating project performance, emphasizing its role in understanding project costs and the impact of various factors on project performance. Chavan and Bhamre[18,19] focused on efficient planning and scheduling of residential projects, addressing various aspects such as manpower organizing, project planning, and delay analysis. Vyas and Birajdar[20] tracked the progress of construction projects using earned value management, emphasizing its efficiency in cost and delay analysis. Mayo-Alvarez et al.[3,4] conducted an AHP systematic analysis of EVM techniques, evaluating their effectiveness for controlling and monitoring the performance of construction projects. Araszkiewicz and Bochenek[21,22] presented a study on the use of earned value method for controlling construction projects through a case study, demonstrating its application in the construction industry, and outlining its benefits and limitations. Otuyemi[23,24] discussed the potential use of EVM in the construction sector in the UK as a trend tool, illustrating its practical implementation in three case studies and highlighting its role in project success.

The abovementioned studies, along with several others, collectively contribute to the understanding of earned value management in construction projects, offering insights in-to its application, benefits, and challenges. Despite the widespread use of EVM, its application in the construction industry remains questioned, with limited exploration of potential improvements. Previous studies have highlighted the complexity, lack of accuracy, and time-consuming nature of the EVM process. With advancements in construction tools and technology, there is an opportune moment to develop a well-controlled EVM approach that can overcome these limitations. This thesis addresses the critical need for effective earned value techniques in the construction industry, focusing on project forecasting accuracy in diverse projects in Egypt. The inconsistency in the preference for Earned Schedule in renovation and residential projects and Earned Duration in industrial, commercial, and educational projects prompts the need for a systematic approach to method selection. The challenge is to reconcile the overall effectiveness of the Earned Duration method with nuanced variations under different performance factors and project types, providing a comprehensive framework for project managers in the Egyptian construction context.

Research goal and objectives

The goal of this research is to enhance the application and accuracy of earned value techniques in construction projects through a comprehensive evaluation of Earned Duration, Earned Schedule, and Planned Value methods. The research seeks to understand variations in technique accuracy based on project type, particularly focusing on preferences for specific methods in different project categories. Key goals include developing a systematic approach for selecting the most accurate technique, assessing and refining practical guidelines for decision-making, and exploring the impact of performance factors on project duration percentage like SPI and CPI. Ultimately, this will promote the adoption of earned value techniques for improved project forecasting in the Egyptian construction sector.

The objectives of this research are as follows:

1. Evaluate the effectiveness of earned value techniques in forecasting project completion dates across diverse construction projects in Egypt based on project type and duration.
2. Examine the interplay of performance factors, including Schedule Performance Index (SPI) and Cost Performance Index (CPI) for different project types, to gain a more nuanced understanding of their impact on the accuracy of earned value techniques.
3. Develop a comprehensive and applicable framework that reconciles the overall effectiveness of the Earned value methods with nuanced performance variations under different performance factors and project types, aiming to provide practical guidance for project managers in the Egyptian construction context.

Research questions

This study seeks to address the following key research questions:

1. How do different earned value techniques—Earned Duration, Earned Schedule, and Planned Value compare in terms of forecasting accuracy across diverse construction projects?
2. How does project type (e.g., residential, commercial, educational, industrial, renovation) influence the accuracy and reliability of these earned value techniques?
3. At what stages of project progress do different earned value techniques yield the most accurate completion date predictions?
4. How do performance factors such as the Schedule Performance Index (SPI) and Schedule Cost Index (SCI) impact the effectiveness of these earned value techniques?
5. What practical guidelines can be established for selecting the most appropriate earned value technique based on project characteristics and progress stages?

By answering these questions, this research aims to refine the selection and application of earned value techniques in construction project management, ultimately enhancing forecasting accuracy and decision-making.

Novelty of the study

This research introduces several novel contributions to the field of EVM in construction project management, particularly in the context of forecasting project completion dates. Based on recent studies, this research presents the following unique aspects:

1. *Comprehensive evaluation of forecasting accuracy*: While previous studies have examined the application of EVM techniques, few have systematically assessed their accuracy across different project types and stages of

progress. This study bridges this gap by evaluating Earned Duration, Earned Schedule, and Planned Value on a dataset of 30 diverse construction projects. The study also uniquely investigates the role of SPI and CPI in improving forecasting accuracy.

2. *Context-specific method selection framework*: Unlike general applications of EVM, this research introduces a structured framework to select the most appropriate forecasting method based on project type and stage. This insight enhances the practical applicability of EVM techniques, offering tailored recommendations for project managers.

3. *Empirical validation across multiple construction sectors*: By analyzing residential, commercial, educational, industrial, and renovation projects, this study extends EVM validation beyond a single domain, providing broadly applicable insights for different types of construction projects.

By addressing these aspects, this study advances the understanding of EVM application in construction projects and contributes to the ongoing discourse on improving project forecasting accuracy.

Literature review

This section reviews previous studies on the application, comparison, and accuracy of various EVM techniques, identifying research gaps and highlighting the novelties of this study. Several studies have explored the implementation of EVM in the construction sector. Bhosekar and Vyas[11,12] investigated cost control in real estate projects using EVM, demonstrating its usefulness in tracking budget performance. Similarly, Araszkiewicz and Bochenek[21,22] analyzed EVM as a control tool in construction projects through case studies, highlighting its role in project monitoring. Otuyemi[23,24] examined EVM applications in the UK construction industry, showcasing its benefits in improving project transparency and financial predictability. While these studies affirm EVM's importance in construction management, they largely focus on its theoretical advantages rather than its forecasting accuracy.

A few studies have compared different EVM-based forecasting techniques. Virle et al.[13] analyzed Earned Schedule (ES) and Earned Value Management (EVM) in construction projects, highlighting the advantages of ES in improving time-based performance tracking. Gaddam and Landage[14,15] reviewed the efficiency of ES and EVM in infrastructure projects, demonstrating their effectiveness in evaluating progress and cost control. However, these studies do not provide a comprehensive analysis of how different techniques perform across various project types and progress stages. Furthermore, they do not establish clear guidelines for selecting the most appropriate method for forecasting project completion dates.

Suresh and Ganapathy[16,17] investigated the accuracy of Earned Value Analysis (EVA) in predicting project performance, emphasizing its role in evaluating cost deviations. Chavan and Bhamre[18,19] studied its efficiency in residential projects, but their analysis was limited to planning and manpower organization rather than forecasting accuracy. Mayo-Alvarez et al.[3,4] conducted a systematic analysis of EVM techniques, assessing their reliability in controlling construction projects but without a clear distinction between their forecasting effectiveness at different project stages.

Several studies have examined the impact of performance indices on project forecasting accuracy. Anbari[25] and Vanhoucke[26,27] discussed the importance of SPI and CPI in assessing project status, while Kim et al.[28,29] explored how these metrics enhance EVM applications in complex projects. However, the relationship between different performance indices and forecasting accuracy remains underexplored.

