Earned Value Management System State of Practice: Identifying Critical Subprocesses, Challenges, and Environment Factors of a High-Performing EVMS

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Abstract: For more than five decades, Earned Value Management Systems (EVMS) have been applied by organizations to manage their projects in different industries. However, many organizations still struggle to apply Earned Value Management (EVM) techniques to assess and reliably control their project outcomes. This work investigated the state of practice of EVMS. This paper identifies challenges facing practitioners, critical EVMS subprocesses, and key EVMS environment factors, based on a large survey of 294 expert respondents. Sample respondents had project management experience of greater than 20 years on average, and represented a diverse set of projects and industries (e.g., capital projects, aerospace, defense, energy, and others). The responses from this survey helped craft an agreed-upon set of definitions for EVM, EVMS, EVMS maturity, and EVMS environment that are all provided in this paper. Moreover, out of 10 total EVMS subprocesses, planning and scheduling was ranked as the subprocess with the greatest impact on EVMS, by far. When ranking the top factors that impact the EVMS environment, the following factors rose to the top: organizational culture; efficient EVMS development process; leadership's past EVMS experience; effective and accountable leadership; and quality and level of data available. Moreover, leadership attitude toward EVMS was found to be the most critical EVMS challenge, by a wide margin. Comparing different perspectives, the data showed that project/program owners consider EVM implementation costs to be a major challenge, while contractors and consultants consider adequate calendar time needed for preparing EVMS to be a critical EVMS environment factor. Overall, this paper contributes to the engineering management body of knowledge by identifying the most important subprocesses and factors of a high-performing EVMS applied to a diverse array of complex projects and programs (e.g., aerospace, defense, construction, software, etc.) and uncovering corresponding key challenges. **DOI: 10.1061/(ASCE)ME.1943-5479.0000925.**

Introduction

An Earned Value Management System (EVMS) is a project management tool or method that is widely used and applied in many industries including infrastructure, residential, telecommunications, construction, and oil and gas (Sruthi and Aravindan 2020; Sutrisna et al. 2020; Widiningrum et al. 2020; Demachkieh and Abdul-Malak 2018; Baker 2015; Dinsmore and Cabanis-Brewin 2014; Kim et al. 2003). Therefore, various industry organizations and experts have defined EVMS to serve different purposes in their project management efforts (McGregor 2019; DoE 2018b; ISO 2018; NASA 2018; NDIA 2018c; Humphreys 2018; DoE 2012). For example, Humphreys (2018) defined EVMS as "a set of processes and tools used to facilitate the management of a project." Another example is "an integrated set of policies, procedures and practices to objectively track true performance on a project or program. EVMS represents an integration methodology that is able to provide an early warning of performance problems while enhancing leadership decisions for successful corrective action" (DoE 2018b). Please note that although the terms "project" and "program" are both addressed in this study, the authors use the term "project" in this paper for brevity.

In this study, EVMS maturity is a measure of the degree to which an EVMS complies with standards and guidelines encompassing the following 10 core EVMS subprocesses: organizing; planning and scheduling; budgeting and work authorization; accounting considerations; indirect budget and cost management; analysis and management reporting; change control; material management; subcontract management; and risk management (NDIA 2020, 2018b). In contrast, EVMS environment is complementary to maturity; the assessment of EVMS environment encompasses more qualitative factors that can impact EVMS applications, such as culture, people, practices, and resources. Many studies indicate that the environment of EVMS implementation and execution is significant for successful project management (e.g., Bryde et al. 2018; Orgut et al. 2018; Kim et al. 2003). Examples include team's past experience and communication effectiveness. The Project Management Institute (PMI 2018) estimates that 9.9% of every dollar spent on a project is wasted due to poor project performance. A number of studies have demonstrated the importance of effective EVMS application for managing and controlling cost

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and schedule performance, to increase the likelihood of project success (e.g., Bryde et al. 2018; Bowman and Sabouri 2014).

EVMS is also referred to as integrated cost and schedule control (Batselier and Vanhoucke 2015). Evaluating project controls compliance against Cost and Schedule Control System Criteria (C/SCSC) has been a common practice performed by US government organizations since 1967 (Christensen 1998). It was at that time that the US Department of Defense (DoD) started to assess whether its contractors' project management control systems were in compliance with the system criteria, and hence checked the effectiveness of their systems for selected contracts (Christensen 1994). EVM was used as a policy, and evolved from earlier concepts such as the Program Evaluation Review Technique (PERT) (Abba 2017; Driessnack 2017; Humphreys 2016; Morin 2016; Abba 2000; Christensen 1994; Fleming and Ervin 1962). Since the 1960s, guidelines and standards, such as the 35 C/SCSC specification standards, became the fundamental references for EVMS application (Fleming and Koppelman 2010). Furthermore, when defining EVMS, Fleming and Koppelman (2010) stated that "any management control system which satisfies the 32 criteria as specified in the ANSI-EIA Standard 748 (ANSI-EIA 748) will represent a full and robust earned value system." Also, the National Defense Industrial Association (NDIA 2018a) stated that compliance with its guidelines is essential for effective EVMS application. Because guidance is needed for effective EVMS application, many agencies have published EVMS guides and standards to assist professionals in improving EVMS applications (e.g., GAO 2019; McGregor 2019; DoE 2018a; ISO 2018; NASA 2018; NDIA 2018b; PMI 2019). One example is the compilation of 32 EVMS guidelines by NDIA (2018b).

On many projects, especially large government projects, the customer requires contractors to comply with a specific set of guidelines, and in some cases their EVMS is to be certified (DoE 2018a; Crowe and Basche 2011). The EVMS compliance assessment methods and instruments must be clearly defined, defendable, and result in clarity and consistency to position a given project for success (DoE 2018a, 2013). Compliance is based on an understanding of best practices. Further publications around best practices have supported the reliability of EVMS application (PMI 2017; AACE 2016; GAO 2015; Garrett et al. 2006; AACE 2014a, b). Practices for using EVMS as a reliable and accurate schedule forecasting technique can also enhance project success (Martens and Vanhoucke 2020; Chang and Yu 2018; Leon et al. 2018; Lipke 2017). Many previous studies have also focused on issues related to monitoring and forecasting cost using EVMS (e.g., Kim and Pinto 2019; Kim 2016; Mortaji et al. 2015; Kim and Reinschmidt 2011). Another successful project management practice is for the EVMS to take into account and integrate the risk management process (Nouban et al. 2020; Kim and Pinto 2019; Babar et al. 2017; APM 2008; Solomon and Young 2007).

