AMERICAN UNIVERSITY OF BEIRUT

DECISION-AID FRAMEWORKS FOR AN ENHANCED EMPLOYABILITY OF THE EARNED VALUE MANAGEMENT METHOD BY THE CONSTRUCTION CONTRACT ENGINEER

by
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AN ABSTRACT OF THE DISSERTATION OF

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Title: Decision-Aid Frameworks for an Enhanced Employability of the Earned Value Management Method by the Construction Contract Engineer

Construction project control is a process that is concerned with attempting to complete the contracted works within the allocated timeframe and the pre-agreed budget, all in accordance with the set quality standards. To this end, the earned value management (EVM) method is undoubtedly recognized as a well-established technique offering an integrated approach for the efficient monitoring and controlling of the project's cost and schedule targets during the course of execution. However, several limitations have been steadily reported in the literature concerning the underlying assumptions and practicability of this method, as perceived by key players in a number of industries, and more so in the construction industry. These implementation obstacles have led to the performance of extensive investigations dealing with ways and means that can improve the representation, usage, and measurements of the EVM sets of metrics. That said, this research aimed at investigating several decision-aid frameworks that can systematically guide the construction contract engineer in making the EVM tool better accustomed and suited for exercising project controls and administrating construction contracts, while making use of and benefiting from the enhanced capabilities of the technique that are widely spread in the archived literature. To this effect, the adopted multi-step methodology included: (1) the verification of the degree of importance of project controls in relation to project success, in order to establish the continued need for improving on the current practices related to putting in place effective project control processes; (2) the classification of the shortcomings and challenges reported to be encumbering EVM's employability as a project controls tool; and (3) the compilation and synthesis of the encountered improvements, with the aim of gaining discernment on how the reported EVM shortcomings may probably be overcome. The main research outcomes involved developing several EVM-based frameworks, which shall be of value to the construction contract engineer, through stipulating an integrated set of methods and metrics used for: (i) checking the analytical schedule-based cash flow S-curve (i.e., planned value) submitted by the contractor, (ii) dealing with interim-payment valuations and certifications, and (iii) forecasting and updating the remaining duration for the construction project on hand. Finally, these outcomes revealed an opportunity for developing a number of particular provisions that can be adopted by contract administration practitioners when deciding on or drafting the construction contract conditions. As such, the developed particular conditions clarify and set out the related requirements to be met by contractors and the types of authority to be entrusted with the engineer for facilitating the employability of the proposed frameworks, thereby potentially minimizing the likelihood of conflicts and disputes to arise between owners and contractors on construction projects.

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CHAPTER 1

INTRODUCTION

1.1 Background

A project has a well-defined objective of developing a new product, capability or increasing capacity, with a definite period of time and budget. Examples of a project include construction of a highway, commercial centers, bridges, dams, schools, universities, water tanks, factories, nuclear plants, mosques, and churches. In addition, projects may include the development of a new product such as an automobile or an engine, or research and development such as launching new software or advanced computer hardware. To this effect, the Project Management Institute (2008) defines a project as “a temporary endeavor undertaken to create a unique product, service, or result. The temporary nature of projects indicates as a definite beginning and end. The end is reached when the project’s objectives have been achieved or when the project is terminated because its objectives will not or cannot be met, or the need for the project no longer exists.”

The construction industry is huge, unpredictable, and requires immense capital expenditures (Kaliba et al. 2009). Nevertheless, it has seldom been reported that the project was completed on time, to budget and at the required quality (Morris and Hough 1987). As such, client satisfaction during project execution is threatened due to cost overrun and/or schedule slippage (Kaliba et al. 2009). However, there are many uncertain factors that have probable bearing on project time and cost during project execution

(Olawale and Sun 2015). To this effect, Barraza et al. (2004) stated the common uncertain factors that may occur in construction projects to include: (a) unanticipated cost fluctuations, (b) material shipment delays, (c) scope deviation, (d) variations in the project execution plan, and (e) poor subcontractor performance. Yet, the inferior performance of projects, leading to the disappointment of project stakeholders, appears to have become “the rule and not the exception” in the construction industry (Ika et al. 2012).