The conducted literature review revealed several research gaps; as described in the bullet points below and Table 1:

- Most studies focus on EVM's role in monitoring and controlling projects rather than evaluating its forecasting accuracy.
- Comparisons between Earned Duration, Earned Schedule, and Planned Value are limited, with few studies analyzing their relative effectiveness at different project progress stages.
- The influence of performance indices (SPI, SCI, CPI) on forecasting accuracy is underexplored.

There is no clear methodology for selecting the most suitable forecasting technique based on project type and progress percentage.

Study	Focus area	Methodology	Key findings	Limitations	Research gap
Bhosekar and Vyas[11,12]	EVM in real estate projects	Case study	EVM improves cost control	Did not assess forecasting accuracy	Lack of comparative analysis on different EVM techniques
Virle et al.[13]	Earned schedule (ES) in construction	Case study	ES enhances project tracking	No discussion on accuracy across different project types	No assessment of project duration impact
Gaddam and Landage[14,15]	EVM & ES in infrastructure	Case study of a flyover project	ES is useful for control	No cross-sector comparison	Limited to one project type
Araszkiewicz and Bochenek[21,22]	EVM in project control	Case study	EVM improves monitoring	Lacks discussion on SPI/SCI impact	No evaluation of forecasting accuracy
This study	Comparison of EVM techniques for forecasting	Empirical analysis of 30 projects	Identifies best forecasting technique per project phase	Addresses limitations of previous ones	Addresses project duration and performance factors

Table 1. Characteristics of key similar studies.

Tools and methods

The research employed 3 major steps: (1) data collection, (2) data analysis, and (3) synthesis of findings into useful guidelines. This research did not involve any human or animal experimentation. Furthermore, no personal or identifiable information was collected, used, or disclosed during the course of this study.

Data collection

Data was collected for 30 construction projects in Egypt, covering diverse sectors. Methods, including site visits, and document analysis, were employed for accurate and reliable data. The data, sourced from reputable contractors across various cities, utilized tools such as Primavera P6, Microsoft Excel, and PowerPoint presentations. Validation measures, including multiple site visits, were implemented, with ethical considerations ensuring confidentiality. The data collection spanned a year, addressing challenges such as extensive site visits. The projects values ranged from EGP 39 million to EGP 1.9 billion. Table 2 shows the key data of the collected projects. The authors went through significant efforts to collect progress data of the projects. The projects were selected based on their type, value, and finish date. It was essential to choose projects that have been completed (so that that gathered progress data is complete). Another criteria that the authors followed for sampling is to have projects that started within the past 5 years so that they are more recent and relevant. Project costs also were selected to be between EGP 39 million to EGP 1.9 billion; which is around USD 1 million to USD 40 million. This is considered a representative sample of the construction projects in Egypt. There are no official records that show the distribution of project sizes in Egypt. But given the authors' experience in the Egyptian market, the selected margin represents a significant portion of the Egyptian construction market; as most construction projects in Egypt lie in this range.

Determining an appropriate sample size is a fundamental aspect of research design, particularly in engineering studies, where data reliability and statistical validity are essential. This study analyzed data from 30 projects, and the justification for this sample size is based on established guidelines and previous research in the field. Roscoe[30] suggested that for most research studies, a sample size ranging between 30 and 500 is appropriate, with 30 being the minimum threshold for meaningful statistical analysis in general research[30]. This threshold

Project	Type	BCWS (EGP)	ACWP (EGP)	Planned finish	Actual finish
1	Commercial	160,387,330	171,886,590	20-Feb-18	30-Oct-18
2	Educational	145,263,973	157,985,453	30-Apr-17	20-Dec-17
3	Industrial	322,179,850	334,650,146	19-Apr-19	30-Sep-19
4	Commercial	498,371,317	510,650,568	4-Sep-19	30-Nov-20
5	Residential	1,844,515,667	1,297,649,614	13-Jan-24	30-Jun-24
6	Commercial	505,782,177	455,858,281	30-Mar-21	30-May-21
7	Renovation	129,946,203	149,674,697	30-Sep-21	30-Dec-21
8	Educational	524,011,456	491,657,287	25-Sep-20	20-Nov-20
9	Residential	934,084,850	908,852,210	25-Oct-22	28-Feb-24
10	Commercial	101,460,922	103,647,402	20-Mar-16	28-Feb-17
11	Commercial	278,072,672	276,227,816	7-Dec-21	30-Nov-22
12	Commercial	224,382,775	231,577,203	1-Oct-19	31-Mar-20
13	Industrial	391,381,394	345,945,404	21-Feb-17	30-Dec-17
14	Educational	237,039,879	228,301,480	20-Jul-19	14-Sep-19
15	Commercial	106,717,901	99,209,499	31-Dec-20	25-Jan-21
16	Commercial	209,859,079	237,328,844	17-Nov-22	30-Jun-23
17	Educational	583,273,944	677,666,732	17-Apr-23	30-Oct-23
18	Commercial	550,151,073	553,748,233	4-Aug-23	30-Mar-24
19	Industrial	154,528,736	136,354,130	20-Jun-20	29-Jul-21
20	Commercial	758,418,631	628,632,758	31-May-22	30-Mar-23
21	Residential	39,050,912	38,163,075	22-Apr-20	30-Jun-20
22	Industrial	1,540,046,857	1,253,676,323	12-May-20	30-Sep-21
23	Industrial	188,803,564	200,787,624	3-Apr-21	15-Jun-21
24	Commercial	61,742,362	57,837,539	30-Jan-19	30-Apr-19
25	Commercial	341,780,342	360,220,926	23-Jan-23	30-Dec-23
26	Commercial	74,027,664	80,492,656	26-May-22	30-Aug-23
27	Commercial	172,742,103	192,355,326	2-Mar-20	30-Dec-20
28	Residential	299,554,952	339,899,961	24-Jul-17	30-Apr-18
29	Industrial	167,766,090	160,622,767	31-Jan-19	30-Apr-19
30	Industrial	106,927,735	95,321,477	15-Feb-17	30-Sep-17

Table 2. Information about the collected projects.

aligns with commonly accepted heuristics in experimental design, where a sample size of at least 30 is considered sufficient to approximate normal distribution properties, allowing for valid statistical inference.

Additionally, research on sample size heuristics indicates that a sample of approximately 30 observations strikes a balance between feasibility and statistical power, making it a widely accepted benchmark in empirical studies[31]. This is particularly relevant in engineering studies, where practical constraints often limit data collection while maintaining the need for meaningful statistical interpretation.

In addition, although the sample consists of 30 construction projects, each project contributed a large number of repeated measurements, as monthly planned versus actual progress data were collected throughout the project life cycle. Thus, the study benefits from a substantial number of total observations, enhancing the reliability of the statistical analysis. From a statistical perspective, the sample size of 30 independent projects is appropriate based on the Central Limit Theorem (CLT), which states that for samples of size 30 or more, the sampling distribution of the mean tends to approximate a normal distribution, regardless of the original data distribution[32]. This ensures that the statistical comparisons between forecasting techniques are valid and that inferential analysis (such as accuracy comparisons) can be meaningfully conducted. Moreover, the use of longitudinal data (monthly observations) increases the study's statistical power, as it provides a much larger effective sample size at the observation level. With repeated measures per project, variance across time is captured, enabling more robust and nuanced evaluations of forecasting performance.