Moreover, data-driven compliance metrics are becoming more prevalent, resulting in a need to define and quantify their characteristics and tests, to help assess the reliability of the project's integrated EVMS and its degree of accuracy (DoE 2018a; Djali et al. 2010). Data-driven compliance metrics are predefined sets of criteria or attributes of a system tied to compliance to standards and guidelines, similar to key performance indicators (Djali et al. 2010).

This paper also builds on work outside the EVMS realm. Several examples from other industries indicate the importance of metrics-based approaches to assess process maturity. One such application is in the Front-End Planning (FEP) literature for large industrial projects, entitled the Project Definition Rating Index (PDRI) Maturity and Accuracy Total Rating System (MATRS) (Yussef et al. 2019, 2018). This work found that the maturity of the FEP process and its environment are strongly correlated with project success.

The ultimate objective of the current work is to develop a structured and proven method to assess the two dimensions, EVMS maturity and EVMS environment, which is aimed at improving project performance for organizations using this method. However, EVMS maturity and environment assessments do not yet exist. As a critical step toward developing assessments of these two dimensions, this paper's specific objective is to investigate the state of practice of EVMS in diverse industries, particularly focused on identifying critical EVMS subprocesses and environment factors through a large survey of expert practitioners. Other objectives of this work are to understand EVMS's role in improving project success and EVMS compliance assessment practices in use, and to lay a strong foundation to develop a more comprehensive method for evaluating the efficacy of EVMS.

Literature Review

A literature review was conducted to provide an in-depth understanding of the existing EVMS body of knowledge, as well as gaps in the EVMS literature. Furthermore, the review informed the development of key definitions for the study, while also providing critical input into the industry survey. The literature review is divided into two areas of investigation that are related to the current work.

EVMS Maturity

The concept of maturity originated with the Software Engineering Institute in 1989 to improve the effectiveness of the software-building process and software quality (Humphrey 1989). Similar maturity models were later adapted in other areas such as quality management, human resources, knowledge management, project management, lessons learned systems, FEP, and safety (Hartono et al. 2019; Pinto 2019; Yussef et al. 2019; Goncalves Filho and Waterson 2018; Kerzner 2017; Andersen and Jessen 2003; PMI 2013; Caldas et al. 2009; Crawford 2001; Gareis and Huemann 2000). Only one reference that presents a maturity model for EVMS was found in the literature: Stratton (2006) proposed a scalable approach to maturity that can be used to assess the application of EVMS, including compliance with guidelines, which creates an opportunity to address the knowledge gap in EVMS maturity.

EVMS Environment

Beyond maturity, the literature review unveils issues related to EVMS environment. Previous studies have looked at the environment factors that impact the effectiveness of EVMS application. These include project controls experience (Wolf 2014), project management ability (Weaver 2016), culture (King 2018), communication (McNamee and Immonen 2019; Turner and Müller 2004), EVM technical knowledge (Kim 2000), effective decision making (Bolinger and Phillips 2018; Younossi et al. 2005), accurate and timely data (Shi 2019; Hunter et al. 2014), technology tools (Weaver 2016), and lack of engagement (Kim 2000), among many others. In the EVMS knowledge area, some specific EVMS environment factors have been investigated; however, there is a need for a comprehensive EVMS environment factor compilation made up of key factors around which an assessment method can be designed.

Previous studies have also looked at environment factors beyond EVMS, focused on other project processes, such as FEP,

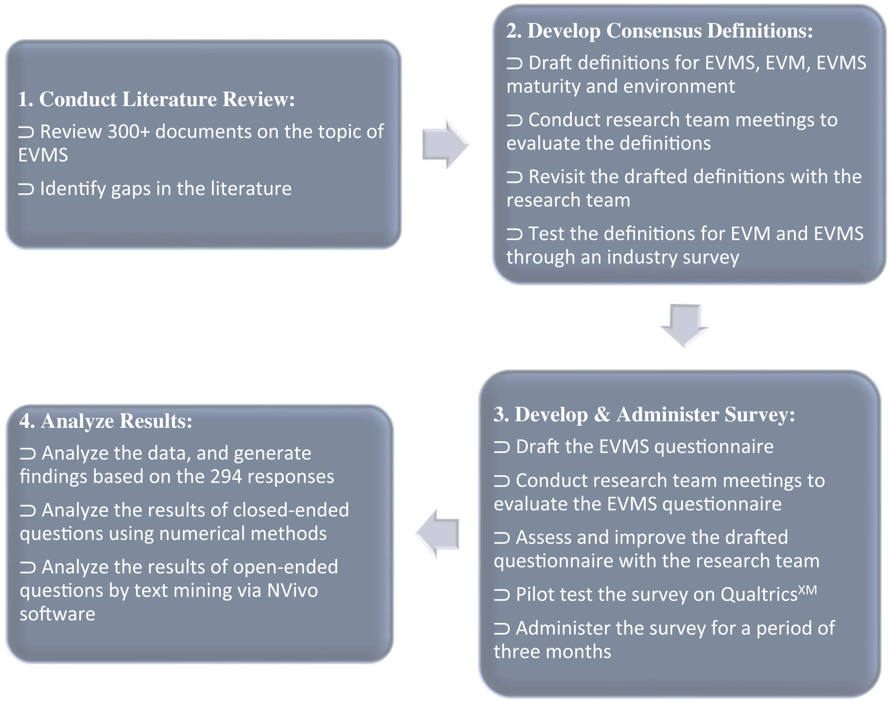

Fig. 1. Research method.

front-end engineering design, and team alignment (e.g., Yussef et al. 2020, 2019, 2018; ElZomor et al. 2018; Collins et al. 2017a, b). To develop the survey questions related to EVMS environment, the authors leveraged the environment factors found in the literature and adapted them to EVMS. These EVMS environment factors need to be taken into consideration in parallel with EVMS maturity.

Literature Review Findings and Gaps

The literature review revealed a large body of knowledge on EVMS, covering topics such as forecasting, predictability, practices, and guidelines (Cho et al. 2020). However, gaps exist in the literature with respect to EVMS maturity and environment. First, there is a gap in methods to assess EVMS maturity. Second, although EVMS environment factors are widely discussed, there is neither a comprehensive listing of key factors nor an assessment method to gauge EVMS environment factors. The literature review was critical to identify these gaps, develop common terminology and definitions, and design the industry survey.