As such, the delivery of construction projects under the pressure of respecting the agreed completion time and contract price, and while being in accordance with the set quality standards, serves the interests of all project participants (Bubshait and Almohawis 1994; Gorse and Emmitt 2003; Aliverdi et al. 2013). Accordingly, this calls for the need of innovative planning, scheduling, and control mechanisms (Abeyasinghe et al. 2001; Azimi et al. 2011; Chen et al. 2012; Colin et al. 2015; Hazır 2015; Olawale and Sun 2015), intended to: (1) specifying the performance standards, (2) measuring actual cost and progress and comparing them with the planned values, (3) reporting the project status of the project, (4) pinpointing and analyzing the deviations from the project plans, and (4) implementing prompt corrective measures in case of unsatisfactory actual status outcomes so that project targets are achieved (Nicolas and Steyn 2008; Kerzner 2013; Acebes et al. 2014; Hazır 2015; Willems and Vanhoucke 2015). In a project context, Reschke and Schelle (1990) defined project control as “the skill required to bring a project from the start to the end without jeopardizing pre-defined goals”. As reported by Görög (2009), planning and control are “twin brothers” during project delivery; adequate control processes cannot be efficiently applied without sufficient planning.

Hoffman et al. (2007) found that 72% of 332 projects sponsored by the US Air Force were not finished within the baseline planned duration. In addition, Shehu et al. (2014) conducted a survey of 359 projects in Malaysia and revealed that 55% of those projects experienced cost escalations. To this effect, time and cost are two of the essential areas that need to be controlled in construction projects (Cooke and Williams 2013). Ruskin and Estes (1994) found that project cost control is confirming that project work packages are executed within their corresponding budget (Ruskin and Estes 1994). Therefore, it is critical to control cost in construction projects, which usually comprise a substantial amount of capital investment, to serve the interests of both the owner and the contractor (Olawale and Sun 2015). On the other hand, schedule control involves assessing the project schedule status, assessing whether changes have taken place or must have, and dealing with schedule changes (Heldman 2010).

One of the most well-known techniques to evaluate a project's performance is the earned value management (EVM) method (Fleming and Koppelman 2009). EVM is undeniably one of the most straightforward and most extensively disseminated tools for monitoring and controlling construction projects at regular time intervals (Willems and Vanhoucke 2015). The Project Management Institute (2008) defined EVM as "a method for integrating scope, schedule, and resources, and for measuring project performance." This control tool adopts a set of key parameters and provides the user with a set of performance measures used for evaluating the project status and forecasting the expected-at-completion figures for the duration and cost given the project performance-to-date (Vanhoucke 2018). According to Chou et al. (2010), EVM is an important project controls technique for project managers to evaluate performance and perceive problems early enough for corrective actions to be taken, due to its ability to consolidate cost, schedule and technical performance under the same framework. Recently, Czemplik (2014) considered EVM as a worldwide standard for monitoring and controlling project performance. Similarly, Willems and Vanhoucke (2015) reported that EVM was developed with the purpose of integrating cost, time, and scope to effectively and proficiently monitor and control a project during construction. In fact, a wide agreement is spread among academicians, researchers, and practitioners about the effectiveness of EVM as a main project monitoring and controls tool throughout the life of the project with broad research on the extensions and applications of this tool in the recent literature (Bhosekar and Vyas 2012; Vanhoucke 2012; Khamooshi and Golafshani 2014; Kim 2014; Hazır 2015; Chen et al. 2016; Chang and Yu 2018).

Although EVM is gaining a lot of importance among project managers, many researchers and practitioners have proclaimed various shortcomings associated with implementing this technique in practice, some are found to be related to EVM technical aspects (Moslemi-Naeni et al. 2011; Hall 2012; Narbaev and De Marco 2014; Babar et al. 2016; Najafi and Azimi 2016), whereas others are found to be concerned with EVM practical implementation issues (Valle and Soares 2006; Bell 2009; Luis Felipe Cândido et al. 2014). In light of the backdrop stated above, the work presented in this research work has been motivated by the need to emphasize the significant importance of applying adequate project controls processes in order to achieve project success and to identify the main shortcomings hindering the employability of EVM as a main project control tool, with the aim of gaining discernment on how the reported EVM shortcomings may probably be overcome as a way to lessen the magnitude of cost and time overruns and improve the construction project control process in practice.

1.2 Thesis Outline

The upcoming sections of the thesis are organized as follows. Chapter 2 illustrates an in-depth review of the archived literature, where it covers three main topics, namely: (a) critical success factors (CSFs), (b) project controls and (c), EVM method as a main project controls tool. Chapter 3 discusses the research motivation, objectives, and contributions in order to retrieve the drivers for this study. The research objectives and questions are also highlighted to guide the design of the research methodology. Chapter 3 also summarizes the research methodology, divided into three main stages. Chapter 4 validates the importance of project controls as a main critical success factor. The technical and implementation barriers of EVM as the underlying platform of project controls are thoroughly analyzed and investigated in Chapter 5. Chapter 6 discusses the synthesis of improvements to EVM metrics representation. Chapter 7 discourses the comparative analyses of construction cash flow predictions using empirical S-curves. The administration of construction contract interim payments based on earned-value reduction techniques is thoroughly discussed in Chapter 8. Chapter 9 presents the emergent EVM techniques for construction schedule performance measurement and control. Chapter 10 presents the practical implications of the proposed enhancements. Lastly, conclusions are drawn, and suggestions for future research works are made.