Given these considerations, the sample size of 30 projects in this study is justified based on established research guidelines and common practices in engineering and empirical studies. While larger samples can enhance generalizability, this sample size is sufficient for identifying key trends and deriving meaningful conclusions within the study's scope. Future research may explore larger datasets to validate findings across broader contexts.

The study acknowledges potential limitations in the generalizability of the findings due to its regional focus on Egypt. While the sample offers valuable insights into the Egyptian construction sector, further studies involving additional geographic contexts may be required to confirm broader applicability of the results.

The study does not assume that SPI and SCI remain constant across different projects. On the contrary, these performance indices were part of the collected data and varied across the analyzed projects. The empirical analysis incorporated project-specific SPI and SCI values, reflecting the dynamic nature of project environments. By considering these variations, the study ensures a more realistic evaluation of forecasting techniques and their applicability across diverse construction projects. Future research could further explore the impact of fluctuating SPI and SCI trends over time to enhance forecasting accuracy in dynamic project settings.

Data analysis

Earned value (EV), planned value (PV), and actual cost (AC) data for each project in each week were obtained and analyzed separately using three different techniques: (1) Earned Schedule Method, (2) Earned Duration Method, and (3) Planned Value Method. Each of those methods offers distinct approaches to measuring project performance. The Earned Schedule Method (ESM) focuses on time-based schedule performance using metrics like Earned Schedule (ES) and Schedule Performance Index (SPI(t)), providing a more accurate assessment of schedule adherence but requiring detailed scheduling data and a good understanding of Earned Value Management (EVM) concepts. In contrast, the Earned Duration Method (EDM) also emphasizes time but through duration-based metrics such as Earned Duration (ED), making it simpler to understand and implement, though it is less commonly used and supported. The Planned Value Method (PVM), on the other hand, is a widely adopted and understood method that concentrates on cost-based schedule performance, using metrics like Planned Value (PV). While the Planned Value Method is generally easier to implement, it may not always accurately reflect the true schedule performance if cost and schedule are not perfectly aligned. Each method offers unique advantages and is suitable for different project management contexts depending on whether the primary concern is time, duration, or cost. In this research, all of those methods were evaluated. Table 3 summarizes the distinctions between these methods and outlines the calculations involved in forecasting the project's completion date.

In Earned Value Management (EVM), the Estimate at Completion (EAC) is a forward-looking metric used to project the final cost of a project based on current performance. The calculation of EAC depends on the specific performance factors chosen, each of which offers a distinct perspective on project efficiency and budget adherence. These performance factors include indices such as the Cost Performance Index (CPI) and the Schedule Performance Index (SPI), both essential for determining how effectively resources are utilized. The CPI is a critical measure of cost efficiency, defined as the ratio of earned value (the budgeted value of completed work) to the actual cost incurred; a CPI greater than 1 indicates cost savings, while a CPI below 1 suggests cost overruns. On the other hand, the SPI evaluates time efficiency by comparing the value of work completed to the planned value. An SPI greater than 1 suggests the project is ahead of schedule, while an SPI below 1 indicates delays.

The choice of performance factor for calculating EAC depends on the project's priorities. If maintaining the budget is paramount, a CPI-based EAC calculation would be most relevant, as it focuses on cost efficiency. Conversely, if the primary concern is adherence to the project schedule, an SPI-based EAC might be more informative, as it emphasizes timeliness. However, when both cost and schedule are crucial, an integrated approach using both CPI and SPI could yield a more balanced forecast. Table 3, referenced here, outlines the variations in EAC calculations based on these performance factors, while Table 4 details the specific performance factors utilized in this analysis to provide a nuanced understanding of project trajectory and potential final costs. This strategic selection of performance indices allows project managers to adjust their forecasts dynamically, enabling better resource allocation and timely adjustments to meet project objectives.

For the collected data of the construction projects, different EACs were calculated at different progress levels using the methods described in Table 3 and using multiple performance factors for each method. Since the

Method	Metric	Definition	Formula
Earned schedule method	Earned schedule (ES)	The duration of time that a project merits based on its current progress	$ES = t + \frac{EV - PV_t}{PV_{t+1} - PV_t}$
	EAC_1	Estimate at completion when the performance factor is equal to 1	$EAC_1 = AT + PD - ES$
	EAC_2	Estimate at completion when the performance factor is equal to SPI	$EAC_2 = AT + \frac{PD - ES}{SPT(t)}$
	EAC_3	Estimate at completion when the performance factor is equal to SCI	$EAC_2 = AT + \frac{PD - ES}{SCI(t)}$
Earned duration method	Earned duration (ED)	Amount of time accrued or earned in accordance with the project's progress at a specific point in time	$ED = SPI\,x\,AD$
	EAC_1	Estimate at completion when the performance factor is equal to 1	$EAC_1 = AC + PD - ED$
	EAC_2	Estimate at completion when the performance factor is equal to SPI	$EAC_2 = AC + \frac{PD - ED}{SPI}$
	EAC_3	Estimate at completion when the performance factor is equal to SCI	$EAC_3 = AC + \frac{PD - ED}{SCI}$
Planned value method	Planned rate per time (PV_{rate})	Predetermined pace required to complete the project within the scheduled time frame	$PV_r = \frac{BAC}{PD}$
	EAC_1	The Time Estimate at Completion is a projected duration for the project under the assumption that the performance factor is 1, indicating that the remaining work will be completed as initially planned	$EAC_1 = PD - TV$
	EAC_2	The Time Estimate at Completion is a projected duration for the project under the assumption that the performance factor is SPI	$EAC_2 = \frac{PD}{SPI}$
	EAC_3	Estimate at completion when the performance factor is equal to SCI	$EAC_3 = \frac{PD}{SCI}$

Table 3. Estimate at completion calculations.

Performance factor (PF)	Description	Formula
SPI	Schedule Performance Index	$SPI = \frac{EV}{PV}$
CPI	Cost Performance Index	$CPI = \frac{EV}{AC}$

Table 4. Performance factor calculations.

actual finish date and cost of those projects already has been known, the accuracy of the calculated EACs using Eqs. 1 is applicable.

$$\text{Accuracy} = 1 - \frac{|AD - EAC_t|}{AD}$$

It shall be noted that there are no experiments conducted on live vertebrates in this research.