The application of EVMS requires both developing the system itself (i.e., technical effectiveness) and effective interactions with the system (i.e., human inputs). Focusing on the system while excluding the human factor leads to poor system performance. The approach used in this work is similar to that used in "sociotechnical systems design" methods, underlying the overall functionality of a system, considering human, organizational, and technical factors to understand how the system works and how the work is done (Baxter and Sommerville 2011; Bider and Klyukina 2018).

Research Objectives and Methods

Given the lack of insight in the literature on assessing maturity and environment of EVMS, documenting the industry's EVMS state of practice around maturity and environment can significantly contribute to the body of knowledge. Therefore, the objectives of this paper are to

1. align the definitions of EVM and EVMS that can be used in various industries;
2. determine the industry's state of practice on EVMS maturity assessment;
3. gauge the industry's state of practice around EVMS implementation in terms of challenges, subprocesses, and environment; and
4. identify strategies that organizations employ to mitigate EVMS deficiencies or to take advantage of opportunities for improvement.

To achieve these objectives, the research method shown in Fig. 1 was developed and followed.

Step 1: Conduct Literature Review

A thorough literature review was conducted to investigate the existing knowledge based on EVMS and offer a solid basis for key definitions and development of the survey. The authors referred to the various sources in the literature to form the basis for definitions of EVM and EVMS. The authors adapted the definitions of the terms "maturity" and "environment" from various studies to EVMS. This work also used the industry survey developed by Yussef et al. (2020) as a reference point to draft the questionnaire, by adapting it to EVMS. The goals of the survey included testing the research team's working definitions and documenting the industry's state of practice while highlighting challenges around EVMS.

The library databases and search engines of Google Scholar, Science Direct, Elsevier, Measurable News by the College of Performance Management, American Association of Cost Engineering (AACE), PMI, and American Society of Civil Engineers (ASCE) were used to search the following keywords: EVM, EVMS, maturity, environment, and EVMS assessment models.

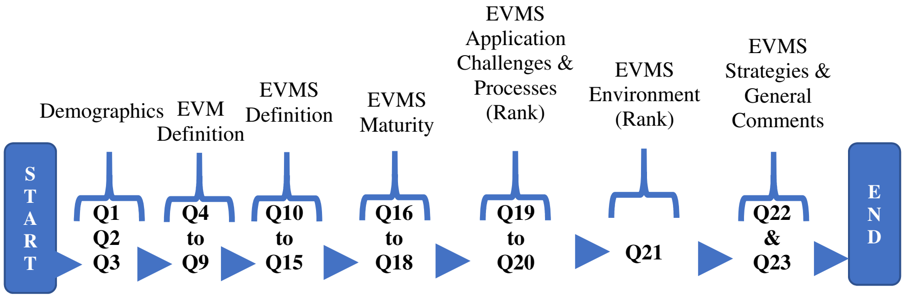

Fig. 2. Survey flow and type of questions.

Early findings of the literature review were published by the authors (Cho et al. 2020).

Step 2: Develop Consensus Definitions and Terminology

The literature contains organization-specific documents that have defined EVM, EVMS, and related terms. The authors integrated the definitions of various organizations (e.g., McGregor 2019; ISO 2018; NASA 2018; NDIA 2018c; Humphreys 2018; DoE 2012) with feedback from the research team. Because definitions for EVMS maturity and EVMS environment did not exist in the EVM/EVMS literature, and as they are both critical to this work, definitions for maturity and accuracy previously used in the FEP process literature were leveraged and adapted to EVMS (Cho et al. 2020; Esnaashary Esfahani et al. 2020; Yussef et al. 2019).

The outcomes from the literature review regarding definitions and terminology were presented to the research team of 27 industry experts established to oversee this research investigation. The research team represented 16 owners and 11 contractors from governmental and nongovernmental organizations, as well as the four authors representing the academic perspective. Research team members had average industry experience of 20 years. The industry fields they represented included energy, military, nuclear, security, chemical waste, aerospace, infrastructure, industrial, engineering, and manufacturing. The research team members' positions included project controls director, director of program controls, chief operations officer, program management vice president, program manager, program analyst, earned value manager, and others.

With three in-person group meetings between the academic researchers and the industry team members, the definitions for EVM, EVMS, maturity, and environment were reviewed and evaluated with valuable inputs. The authors facilitated the group meetings using brainstorming techniques focused around the definitions. The sessions were also supported by followup conference calls and individual reviews. The research team agreed on the following key definitions:

- EVM is the use of performance management information, produced from the EVMS, to plan, direct, and control the execution and accomplishment of contract/project cost, schedule, and technical performance objectives.
- EVMS is an organization's management system for project/program management that integrates a defined set of associated work scopes, schedules, and budgets for effective planning, performance, and management control.
- EVMS maturity is the degree to which an implemented system, associated subprocesses, and deliverables serve as the basis for an effective and compliant EVMS.
- EVMS environment is the degree of confidence in the outputs of the EVMS, associated subprocesses, and deliverables that serve as a basis for effective program/project management and decision making.

The aligned definitions of EVM and EVMS were later tested through the survey with industry professionals for validation purposes, with outcomes provided later in this paper. The authors sought consensus and clarity around the terminology, with the goal of helping to improve alignment on common understanding across the research team and the diverse industry sectors. It should be noted that in some cases, the terms EVM and EVMS are inaccurately used interchangeably; EVM and EVMS are not the same. Based on the definitions presented earlier, EVM is a project management technique used to measure project performance and progress based on information produced from the EVMS, whereas EVMS is the overarching system and interconnected tools and processes that produce that information.

Step 3: Develop and Administer Survey

The survey was developed based on the findings from the literature and research team meetings. The survey consisted of 23 questions. Initial questions requested that respondents voluntarily fill in their names, organizations, phone numbers, and email addresses. Demographics included the respondent's type of employer, employment role, and number of years of career experience in the industry. The demographic information proved useful later when analyzing the results, because it enabled a study of the different perspectives in the data by demographic category of the respondents. The next two questions were focused on testing the developed definitions of EVM and EVMS. The following questions of the survey focused on EVMS maturity, then EVMS environment aspects, through rank ordering. These ranking questions revealed the most challenging aspects, subprocesses, and environment factors that impact EVMS effectiveness. The development of the ranking questions' methodology is based on the literature on the Nominal Group Technique, allowing the determination of top preferences through rank-ordering of discrete choices (McMillan et al. 2016, 2014). The last two survey questions were open-ended questions focused on strategies for improvement of EVMS applications, as well as general comments on EVMS assessment. Fig. 2 helps visualize the survey and its different sections.