CHAPTER 2

LITERATURE REVIEW

2.1 Preamble

The execution of "complex, large scale, resource intense projects" relies on project management tools and methods to help better plan, control, monitor, and predict the projects' diverse performance indicators. To this effect, the need for innovative control methods for better performance holds upon the success of construction projects. In other words, the successful implementation of the construction projects needs a great deal of thorough planning followed by a vigilant progress monitoring and a prudent approach for formulating corrective actions, starting from the design to the operation stage (Kerzner 2013).

A well-established project management method has been developed and reserved its place beside other techniques, known as earned value management (EVM) method. To this effect, the EVM method is a reliable project management tool that most firms rely on, especially in the US government sector. According to Willems and Vanhoucke (2015), the EVM technique was developed with the purpose of integrating cost, time and scope to effectively and proficiently monitor and control a construction project during the execution stage. Similarly, Sandersand and Whitake (2005) described the EVM method as the best answer to the question, "Up to this point, has the project made the planned progress for the money that has been spent?"

To this end, the EVM tool is considered as the most adequate monitoring and control method used for tracking the project status and providing approaches and tools to infer the expected final figures for a project's duration and cost (Moreira and Figueiredo 2012). Similarly, Vanhoucke (2012) considered the EVM as an early "warning signal system," used for spotting problems and identifying opportunities in a straightforward way. Nevertheless, both researchers and industry practitioners have been undergoing obstacles related to the EVM basic assumptions and its feasibility. Summarizing, many issues have been raised concerning the technical and practical employability of this tool, leading to the adoption of new approaches and revised methods originating from various research lines, such as fuzzy approaches (Moslemi-Naeni et al. 2011), Bayesian statistics (Caron et al. 2016) and artificial intelligence techniques (Chao and Chien 2009).

2.2 Project Critical Success Factors

Research work on construction project success has been of increasingly substantial interest to various industries, including that of engineering and construction. Factors such as organizational rules, executive procedures, and environmental conditions have been recognized as being critical to the success of projects of all types and sizes (Pinto and Slevin 1989). Jaselskis and Ashley (1991) defined project success as a construction exertion perceived by the project manager, and therefore by his company, to obtain outstanding outcomes for key project participants. Similarly, Parfitt and Sanvido (1993) defined project success as the complete accomplishment of project objectives and expectations, related to a variety of factors, namely "technical, financial, educational, social, and professional issues".

According to Babu and Suresh (1996), successful projects have all common characteristics; they have a well-defined and organized scope of work, achievable schedule and a realistic budget. Although these characteristics are the core of a successful project, managing and controlling those projects, learning from mistakes, and managing performance are the backbone for a successful project. They stated that managing performance is the prime factor observed on successfully managed projects because the better something is measured, the better it is managed. Likewise, Chua et al. (1999) recommended categorized model for the success of construction projects, claiming that budget, schedule, and quality are main parameters.

Al-Jibouri (2003) stated that “a project is highly unlikely to proceed in all respects entirely according to plan, particularly when the plan has been expressed in some detail.” Additionally, Torp et al. (2004) conducted a survey on public projects in Norway and reported that “project planning and control” ranked third among the recognized critical success factors for project performance after “project organization” and “contract strategy”. Furthermore, Chan et al. (2004) mentioned that the key factors leading to the success of construction projects, referred to as critical success factors (CSFs), can be classified into four essential groups, mainly related to: project, procurement, project management, and project participants. Likewise, Shtub et al. (2005) mentioned that effective monitoring and control system is an essential requirement in project-based organizations. Toor and Ogunlana (2009) stated that “effective project planning and control” is a top critical success factor for construction projects. To this effect, Demachkieh and Abdul-Malak (2018) confirmed the continued need for improving the efforts, systems, or mechanisms related to putting in place effective project control processes for achieving success in all industries and more critically for projects in the construction industry.