Results
Holistic analysis

The studied projects span various types, including commercial, industrial, educational, residential, and renovation, situated across multiple cities in Egypt. The analysis focused on estimating accurate project finish dates and determining the most suitable method for different cases. The data collected monthly from multiple contractors includes Budgeted Cost of Work Performed (BCWP), Budgeted Cost of Work Scheduled (BCWS), and Actual Cost of Work Performed (ACWP). Table 5 shows the accuracy of each method at each performance factor at each progress level of the projects. The methods evaluated include the Earned Duration Method (EDM), Planned Value Method (PVM), and Earned Schedule Method (ESM), with performance factors (PF) set to 1, Schedule Performance Index (SPI), and Schedule Cost Index (SCI). Primarily, it can be deduced that the Earned Duration method emerged as the most accurate among the three techniques across various metrics, including average accuracy, performance factor set to 1. However, under the performance factor set to SPI and SCI, Earned Schedule surpassed Earned Duration. This underscores the Earned Duration method's exceptional efficacy in predicting project completion dates across a diverse spectrum of project types and durations. Figure 1 and Table 5 demonstrates the abovementioned observations.

The analysis of Table 5 and Fig. 1 reveals several insights into the effectiveness and accuracy of different earned value methods for forecasting project outcomes as a construction project progresses. These methods—Earned Duration Method (EDM), Planned Value Method (PVM), and Earned Schedule Method (ESM)—demonstrate distinct behaviors in terms of accuracy, particularly with various performance factors (PF), such as Schedule Performance Index (SPI) and Schedule Cost Index (SCI). Based on Table 5 and Fig. 1, it can be concluded that:

- Earned duration method (EDM): The EDM's accuracy consistently improves as the project advances, largely because more actual performance data become available. The highest accuracy with EDM is observed when

Progress (%)	Earned duration method			Planned value method			Earned schedule method		
	PF = 1 (%)	PF = SPI (%)	PF = SCI (%)	PF = 1 (%)	PF = SPI (%)	PF = SCI (%)	PF = 1 (%)	PF = SPI (%)	PF = SCI (%)
10	92.65	84.96	67.48	93.35	84.96	65.65	93.43	93.17	73.82
15	92.69	88.79	73.00	93.27	88.79	69.87	93.45	93.43	73.56
20	93.25	92.53	79.69	93.39	92.53	75.88	93.46	93.45	79.86
25	93.73	94.39	83.39	93.57	94.39	78.82	99.86	78.43	93.13
30	93.12	92.53	86.71	93.33	92.53	83.28	93.46	93.45	87.01
40	94.30	95.33	94.11	93.85	95.33	93.11	97.84	82.87	83.14
45	94.39	95.33	95.64	93.89	95.33	95.95	97.79	97.16	95.68
50	94.52	95.33	96.98	93.94	95.33	99.14	99.94	93.78	90.61
55	94.60	95.33	99.10	93.98	95.33	94.93	97.79	99.06	93.77
60	95.73	96.72	99.85	95.29	96.72	92.05	97.77	92.51	86.26
65	95.67	96.34	99.05	95.68	96.34	92.11	99.94	97.54	93.11
75	95.75	96.20	98.23	95.92	96.20	91.59	99.87	98.42	95.01
80	95.88	96.14	97.35	96.04	96.14	91.39	99.97	98.89	96.58
85	94.98	95.09	95.98	95.06	95.09	90.99	97.84	96.41	93.98
90	94.30	94.33	94.80	94.33	94.33	91.62	97.82	98.15	99.26
95	98.09	98.09	98.13	93.69	93.69	92.19	95.61	94.79	93.66
100	100.0	100.00	100.00	93.46	93.46	92.35	99.93	99.92	99.91

Table 5. EAC Accuracy achieved at different project progress levels.
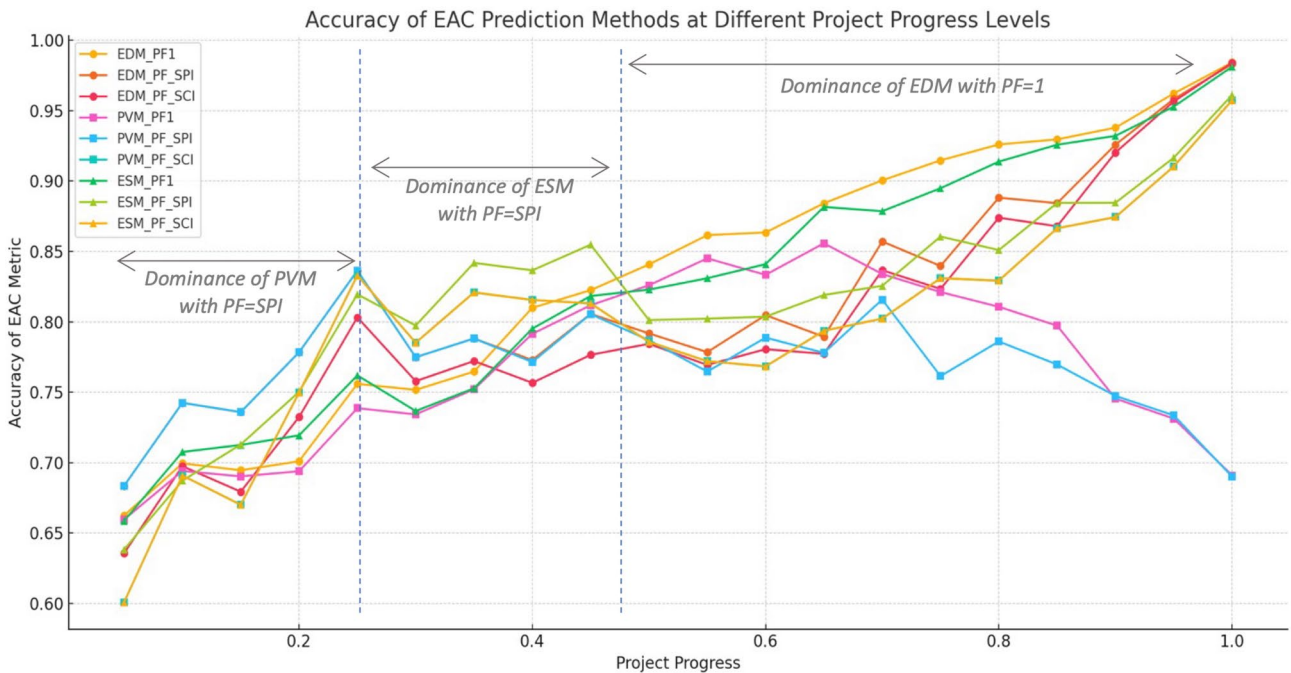

Fig. 1. Visualization of the EAC accuracy achieved at different project progress levels.

PF is set to SPI, indicating that EDM is especially effective in time-based assessments, with SPI accurately capturing time-related efficiency as the project develops.

- Planned value method (PVM): Similar to EDM, the accuracy of PVM increases over time, showing greater predictive reliability as the project progresses. With PVM, PF = SPI also tends to yield the best results, suggesting that SPI is a particularly strong predictor for project timelines and cost estimates within this method. In practice, PVM can serve as a simpler, baseline forecasting method, suitable for early to mid-project assessments, especially when quick updates on expected timelines are needed without complex modeling.
- Earned schedule method (ESM): ESM, like EDM and PVM, shows improvement in accuracy as the project progresses, but it particularly benefits from using PF = SCI. This aligns with ESM's design to address schedule-based performance and suggests that SCI—combining schedule and cost indices—captures more nuanced performance aspects in later project stages. ESM's consistency with PF = SCI, especially in later stages,

underscores its reliability in handling complex project conditions where both time and cost considerations are intertwined. Unlike EDM and PVM, which are more sensitive to the choice of performance factor, ESM delivers consistent results, especially in later project stages, where schedule and cost variables become increasingly intertwined. This suggests that ESM is particularly advantageous in complex or resource-constrained projects, where maintaining a balance between time and cost is critical. The SCI factor enhances ESM's forecasting ability by integrating both schedule slippage and cost overruns—making it a practical choice for projects nearing completion or facing scope changes.