The draft version of the survey was pilot-tested internally by 27 members of the research team. All the issues identified in the pilot were addressed, and improvements were made as a result. The survey was then distributed electronically via Qualtrics through different external channels. The survey was targeted at professionals representing owners, contractors and consultants, with a significant amount of industry experience and knowledge of EVM, EVMS, and project management. Data confidentiality requirements were followed, allowing anonymity of respondents. The survey was used to collect as much data as possible from practitioners.

A convenience-sampling strategy was selected, given that obtaining a sample representative of the overall population of practitioners was impossible. To obtain a representative sample of EVM practitioners that would provide a rich dataset, the authors, with help from the research team, aimed to collect a large number of responses, targeting various types of organizations, governmental and nongovernmental, inside and outside of the United States. The survey was open for response for a 3-month period to several hundred industry professionals from the USDOE, USDoD, NDIA, PMI, US Government Accountability Office (GAO), the National Aeronautics and Space Administration (NASA), the Energy Facility Contractors Group (EFCOG) and others.

Step 4: Analyze Results

Different approaches were used when analyzing the survey results, depending on the type of the survey question (demographics, closed-ended questions, or open-ended questions). The purpose of the demographics questions was to add credibility to the data collected and to be used for internal comparisons. A quantitative analysis was applied on the ranking questions. The quantitative analysis method applied numerically measures the relative weight of given factors, to rank the top factors relative to one other. Eq. (1) shows the relative weighted average calculation of factors

$$\overline{x_n} = \frac{\sum_{i=1}^{n} w_i x_i}{N \times \text{mean score} \times \text{rank choices}} \quad (1)$$

where $\overline{x_n}$ = weighted average; w_i = frequency of answer; x_i = score of answer; and N = total number of responses.

For example, out of 277 respondents [N in Eq. (1)], 177 respondents [w_i in Eq. (1)] ranked the factor, "Leadership/manager attitudes toward EVMS," when asked to rank the top three most challenging factors that affect EVMS. These ranks were put into a spreadsheet, and each rank was translated to an importance score. Factors ranked first in terms of challenge received a score of 3, factors ranked second received a score of 2, third received a score of 1, and factors that were not ranked received a score of 0. Scores were then aggregated across all respondents, and an average score for each of these factors was generated. The "Leadership/manager attitudes toward EVMS" factor received a score of 2.401 [x_i in Eq. (1)]. Eq. (1) was then used to calculate the relative percentage weights for all factors [$\overline{x_n}$ in Eq. (1)]. In the case of the "Leadership/manager attitudes toward EVMS" factor, the result was 25.6% {the result of $[177 \times 2.401]/[277 \times 2 \times 3]$}. All the factors' relative percentage weights sum to 100.

Furthermore, the authors performed normality tests and applied the Mann–Whitney U test to check internal consistency of respondents when ranking the responses. It was used for comparing two different subgroups. First, the perspectives of respondents representing government owners were compared with those of other respondents, including contractors and consultants. Second, the perspectives of respondents with career experience greater than 25 years were compared with those of less-experienced respondents. The results of both tests are provided in the results section of this paper.

A qualitative analysis approach was used to analyze the results of open-ended questions. The selected approach was considered because there was a need for deeper understanding of the rich information provided in text format by participants (Bazeley and Jackson 2013). The open-ended answers were specifically analyzed based on a content analysis using NVivo version 12 Plus software— first, coding was conducted, then querying the most repeated keywords or words, and then developing frequency counts to extract valuable insights on the study (Chen and Jin 2013). The software enabled the authors to manage data easily and increase the speed of analysis of the large dataset (AlYahmady and Al Abri 2013; Creswell 2013; Hoover and Koerber 2011). In general, the analysis process for each of the open-ended questions was adopted from Creswell's data analysis steps (Creswell 2013), and adapted as illustrated in Fig. 3 and as follows:

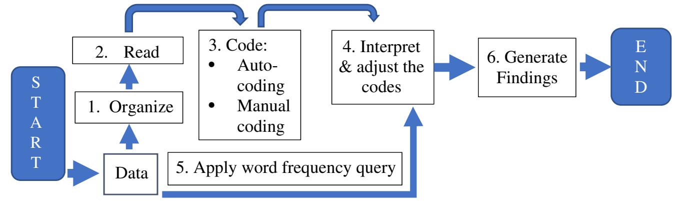

Fig. 3. Analysis process for open-ended questions.

1. Organize the collected data;
2. Read all the data to get a sense of all of the existing information;
3. Describe, classify, and interpret data into codes and themes;
4. Interpret the codes further and convert them into verbal statements;
5. Apply word frequency query as a support to coding, to ensure that the most common themes were captured; and
6. Record the themes and generating findings.

The authors applied autocoding and manual coding to conceptually label abstract ideas found in the data (Corbin and Strauss 1998). Moreover, following Hoover and Koerber (2011), who emphasized the need for careful reading of every response to improve the quality of the findings, the authors read all the data and adjusted the codes manually. Reading all the data improves the analysis (Strauss 1987), which also included a comparative analysis to look at each response versus all the codes that emerged to avoid repetitions and overlaps (i.e., constant comparison).

Survey Results and Findings

After the completion of the survey, the authors compiled the data and analyzed it statistically. The sections below provide information about the respondent characteristics, followed by discussions of the various results focused on EVM and EVMS definitions; EVMS maturity, looking at its subprocesses; implementation challenges; EVMS environment; and opportunities and strategies to improve EVMS applications.

Respondents

The survey was distributed to EVMS experts in both government and industry, through professional organizations and conferences including NDIA, EFCOG, DoE Project Management Workshop, PMI, GAO, Office of Management and Budget, and others. A total of 294 usable responses were returned. Among them, 201 respondents identified the name of the organization they represented; a total of 92 organizations were represented. Figs. 4–6 provide the breakdown of the respondents' characteristics in terms of organization type, employment role, and years of experience.

As shown, almost half of the respondents were representatives of government contractors (49%), and the second highest group represented consisted of government agencies (36%). The majority of respondents (64%) had roles in project/program management or controls. More than half of the respondents had more than 25 years of experience. With widely diverse respondent characteristics from both owner and contractors, the study could obtain extensive knowledge from the survey findings.