2.3 Project Management

The execution of "complex, large scale, resource intense projects" relies on project management tools and methods to better plan, monitor, control, and predict diverse features of the project (Keil et al. 2003). As such, the evolution of project management concepts is necessary for controlling cost and time during project execution (Chen et al. 2012). To this effect, project management is the ability to keep the project on track, and to take decisions in case of amendments to the plan, with the purpose of reducing the risk of failure (Khamooshi and Golafshani 2014). That is, project management consists of planning, monitoring, and control processes (Babu and Suresh 1996). Project planning includes work definition and the estimation of quantities of material and resources needed (Babu and Suresh 1996). However, project monitoring and control consists of (1) witnessing and gathering data on the implementation of the project plan, (2) comparing the actual results with the planned ones, (3) interpreting the project performance measures, and (4) making adjustments if needed to keep the project within the preset budget and duration (Khamooshi and Golafshani 2014).

2.4 Project Monitoring

The main purpose of project monitoring is to perceive how the project is doing, and how it will be in the future. To this effect, collected data must be correlated to performance standards, such that project plan, budget, schedule, specifications, etc. Sources of data may include timesheets of workers, variation orders notices, site test results, material purchasing invoices, etc. Equilibrium must be done to assess the right quantity of data to be collected: too much data will be very expensive to gather and interpret, however, too little will not portray the full status of the project (Nicolas and Steyn 2012).

In construction projects, the control cycle consists of the following steps: 1) creating a plan, 2) executing the plan, 3) monitoring actual output and recording it, 4) reporting actual and planned parameters and their deviations, and 5) taking corrective action. By providing quantitative information, the monitoring process offers the platform on which control actions are initiated. However, in case of the lack of formal information provided from the monitoring process, control actions are taken based on informal information systems; intuitions; opinions and recommendations (Al-Jibouri 2003).

2.4.1 ***Methods of Monitoring Projects***

As mentioned earlier, monitoring project performance consists of making measurements and comparing them with the planned or estimated values. However, the cost of data collection and the existing company policies may form a barrier for the abundance of measurements (Al-Jibouri 2003). The most used monitoring methods are detailed below.

2.4.1.1 Leading Parameter

Just like "unit costing", the leading parameter is "a technique based on the idea of choosing one or more of the major types of work as measures of the performance of the whole project" (Gobourne 1973; Pilcher 1992). For instance, taking the "concrete" as the leading parameter in a building project, the amount of concrete poured at any instant of time signifies the performance of the completed work. The actual cost per leading parameter and the total cost of the project are normally compared with the planned costs for the same duration. However, in projects consisting of many areas with different types of work, a different parameter for each section is used to measure performance. However, projects usually contain many important types of work, and that the ‘goodness’ of a particular parameter chosen for evaluating the project performance may not be constant over the construction period. To defeat this problem, different parameters are used during the project. However, the changeover period between the parameters may cause some difficulties. Moreover, this technique does not reveal the reasons for the deviations of the project performance (Al-Jibouri and Mawdesley 2001).

2.4.1.2 Activity Based Ratios

The activity-based ratio method uses the ratios between the earnings and expenses of the project activities with the purpose of assessing performance. The three ratios adopted are:

$$Planned\ Performance = \frac{Planned\ Earning}{Planned\ Expenditure}$$

$$Actual\ Performance = \frac{Actual\ Earning}{Actual\ Expenditure}$$

$$Efficiency = \frac{Actual\ Performance}{Planned\ Performance}$$

Both planned and actual work should be assessed based on the same rates for earning as well as for expenditures. To be noted is that those ratios are easy to compute and to analyze. Additionally, they can be computed at any point in time during project execution and can be used to measure contributions of subcontractors to the construction project. However, the computed ratios are exclusively based on the project plan and are not statistically reliable (Mawdesley et al. 1997; Al-Jibouri and Mawdesley 2001).

2.4.1.3 Variances and Earned Value Analysis

The use of variances as a project control method is one of the oldest used tools. By considering the existing and final state of the actual and the planned work, it is potential to form a reasonably comprehensive picture of the project. As such, this method is used to evaluate the performance of the complete project and the performance of individual subcontractors. Two leading types of variances, i.e., the “budget revision variance” and the “total cost review variance,” can be calculated. Those variances are the most important project variances, which may designate an escalation in the cost of the project compared to its baseline costs. However, these variances do not reveal the reasons of the deviation. Thus, breaking down those variances may help in identifying the main causes for the deviations in cost.

An extension of this method is the earned value analysis method. In this method, the baseline bidding prices as well as the schedule are used to form what should have been spent (or earned) at any instant of time during the execution of the project. Using the planned and the actual values of work performed allows the comparison of the actual and future state of the project. Nevertheless, this tool needs a large amount of data and effort than the other two monitoring approaches. Moreover, it has many parameters describing the project state, which cause some difficulties in communicating it to all project personnel (Staffurth 1975; Harrison 1992; Lockyer and Gordon 1996).