- Almost all methods tend to increase in accuracy as the project progresses, which is expected as more information becomes available. The use of performance indices (SPI and SCI) generally enhances the prediction accuracy compared to using a simple PF = 1.
- EDM versus PVM versus ESM: While all three methods gain accuracy with project progress, EDM and PVM appear more sensitive to the choice of performance factors. This suggests that using the correct PF (especially SPI) is critical for accuracy in these methods. In contrast, ESM demonstrates a more consistent and stable improvement in accuracy, particularly when using PF = SCI, making it a reliable choice in later project stages.
- Performance factors: The selection of performance factors significantly impacts forecast accuracy. PF = SPI frequently yields the best accuracy across methods, underscoring its robustness in capturing project performance trends. However, SCI is particularly beneficial within ESM, especially in later stages, as it combines schedule and cost perspectives, thus providing a holistic measure of project efficiency. This insight reinforces the importance of carefully selecting the performance factor based on the project's specific needs and method in use.

Different Earned Value Management (EVM) methods perform better at different stages of a project due to variations in data availability and how each method interprets performance indicators. In the early stages of a project, performance data is limited, making simpler methods like the Planned Value Method (PVM) more suitable. PVM compares planned and earned values and provides a rough estimate of progress, though it lacks the nuance to handle delays or recoveries effectively. As the project advances, more accurate and complete performance data becomes available, allowing methods such as the Earned Duration Method (EDM) and Earned Schedule Method (ESM) to offer improved forecasting. EDM becomes particularly effective in mid-to-late stages by leveraging actual duration data, especially when paired with the Schedule Performance Index (SPI), a strong indicator of time efficiency.

ESM, on the other hand, continues to improve as the project nears completion and demonstrates notable stability and accuracy when combined with the Schedule Cost Index (SCI), which integrates both schedule and cost performance. This makes ESM particularly valuable in complex or resource-constrained projects where both dimensions must be monitored closely. Additionally, while SPI generally yields high forecasting accuracy in most methods, SCI proves more insightful during the later stages of a project, especially when cost overruns or underruns begin to affect outcomes. Ultimately, the effectiveness of each method is dynamic and should be matched to the project's phase and complexity. Project managers who adjust their forecasting approach as the project evolves are better positioned to maintain control and make informed decisions.

The accompanying Fig. 2 represents the accuracy difference between the three methods based on different performance factors.

Nevertheless, it is important to emphasize that the selection of the most effective technique is contingent on the specific project type and its duration. For renovation and residential projects, the Earned Schedule method demonstrated superior performance, attaining the highest level of accuracy. Conversely, for industrial, commercial, and educational projects, the Earned Duration method consistently proved to be the most accurate.
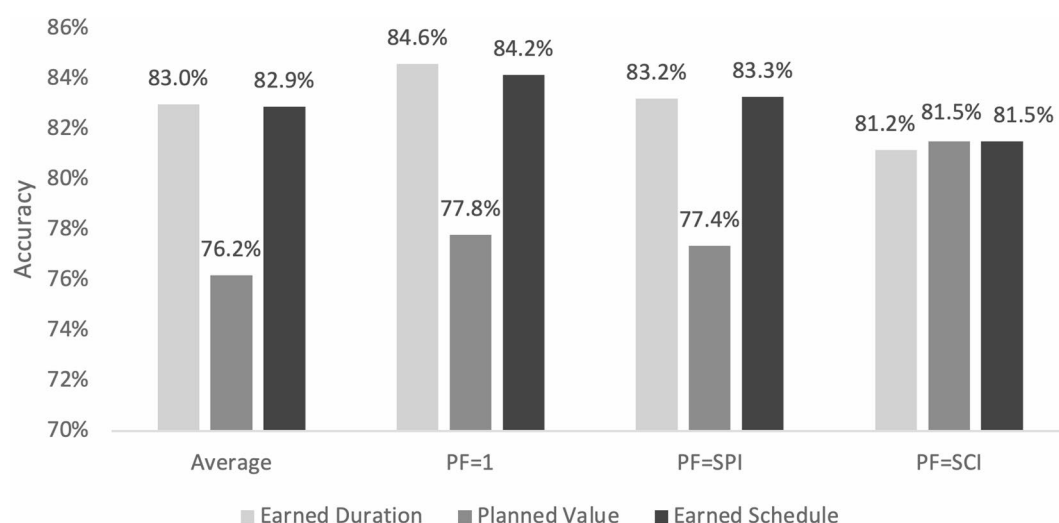

Fig. 2. Overall accuracy achieved of the studied EV methods.

Analysis per project type

The detailed examination of outcomes for each project type commences with industrial projects. As previously mentioned, the Earned Duration method produces the highest overall percentage. However, in cases where the performance factor is set to SPI, the Earned Schedule method takes the lead in accuracy. In order *not* to consume a significant portion of the manuscript, the authors opted to have the tables showing the accuracy per project type in the Appendix. The following is a discussion of those tables. In commercial projects, the Earned Duration method attains the highest overall percentage, and this trend persists when the performance factor is set to 1. Conversely, when the performance factor is SPI, the highest accuracy percentage is achieved by the Earned Schedule method. In the case of educational projects, the Earned Duration method achieves the highest overall percentage. Additionally, when the performance factor is set to SPI and SCI, Earned Duration maintains its supremacy. However, under the condition of a performance factor equal to 1, Earned Schedule exhibits the highest accuracy. For residential projects, in contrast to other projects, the Earned Schedule method secures the highest overall percentage.

In conclusion, the examination of diverse project types reveals distinctive trends in the performance of Earned Duration and Earned Schedule methods across various performance factors. In industrial projects, Earned Duration consistently attains the highest overall percentage, except when the performance factor is set to SPI, where Earned Schedule excels in accuracy. This trend is similarly observed in commercial projects, where Earned Duration predominates overall, and Earned Schedule leads under the SPI performance factor. Educational projects present a nuanced scenario, with Earned Duration performing best overall, while Earned Schedule surpasses under a performance factor set to 1. Notably, residential and renovation projects deviate from the general pattern, with Earned Schedule emerging as the method with the highest overall percentage. The detailed visual representations considering project duration percentages and performance factors 1, SPI, SCI, and the average provide a comprehensive overview, facilitating an understanding of the nuanced dynamics of accuracy across diverse project types and conditions.