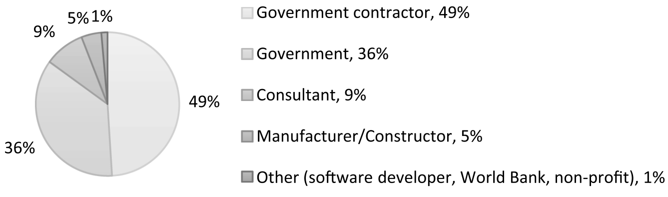

Fig. 4. Survey respondent characteristics: employer type (N = 294).

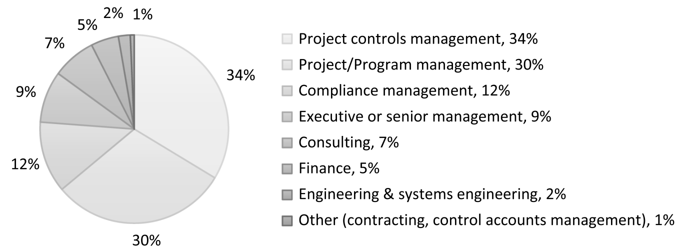

Fig. 5. Survey respondent characteristics: employment role (N = 294).

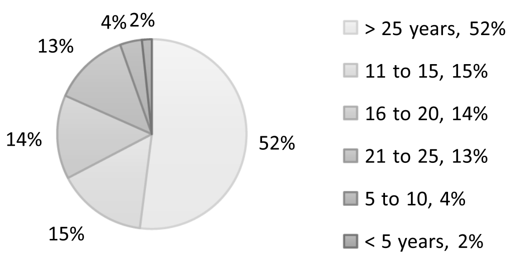

Fig. 6. Survey respondent characteristics: years of experience (N = 294).

Table 1. Results on definitions (N = 294)

	Respondents' organizations having standard definitions		Respondents agreeing with this study's definitions	
Answer	EVM	EVMS	EVM	EVMS
Yes (%)	82	77	82	85
No (%)	18	23	18	15

EVM and EVMS Definitions

The respondents were first asked whether their organizations have standard, organization-specific definitions for EVM and EVMS. Next, they were asked whether they agree with this study's working definitions of EVM and EVMS. The results are shown in Table 1.

As shown, 82% of respondents indicated that their organizations have a standard internal definition for EVM. Similarly, 77% of respondents reported that they have standard internal definitions of EVMS. This finding implies that the majority of the respondents are aware of their organization's standard definitions. The respondents whose organizations had standard definitions for EVM and

Table 2. Feedback on EVM working definition

Comment	Frequency
The definition should address measuring of status and progress against a plan.	9
Forecasting is missing from the definition.	8
Rethink use of the word "control" in the definition.	5
Risk should be included in the definition.	4
EVM is a tool, but it is not the only tool as implied in the definition.	4

EVMS were also asked to provide those definitions in the survey. These definitions differed from one organization to another, but there was commonality among certain terms and ideas. As also shown, 18%–23% of the respondents reported that their organizations did not have standard definitions for either EVM or EVMS or both. Lack of definitions can cause misunderstanding, failure to meet expectations, and difficulty in application of EVMS among stakeholders. Having standard, consensus definitions should allow communication to start from a common point, support alignment in understanding, and unify perceptions, ultimately obtaining the full benefits of the practice.

Moreover, 82% of respondents agreed with the definition of EVM developed as part of this study, and 85% of respondents also indicated agreement with the definition of EVMS. As a large majority of the respondents agreed with both working definitions, the authors and research team considered the working definitions to be valid, with minor changes needed for improvement. Respondents who did not agree with the study's definitions were asked followup questions about the reasons for their disagreement and how the definition could be improved. The feedback received on both definitions was reviewed and analyzed. Table 2 lists some of the top reasons that respondents disagreed with the provided EVM definition, along with associated response frequencies.

The analysis of these results informed the authors and the research team of some minor changes that were needed—specifically, to emphasize performance measurement against a plan, and to include the concept of forecasting. Other comments were also considered. The new definition of EVM was modified as follows:

> EVM is the use of performance management information, produced from the EVMS, to plan, direct, control, and forecast the execution and accomplishment of contract/project cost, schedule, and technical performance objectives versus the plan.

Similarly, Table 3 represents top reasons for which respondents did not agree with the provided EVMS definition.

The analysis of these results shows that an improvement can be made by incorporating "integration with other systems" in the definition. Other comments were also considered. The new definition of EVMS is as follows:

> An EVMS is an organization's management system for project/program management that integrates a defined set of associated work scopes, schedules and budgets for effective planning, performance, and management control; it integrates these functions with other business systems such as accounting and human resources, among others.

The survey results also showed that 43 of 291 respondents (15%) use other terms for EVM; the most common of them are integrated program management, integrated project management, program performance management, program controls, and project

Table 3. Feedback on EVMS working definition

Comment	Frequency
Missing notion of integration with other systems or processes in the definition.	11
The definition should include reference to EIA-748's 32 guidelines or other standards.	7
Decision making is missing from the definition.	4
The definition should indicate that EVMS is a tool to measure performance as well.	4
The word "objective" or to "objectively" measure performance is missing in the definition.	4
The phrase "associated work scopes" is not clear.	4
Notion of risk management or risk is missing from the definition.	4

Table 4. Entity that conducts EVMS maturity evaluation

Entity that conducts the EVMS maturity evaluation	Percentage
EVMS SME or organization's EVMS office	42
Client/customer/owner	21
Third-party peer review	15
Contractor	13
Consulting review	9
Total	100

controls. Additionally, 19 of 284 respondents (6%) use other terms for EVMS, the most common being integrated program management system, performance management system, and project controls system.

EVMS Maturity

This section discusses the survey results related to the maturity of EVMS. Out of 280 respondents to this question, the majority (72%) reported that their organizations do not evaluate EVMS maturity. Only 79 respondents (28%) reported that their organizations evaluate the maturity of EVMS. Out of these, 55 use an internal proprietary maturity model or framework and 24 use a consulting organization's maturity model or framework. The respondents who reported that their organizations evaluate EVMS maturity were asked about the entity that typically conducts the evaluation, and were instructed to check all the options that apply. The results are shown in Table 4.

The organizations that evaluate maturity rely largely on subject matter experts (SMEs) to perform the evaluation. This result highlights the need for an objective EVMS maturity evaluation tool for identifying issues in EVMS application and that could be used by a wide range of project stakeholders, not only SMEs.