Optimal method

The analysis of performance factors and methods relative to project duration percentage reveals a dynamic approach to optimizing Earned Value Management (EVM) based on stages within the project timeline. When project duration percentage alone is considered, excluding the variability of project type, the analysis indicates that different methods and performance factors yield the best results at distinct phases of the project. Specifically:

1. Initial phase (0–25% of project duration): In the early stages of a project, from 0 to 25% of the duration, the most accurate forecasting approach is to use the Earned Duration Method (EDM) with the performance factor set to the Schedule Performance Index (SPI). This choice leverages SPI's ability to provide insights into schedule efficiency, which is crucial during the beginning phases where schedule alignment is a primary concern, and the scope and budget may still be adjusting. SPI helps capture early progress, indicating if the project is on schedule, which allows project managers to make timely adjustments.
2. Mid-phase (25–50% of project duration): As the project progresses into the middle phase (25–50% of duration), the Earned Duration Method remains the preferred approach, with the performance factor still set to SPI. During this phase, the project has typically settled into a more predictable workflow, and SPI continues to provide a reliable gauge of schedule adherence. The consistency of using SPI up to the midpoint of the project emphasizes its robustness in providing accurate duration predictions as the project stabilizes in terms of pace and resource allocation.
3. Later phase (50–100% of project duration): Beyond the midpoint, from 50 to 100% of the project duration, the analysis recommends adjusting the performance factor to a simple factor of 1 while continuing to use the Earned Duration Method. This shift away from SPI to a neutral performance factor reflects a stage where project performance is more predictable, and where past variances have likely stabilized, allowing project managers to rely on simpler calculations. Using a factor of 1 assumes that the project will continue at its established pace without additional variances, providing a straightforward and reliable method for estimating the remaining duration and cost.
4. Practical implications for planners: Table 6 encapsulates these findings, offering a practical guide for project planners. By following this structured approach, planners can select the most appropriate performance factor at each stage of project duration, maximizing forecasting accuracy. This progression—from SPI in the initial and middle phases to a neutral factor in the later phase—aligns with the project's natural evolution and variance stabilization, supporting more reliable projections as the project nears completion. This guideline thus serves as a significant contribution to the field, equipping planners with a phased approach that aligns EVM practices with project timeline stages to improve precision in project control and management.

This context-specific framework differs from existing EVM selection tools in the literature by introducing a phase-based approach that aligns the choice of forecasting method and performance factor with specific percentages of

Duration (%)	PF	Method
5–20	SPI	ED
25–50	SPI	ES
55–100	1	ED

Table 6. Method and performance factors with highest accuracy according to duration percentage.

project duration, rather than relying on a one-size-fits-all or project-type-dependent strategy. While traditional EVM tools often recommend fixed combinations of methods and performance indices regardless of project stage, this study highlights that forecasting accuracy improves when method selection is dynamically adapted to the evolving characteristics of the project timeline.

In a similar fashion, encompassing the project types, the subsequent outcomes were derived from the examination of industrial, commercial, residential and renovation projects in Table 7.

Confidence

The confidence intervals at specified confidence levels, set at 95%, were calculated. These intervals act as statistical bounds, encompassing the range within which the true values are likely to exist. This ensures a thorough exploration of the inherent uncertainty present in our observations. The resulting time series graph shown in Fig. 3, adorned with confidence intervals, provides a visual representation of the dynamic nature of the data. Peaks and troughs in the series are accompanied by corresponding fluctuations in the width of the confidence intervals. Notably, wider intervals during periods of increased volatility underscore the uncertainty associated with those specific time points.

When the performance factor is equal to 1, the highest accuracy for the confidence interval is achieved using the earned duration method during the first 25% of the project. From 25 to 55% of the project duration, the earned schedule method proves to be the most effective. Throughout the entire project, both earned duration and earned schedule methods consistently show high accuracy. However, from 65% until the project's completion, the earned schedule remains the most accurate technique. On the other hand, the planned value method begins to decline in accuracy after 70% of the project duration and continues to do so until the end.

Regarding the confidence interval when the performance factor is equal to SPI, the highest accuracy is attained up to 25% of the project duration when employing the earned schedule method. Up until 55%, the most effective method is using the earned duration, and throughout the entire project duration, both earned duration and earned schedule demonstrate the highest results. Meanwhile, the planned value method shows a decline starting from 70% of the project duration percentage, persisting until the project's completion.

Concerning the confidence interval when the performance factor is equal to SCI, the optimal method to initiate with is the earned schedule. From 10 to 45%, the most effective approach is utilizing earned duration. Up to 100%, the highest accuracy is achieved with both earned duration and earned schedule. Similarly, the planned value method exhibits a decline starting from 70% of the project duration percentage, persisting until the project's completion.

The overall conclusion drawn from the outcomes presented in the figures is that, up to 25% of the project duration, the most effective method is earned schedule. From 25 to 85%, the preferred method for achieving the highest accuracy is also earned schedule. However, from 85 to 100%, the earned duration method outperforms others, yielding the highest accuracy during this latter phase of the project.

The analysis of confidence intervals offers insights into the precision and stability of our time series measurements. Narrow intervals signify periods of heightened certainty, whereas wider intervals indicate greater variability and potential external influences. Peaks and valleys in the time series graph are not only

Industrial projects				Commercial projects			Residential			Renovation		
Progress (%)	PF	Method	Accuracy (%)	PF	Method	Accuracy (%)	PF	Method	Accuracy (%)	PF	Method	Accuracy (%)
5	1	ED	61.91	SPI	ED	69.76	SPI	ED	78.64	1	ES	93.10
10	SPI	ES	72.08	SPI	ED	69.47	SPI	ED	84.92	1	ES	93.43
15	SPI	ED	72.61	SPI	ES	72.77	SPI	ED	80.58	1	ES	93.45
20	SPI	ES	80.72	SPI	ED	76.12	SPI	ED	85.30	1	ES	93.46
25	SCI	ES	81.63	SPI	ED	82.09	SPI	ED	92.01	1	ES	99.86
30	SCI	ES	74.94	SCI	ED	81.14	SPI	ED	88.66	1	ES	93.46
35	SCI	PV	84.25	SPI	ES	84.46	SCI	ED	95.01	1	ES	95.65
40	SCI	PV	77.33	SPI	ES	81.29	SCI	ED	91.31	1	ES	97.84
45	1	ED	79.57	SPI	ES	88.65	SCI	ED	89.65	1	ES	97.79
50	1	ED	79.23	1	ED	82.67	1	ED	88.99	1	ES	99.94
55	SPI	ES	82.36	1	ED	85.18	1	ES	93.06	SCI	ES	99.10
60	1	ED	80.55	1	ED	86.10	1	ES	91.60	SCI	ES	99.85
65	SCI	ED	87.86	1	ED	88.94	1	ES	92.91	1	ES	99.94
70	SCI	ED	89.57	1	ED	90.93	1	ES	92.84	1	ES	99.91
75	SPI	ED	89.96	1	ED	91.56	1	ES	94.22	1	ES	99.87
80	SPI	ED	90.66	1	ED	92.76	1	ES	96.50	1	ES	99.97
85	SCI	ES	94.42	1	ED	93.50	1	ES	93.61	1	ES	97.84
90	SCI	ED	94.18	1	ED	93.10	SCI	ED	95.27	SCI	PV	99.26
95	SPI	ED	96.61	1	ED	96.05	SCI	ED	97.41	SCI	ES	98.13
100	SCI	ES	99.26	1	ED	99.10	SCI	ED	99.11	1	ES	100.00