EVMS Maturity and Subprocesses

To address the maturity of an organization's EVMS, the authors started with the widely used NDIA guides as a foundation to develop the question related to EVMS maturity (NDIA 2020, 2018b). The question focused on the nine subprocesses that make up EVMS according to these sources, while also adding risk management as a 10th subprocess. Fig. 7 shows the results of the respondents' ranking of the top three core EVMS subprocesses that have the highest impact on EVMS effectiveness. Based on the results of this survey item, the authors determined that an effective way to gauge EVMS maturity is by evaluating the maturity of each of the EVMS subprocesses.

"Planning and scheduling" was ranked as the subprocess that had the highest impact on EVMS effectiveness, by far, versus the other EVMS subprocesses. In fact, the NDIA EIA 748-D *Intent Guide* has the highest number of guidelines (10) on planning and scheduling, which reflects the importance of this subprocess (NDIA 2018b); and, in our survey, 156 survey respondents considered planning and scheduling the most important and having the highest impact on EVMS effectiveness, while 74 other respondents considered it either the second or third most-important subprocess. This finding matches those of Chen et al. (2020), Moylan (2002), and Haugan (2001), showing the same subprocess to be highly critical for project management success. The criticality of this subprocess may be due to the fact that it requires integration with all other subprocesses (Moylan 2002). Planning and scheduling is often considered the most important factor for project success because it guides the execution of the project, reduces uncertainty, provides a basis for controlling the project, and clarifies objectives to all stakeholders (Haugan 2001). Overall, the top two subprocesses represent more than half of the total weight for impacting EVMS effectiveness, and the top five subprocesses represent more than 80% of the overall weight. The top five are planning and scheduling, change control, management analysis, risk management, and budgeting and work authorization.

When the results were compared based on the type of respondent (i.e., owner, contractor, etc.), there were no statistically significant differences found between owner responses and others.

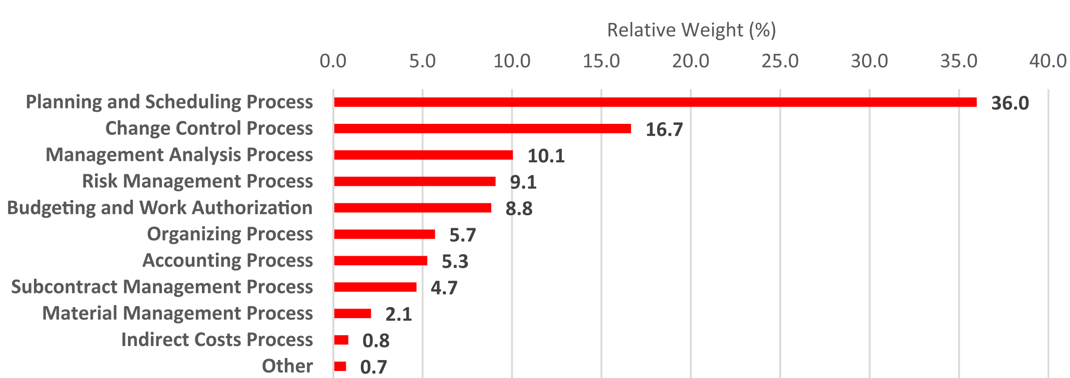

Fig. 7. Top EVMS subprocesses with the highest impact on EVMS effectiveness (N = 275).

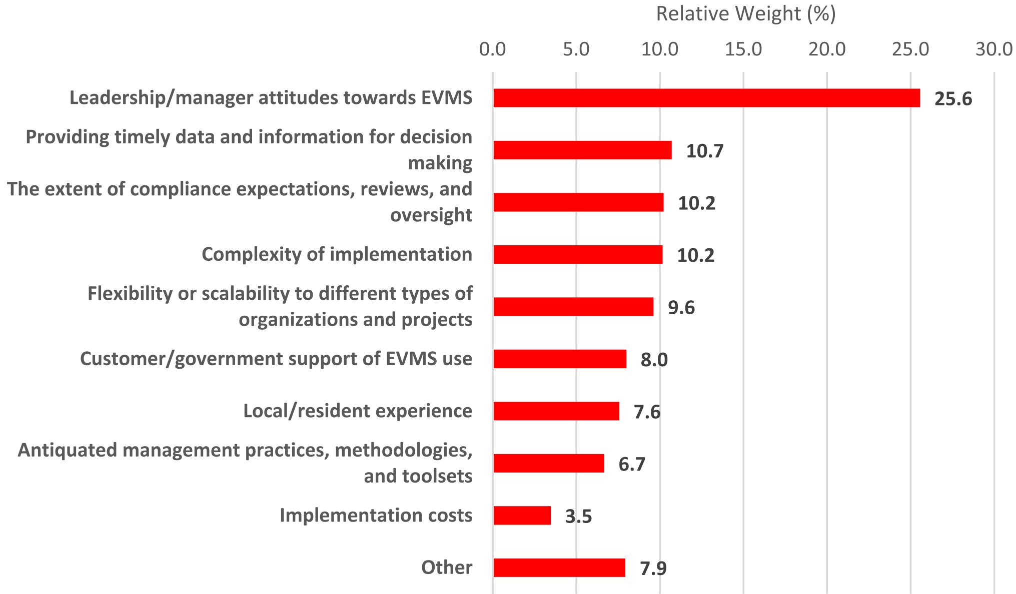

Fig. 8. Top challenging aspects of managing a project/program using EVMS (N = 277).

However, some statistically significant differences were found when comparing the results based on respondent experience. Those differences were found when analyzing the "organizing" subprocess ($U = 144.00$; $p < 0.05$) and the "material management" subprocess ($U = 36.5$; $p < 0.05$). Respondents with more than 25 years of career experience were significantly more likely to consider organizing as having a higher impact on EVMS effectiveness, versus respondents with less career experience. Conversely, less-experienced respondents are more likely to consider material management as having a higher impact on EVMS effectiveness, versus more experienced respondents.

EVMS Challenges

After gauging terminology and EVMS maturity by subprocess, respondents were asked to rank the top three most challenging aspects of managing a project/program using EVMS. The authors provided a list of nine potential answers based on the literature review and research team input. Interestingly, every challenge identified was related to EVMS environment factors; there were no identified top challenges that were maturity related. This strengthened the authors' interest in investigating this new aspect of EVMS, the dimension that considers the environment or context in which the EVMS operates. Eq. (1) was applied on the results to convert ranks into the percentage weights shown in Fig. 8.