Table 7. Method and performance factors with highest accuracy according to duration % and project type.
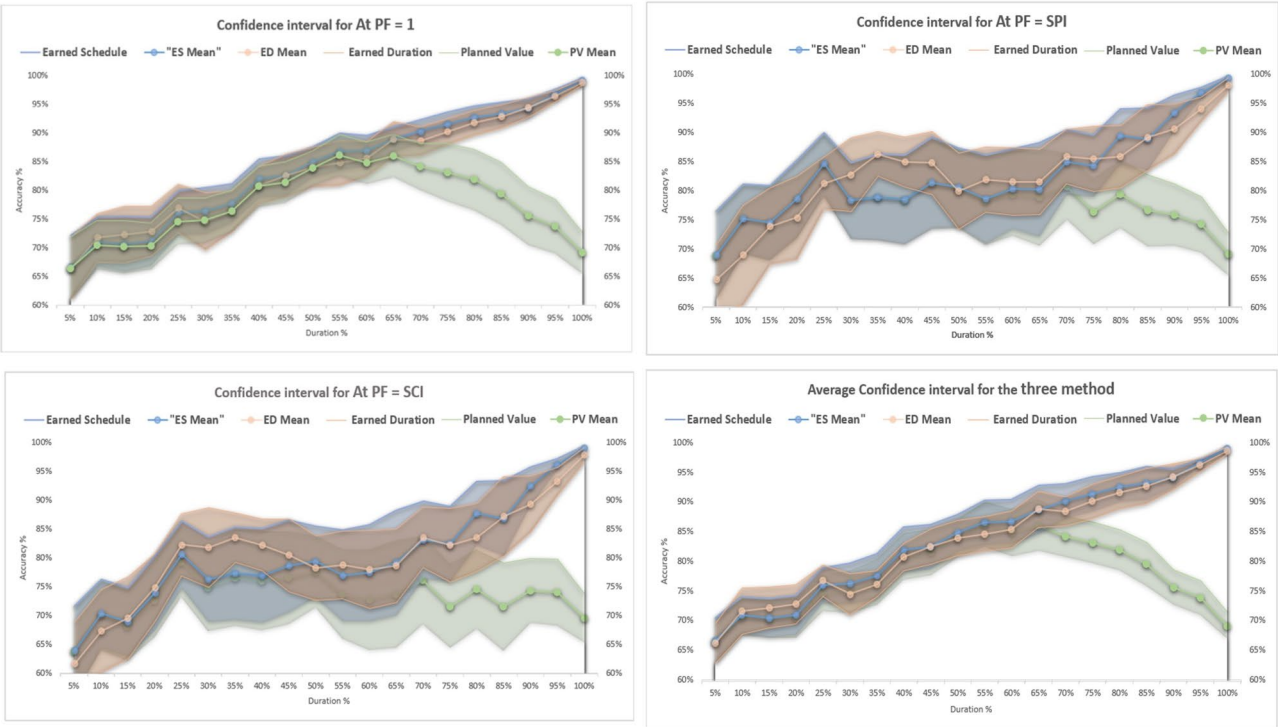
Fig. 3. EAC accuracy of the studied EV methods with 95% confidence level.

	Performance factor = 1			Performance factor = SPI			Performance factor = SCI		
Progress (%)	ED versus ES	ED versus PV	ES versus PV	ED versus ES	ED versus PV	ES versus PV	ED versus ES	ED versus PV	ES versus PV
5–65	X	x	x	x	x	x	x	x	x
70	Yes	Yes	Yes	x	x	x	x	x	x
75–100	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 8. Statistically significant differences of the T-test analysis.

observed but also quantified in terms of their corresponding confidence levels. Understanding these confidence intervals is crucial for informed decision-making and drawing reliable conclusions. The identified patterns and fluctuations enable a nuanced interpretation of the underlying dynamics, contributing to a more comprehensive understanding of the phenomenon under investigation.

Significant difference between earned value methods

Throughout the study, a pairwise comparison was conducted using the T-test to test for statistically significant differences between the different earned value methods at different levels of project progress. The outcomes are shown in Table 8. The analysis from these tests reveals no statistical differences observed up to the 70% project duration percentage. However, beyond this threshold, statistically significant differences emerge between earned duration and planned value, as well as between earned schedule and planned value with a t factor ranging from 0.003 to 2.35×10^{-28}.

Sensitivity analysis

Earned Value Management (EVM) techniques, particularly the Schedule Performance Index (SPI), provide a quantitative measure of schedule efficiency. However, SPI values fluctuate throughout a project's lifecycle, making it essential to analyze their sensitivity to project duration. This study employs a One-Factor-at-a-Time (OFAT) sensitivity analysis to examine how SPI evolves over time across multiple construction projects. By systematically varying the project timeline and assessing its impact on SPI, the analysis aims to uncover trends, deviations, and potential forecasting limitations. The insights gained from this study enhance the understanding of schedule dynamics and improve predictive accuracy for project managers seeking to optimize performance monitoring and control strategies.

Figure 4 illustrates how SPI changes with project completion percentage, showing fluctuations in project performance over time. This trend helps identify phases where projects tend to experience schedule delays or recoveries, offering valuable insights into forecasting accuracy and control measures. Figure 5 is a boxplot
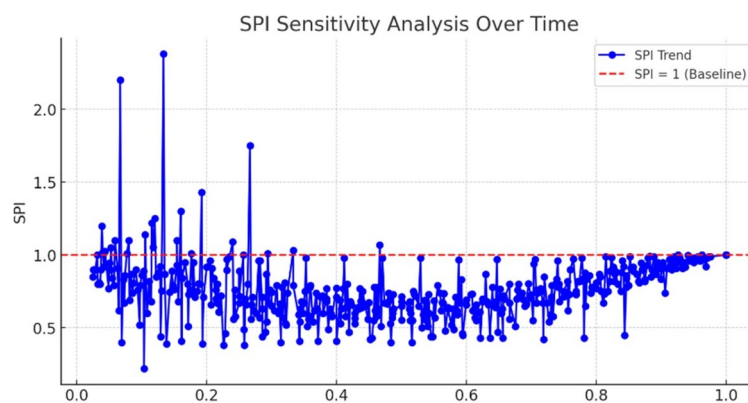
Fig. 4. SPI Sensitivity (x-axis represents project completion percentage).
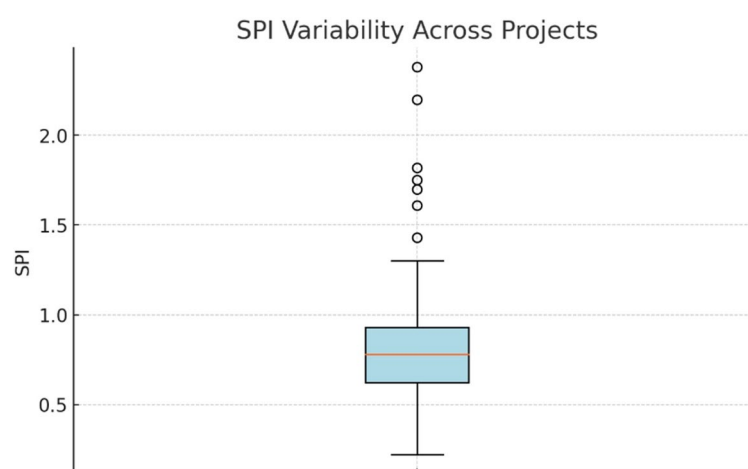