A project's leadership is made up of individuals who assume management roles giving them the ability to influence and direct the project team members. Overall, respondents ranked "leadership attitude toward EVMS" as the most critical challenge in EVMS application, by a wide margin. In response to the request for general comments at the end of the survey, multiple comments were also about leadership. Respondents emphasized the need for the right support of leadership, including accountability and commitment. Leadership commitment represents the sense of obligation toward managing project resources for effective EVMS application leading to effective project execution, and accountability means placing responsibility on the leaders for the results of EVMS application. This result is in line with many past studies that highlighted the importance of leadership to project success, and showed that lack of top management support for EVMS can be a key obstacle to an effective EVMS (e.g., Zhan et al. 2019; King 2018). According to the authors of these studies, leadership plays a critical role in setting up a conducive culture, providing resources, establishing and overseeing practices and processes, and assigning the personnel to implement and execute the EVMS for a project. This cannot be achieved without the leadership's support. In fact, culture was found to be the top EVMS factor that affects the EVMS environment, as shown in the next section. According to Hazy (2006), leadership cultivates the right culture to achieve the project's objectives. Hazy (2006) stated that project leadership should assume the role of increasing a system's effectiveness by encouraging the team members to use the system, and improving the flow of resources and resource capabilities within the system.

Furthermore, the survey uncovered four other challenges that each generated around 10% of the total weight: providing timely data and information for decision making; the extent of compliance expectations, reviews, and oversight; complexity of implementation; and flexibility or scalability to different types of organizations and projects. Together, these top five challenges represent almost two-thirds of the overall EVMS challenges based on this question. Interestingly, of the nine aspects evaluated by the respondents, the cost of implementation was the aspect least viewed as a challenge. Other challenges identified by respondents included project stakeholders' knowledge and understanding of EVMS, inconsistent EVMS tool application, compliance review challenges, and failure to enforce standards.

The results were analyzed further by type of respondent. Owner respondents ranked the EVMS challenges slightly differently than did other respondents, but most of those differences were not statistically significant. However, a factor where the differences between owners and other respondents were statistically significant was implementation costs. Owner respondents were significantly more likely to consider implementation costs to be a major challenge ($U = 87.00$; $p < 0.05$). This result is particularly interesting because this challenge was ranked the lowest collectively by all respondents, possibly because the respondents are more focused on the benefits of EVM and EVMS, which outweigh the

Fig. 9. Top factors that can impact the EVMS environment (N = 272).

implementation costs (Bembers et al. 2015; Hunter et al. 2014; Christensen 1998). Ranking of implementation costs as the lowest challenge overall is in line with the work of Kratzert and Houser (2011), which noted that EVMS implementation costs should not be considered an obstacle for government and contractors. Aside from this one factor, respondents did not have significantly different perspectives regarding EVMS challenges, regardless of their role as owner, contractor, or consultant. The same can be said of less-experienced versus more experienced subgroups—no significant differences were found between their responses. Regardless of their background, respondents agreed on the top EVMS challenges identified in this paper.

EVMS Environment

One interesting finding in the previous section is that some of the key challenges identified were not related to EVMS maturity (i.e., subprocesses), but instead to other contextual factors such as leadership and customer support of EVMS use. This section focuses on these EVMS environment factors. The respondents were asked to rank the top five factors that impact the EVMS environment in order of importance, out of a list of 18 factors identified in the literature. The results are presented in Fig. 9.

The top five factors were close in weight and represent about 50% of the overall weighting. These factors are "Organizational culture fosters trust, honesty and shared values"; "Organization follows a standard EVMS development process"; "Leadership's previous experience"; "Defined, effective and accountable leadership,"; and "Quality and level of data available." The analysis of these results shows that several of the top-rated EVMS environment factors are related to culture (e.g., trust, leadership, communication). This finding is in line with the literature, which shows organizational, culture-related problems being perceived by project stakeholders as critical (Westrum 2004; Kim et al. 2003).

Statistical comparison of environment factor rankings between owner and contractor respondents resulted in no significant differences, implying that respondents, regardless of their roles, generally have similar perceptions about EVMS environment factors. The only exception is one factor for which statistically significant differences were found: Respondents from owner organizations were significantly less likely than other respondents to consider "Calendar time allowed for preparing EVMS and management tools available including technology/software" to be a critical EVMS environment factor ($U = 96.50$; $p < 0.05$). The reason may be that it is the contractor's task to prepare the EVMS and use the software to provide the owner with the EVMS data and results; therefore, contractor respondents would highlight the need for more calendar time to prepare the EVMS results.

When comparing responses of less-experienced and more-experienced respondents, no significant differences were found except for one factor: "Leadership team's previous experience planning, designing and executing an EVMS on a project/program of similar size, scope, and/or location." Respondents with more than 25 years of experience were significantly more likely to rank this factor higher than those with less career experience ($U = 1,385.00$; $p < 0.05$). The reason may be that more-experienced respondents have spent more time and have better knowledge of executing EVMS on projects of similar sizes, scopes and locations, and therefore can better gauge the impact of such experience.

Opportunities to Improve EVMS

Toward the end of the survey, respondents were asked to provide strategies that their organizations employ to mitigate EVMS deficiencies or to take advantage of opportunities for improvement. As previously discussed, the results were analyzed using the NVivo software. A total of 21 strategies were identified. The top six strategies by frequency included the following: EVMS surveillance (74 responses); EVMS reviews (28 responses); compliance with EVMS guidelines and standards (28 responses); project team's proactive engagement and EVMS experience (22 responses); corrective actions (21 responses); and contractor's engagement in EVMS (20 responses).

Using internal, external, periodic, and planned EVMS surveillance was the top strategy by far. EVMS surveillance is the assessment of the system to ensure it produces "reliable, accurate, and timely information that is used to effectively manage cost, schedule, and technical performance, and in making informed decisions" (DoE 2013). It is critical that these reviews be periodic and planned to highlight the fact that this is a disciplined process. According to the survey responses, internal EVMS surveillance is when the project or program manager is the focal point for planning regular EVMS assessments, whereas external EVMS surveillance is when reviews are conducted with customers, consultants, or other SMEs outside of the project team.

Finally, in the last survey question, the respondents were asked to share any other general comments on EVMS assessments. The results were again analyzed using the NVivo software, and 23 different types of comments were received. The top six answers by frequency included the need for a proper application and use of EVMS (13 responses); the importance of the team having adequate EVMS knowledge and experience (13 responses); the need for an effective and improved EVMS assessment (13 responses); the importance of having objective, reliable, timely, sufficient, and accurate EVM data (12 responses); the importance of specific roles of the owner including assessing compliance, future performance prediction, and use of EVMS as early as possible in the project lifecycle (12 responses); and the importance of the contractor's engagement in EVMS through compliance (12 responses).