Fig. 5. SPI variability boxplot.

that visualizes the spread and distribution of SPI values, highlighting variations across different projects and revealing the extent of deviations from the median performance. The presence of outliers indicates projects that faced significant schedule deviations, emphasizing the need for more adaptive forecasting models. These findings contribute to a deeper understanding of project schedule behavior, reinforcing the importance of dynamic EVM techniques for improved accuracy in performance prediction.

Understanding SPI variability has direct implications for real-world project management. For instance, a temporarily low SPI early in a project may not warrant aggressive corrective action if historical trends suggest recovery in later stages. Conversely, a high SPI near project completion might conceal earlier delays that could affect resource allocation and handover timelines. By recognizing these nuances, project managers can make more informed decisions, calibrate control thresholds, and develop more adaptive forecasting models that respond to evolving project conditions. Ultimately, this analysis reinforces the need to integrate dynamic and time-sensitive evaluation methods within EVM frameworks to enhance performance monitoring and improve overall project outcomes.

Discussion
Discussion of outcomes and research questions
The holistic analysis of project forecasting accuracy across Earned Duration Method (EDM), Planned Value Method (PVM), and Earned Schedule Method (ESM) highlights their varying performance across project types and stages of progress. This study was guided by the following research questions:

- *RQ1: How do different earned value techniques compare in terms of forecasting accuracy across diverse construction projects?* The analysis shows that EDM consistently achieves high forecasting accuracy, especially when using a performance factor set to 1. However, when performance factors like SPI and SCI are considered, ESM demonstrates superior forecasting accuracy, particularly in later project stages. PVM showed moderate accuracy but was generally less reliable than EDM and ESM. These results confirm that no single method universally outperforms others; rather, effectiveness depends on performance factor use and project stage.

- *RQ2: How does project type influence the accuracy and reliability of these earned value techniques?* Project type significantly influences method effectiveness. For industrial, commercial, and educational projects, EDM consistently produced the most reliable forecasts. Conversely, for residential and renovation projects, ESM performed better, particularly during the early and middle stages. These findings emphasize that tailoring the forecasting method to project characteristics is essential for achieving higher predictive accuracy.
- *RQ3: At what stages of project progress do different earned value techniques yield the most accurate completion date predictions?* Forecasting accuracy improves as projects advance. In early project stages (up to approximately 50% completion), ESM delivers more accurate predictions. In later stages (beyond 50% progress), EDM becomes the more reliable technique, particularly for industrial and commercial projects. This indicates that a dynamic adjustment in method selection based on project progress can optimize forecasting outcomes.
- *RQ4: How do performance factors such as the Schedule Performance Index (SPI) and Schedule Cost Index (SCI) impact the effectiveness of these earned value techniques?* Performance factors significantly affect technique accuracy. SPI is a better predictor when using EDM and PVM, especially during general project tracking. In contrast, SCI enhances ESM's forecasting accuracy, particularly at later project phases. Understanding how different performance indices influence forecasts allows project managers to fine-tune method selection based on performance trends.
- *RQ5: What practical guidelines can be established for selecting the most appropriate earned value technique based on project characteristics and progress stages?* Based on the findings, the following actionable guidelines are recommended for construction project managers:

  - Early stages: Use ESM for forecasting, especially in residential and renovation projects.
  - Later stages: Transition to EDM for greater accuracy, particularly in industrial, commercial, and educational projects.
  - Performance factor selection: Apply SPI for EDM and PVM during general tracking and SCI to enhance ESM effectiveness in later phases.
  - Project type alignment: Always match the forecasting method to the project type for optimal results.

Study limitations and generalizability
While the findings provide valuable insights, the dataset is limited to projects executed in Egypt. Construction practices, contract types, and economic factors specific to Egypt may influence the results. Therefore, caution is needed when generalizing these findings to other regions. Future studies should validate the outcomes across different countries and construction environments to assess their broader applicability.

Conclusions
This research conducted a thorough evaluation of the Earned Duration, Earned Schedule, and Planned Value methods across 30 diverse construction projects in Egypt, covering commercial, educational, industrial, renovation, and residential sectors. The analysis focused on assessing forecasting accuracy for project completion dates based on project duration percentages, over a study period from January 15, 2015, to December 30, 2023.

Key findings show that the Earned Duration method demonstrated the highest accuracy across most performance metrics, particularly when average accuracy, performance factors set to 1, and SPI were considered. However, when performance was evaluated based on SCI, both Planned Duration and Earned Schedule outperformed Earned Duration. Sector-specific results revealed that Earned Duration was more effective for industrial, commercial, and educational projects, while Earned Schedule was better suited for renovation and residential projects.

Recommendations for practitioners:

- Use the Earned Schedule method during the early stages of projects to improve the accuracy of completion date forecasts.
- Shift to the Earned Duration method as projects progress beyond 50% completion, especially for industrial, commercial, and educational projects.
- For residential and renovation projects, prioritize Earned Schedule over Earned Duration throughout the project life cycle.
- Carefully select performance factors (SPI or SCI) based on project type and risk profile to enhance forecasting precision.

These actionable guidelines aim to equip construction project managers with practical, evidence-based strategies for selecting the most appropriate earned value technique based on project progress and type.

Future research directions should prioritize the following areas:

- Comparative evaluation with advanced techniques: Conduct structured comparisons between EVM methods and machine learning-based forecasting models to enhance predictive capabilities.
- Impact of contract and risk structures: Investigate how different contract types, risk profiles, and economic conditions influence the reliability of EVM forecasting methods.
- Exploration of Monte Carlo simulation and Bayesian methods: Assess the effectiveness of alternative probabilistic forecasting techniques relative to traditional EVM approaches.

By addressing these areas, future studies can build on the current findings to further refine project forecasting methodologies and adapt them to the evolving complexities of construction projects.

Data availability

The information utilized for the research findings is accessible upon request and is not publicly shared to uphold privacy measures. If someone wishes to request data from this study, they shall contact the corresponding author.

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Study conception and design: KN, Data collection: ME and KN, analysis: ME and IA, validation of analysis: FA, manuscript writing: ME and FA, manuscript review: KN and IA.

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The authors declare no competing interests.

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