Limitations

The authors acknowledge that this study has some limitations. Every opportunity was taken to reduce bias, but the sample was based on convenience sampling of EVMS experts, and thus biases may exist within the respondent pool. Although respondents did have fairly balanced demographics, government and government contractors represent about 75% of respondents. Some government-centric biases may be present; however, many of the same government contractors also work extensively for private-sector owners using EVMS. The scope of the survey was intentionally limited to capture the issues at the system macro-level (which is where the gap is) rather than the micro-level within each subprocess (e.g., estimating, scheduling, and so on, where the literature is a lot richer). For example, project scope-related EVMS issues were not studied, nor were detailed estimating issues; and while they can all certainly have a significant impact on the efficacy of any project, they were not considered critical to this exploratory paper. This also allowed the authors to reduce the survey size and reach a broader set of respondents. The results presented are based on a large convenience sample, but caution should be taken when applying the results, as they may or may not be fully representative of the overall population.

Conclusion and Recommendations

This work was based on an EVMS literature review, expert research team meetings with 27 EVMS industry experts, and an industry survey with a sample of 294 respondents. The literature review provided a backbone for the study by highlighting gaps, informing the development of EVM and EVMS definitions, and providing a basis for developing the industry questionnaire. Together, the literature review and survey responses allowed the authors to explore and assess the state of knowledge on EVMS theory and practice.

The majority of the respondents agreed with the researchers' definitions of EVM and EVMS, and provided valuable feedback for improvement. The definitions were revised accordingly. Most respondents indicated that their organizations do not evaluate EVMS maturity. Those who do typically use SMEs or third-party peer evaluations.

The top five EVMS challenges were found to be: (1) Leadership attitude toward EVMS (ranked by far as the greatest challenge); (2) Providing timely data and information for decision making; (3) Extent of compliance expectations, reviews, and oversight; (4) Complexity of implementation; and (5) Flexibility or scalability to different types of organizations and projects. The top five EVMS subprocesses with the highest impact on EVMS effectiveness were found to be: (1) Planning and scheduling (ranked by far as the top subprocess); (2) Change control; (3) Management analysis; (4) Risk management; and (5) Budgeting and work authorization. Finally, the top five EVMS environment factors that impact EVMS effectiveness are: (1) Organizational culture; (2) Efficient EVMS development process and tools; (3) Leadership's past EVMS experience; (4) Defined, effective, and accountable leadership; and (5) Quality and level of data.

Responses from subgroups were statistically compared, based on the type of employer (owner versus contractors and consultants) and experience (above and below 25 years of experience). The perspectives of subgroups did not differ significantly except in a few instances. It was found that owner respondents consider EVM implementation costs to be more of a challenge than other respondents. More-experienced respondents consider the organizing subprocess of EVMS more critical than others, whereas less-experienced respondents consider the material management subprocess more important. Owner respondents were significantly less likely than other respondents to consider calendar time for preparing EVMS as one of the most important EVMS environment factors. Finally, respondents with more than 25 years of experience ranked leadership's previous EVMS experience significantly higher than respondents who were less experienced.

The contributions of this work to the engineering management body of knowledge include identifying and documenting the EVMS state of practice, identifying the most important subprocesses and contextual factors of a high-performing EVMS applied to a diverse array of complex projects and programs (e.g., aerospace, defense, construction, software, etc.), and uncovering corresponding key challenges. This work can help practitioners control and manage engineering projects in different industry sectors, as well as provide researchers with a solid comprehensive EVMS foundation to build on. This paper has documented major aspects around the application of EVMS subprocesses and the environment within which the project team must work, providing EVMS practitioners with a better understanding of efficient and effective use of EVMS. This work developed a common and consistent definition for EVM and EVMS, which can be used to better communicate these concepts to both owners and contractors and, finally, laid out the 10 subprocesses that are important to an efficient EVMS.

Practitioners may want to first focus on the two most important subprocesses of their EVMS system: (1) planning and scheduling and (2) change control, as identified by the survey. Adequate time should be dedicated to these subprocesses that have the highest impact on EVMS. An effective change control subprocess as part of EVMS allows leadership to monitor changes to cost and schedule baselines, enhancing the ability to proactively manage problems in real time. Practitioners should encourage EVMS surveillance, which was identified as a key strategy for EVMS improvement. Expectations for EVMS efficacy should be well developed, disseminated among stakeholders through established communication channels, and supported by contractual requirements. A plan for compliance reviews to standards and guidelines, as required, as well as oversight by a dedicated review team, should be established early in the project lifecycle.

Leadership's attitude of support, accountability, and commitment toward EVMS should be established and communicated among the project or program for successful EVMS implementation by both owners and contractors. Leadership should develop EVMS policies, formal and standard processes, and tools that can be used effectively; they should also provide employees with the right EVMS training. Survey respondents identified other key aspects of the environment surrounding effective implementation of EVMS, including timely availability of accurate EVM data; the need for informed decision making; the importance of a positive culture supportive of EVMS; the existence and use of formal processes and practices to develop and implement EVMS; and having a skilled team with adequate EVMS knowledge and experience involved in executing EVMS. Finally, cultural resistance against open and honest communication and shared values should be addressed by organization leadership.

In summary, effective EVMS subprocesses, supported by the right environment, can be used to generate early warnings of prospective problems. Early warnings can then be used by both contractors and owners to address potential cost overruns and schedule delays, providing enhanced project control.

Moreover, this paper identified a significant gap. Evaluation of EVMS maturity and environment are not widely addressed either in the literature or in practice. As indicated in the survey, those projects that do evaluate EVMS maturity rely largely on SMEs to perform such assessments. Given that the capabilities and availability of SMEs vary widely, this finding highlights the need for an objective EVMS maturity and environment evaluation tool that aids in identifying issues in EVMS application and can be used by a wide range of project stakeholders, not just SMEs, to provide a consistent assessment. The goal of such an assessment would be to "democratize" EVMS to include more than the knowledgeable few, and make the system accessible to all project management professionals. Future research is needed to determine how to evaluate EVMS in a consistent manner in terms of its maturity and environment, and the impact of a mature EVMS on project performance outcomes.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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