2.5 Project Controls

Roman (1980) defined project controls as “assessing actual against planned technical accomplishment, reviewing and verifying the validity of technical objectives, confirming the continued need for the project, timing it to coincide with operational requirements, overseeing resource expenditures, and comparing the anticipated value with the costs incurred”. Subsequently, Abeyasinghe et al. (2001) confirmed that the complexity of design and construction companies involved in today’s projects and the immensity and uniqueness of the product under construction call for “innovative” planning, scheduling and control techniques in order to reach project objectives.

Fleming and Koppelman (2002) considered that a typical project baseline plan involves a comprehensive schedule incorporating the authorized activities, the resources approved for executing the project and the time-phased payments due to the contractor in return for work accomplished, based on the initial certified budget for the work. According to Nicolas and Steyn (2008), project controls has four main essential stages, namely specifying the performance standards, comparing them with the actual performance, taking suitable corrective actions if needed and informing stakeholders of changes to technical specifications along with the actual expenditures, site tests results, percent of work completed, etc.

Figure 1 shows the project control cycle which displays the iterative aspect of “project controls.” In fact, “project controls” is mostly implemented during construction phase of the project, because of nonconformities from the plans. It mainly depends on field information for studying, evaluating, and taking corrective actions. Thus, a fast access to this information is vital, however, this can be achieved by ample coordination between the office and site management teams.

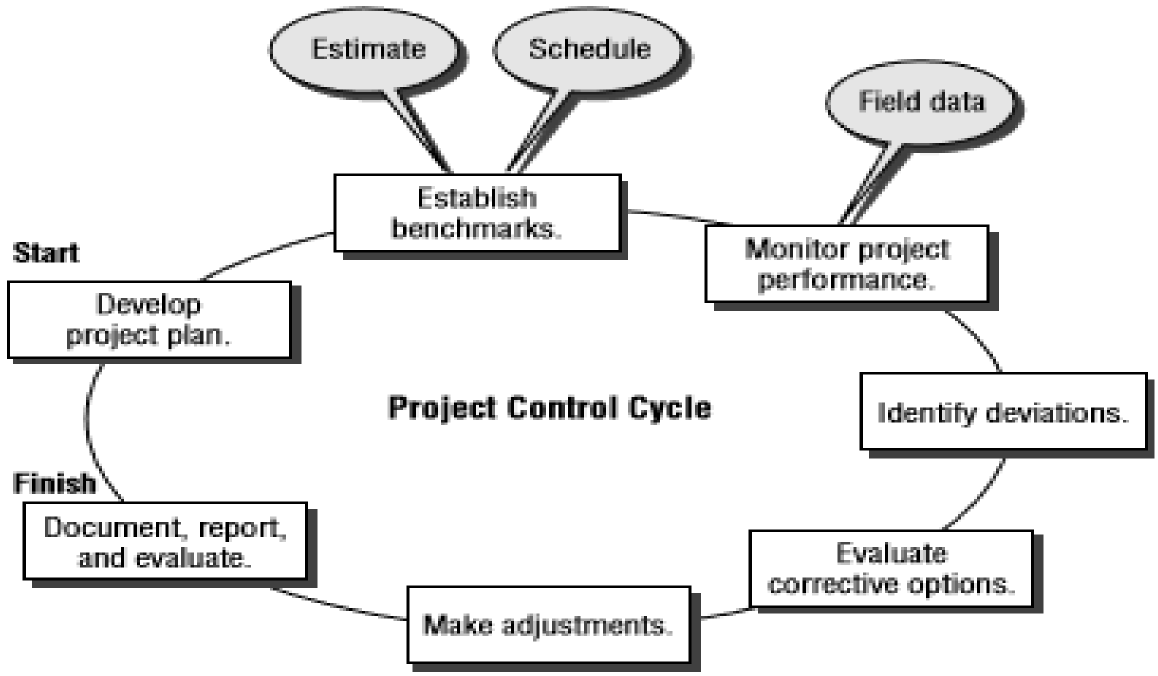

Figure 1. Project control cycle (Jackson 2010)

Besides, Görög (2009) assumed that planning and control as "twin brothers" in the project execution stage. In other words, Görög (2009) stated that planning is useless without control; similarly, control cannot be applied without sufficient planning; iteratively including scheduling, allocating of needed resources, and estimating cost. Further, Chen et al. (2012) stated that construction projects are nowadays more challenging regarding time and budget requirements, thus, the high risk of failure necessitates embracing better monitoring and control mechanisms.

Likewise, Hazır (2015) claimed that project monitoring and control consists of policies, methods and tools that reduce the deviations from the project plans, by identifying and reporting the status of the project, pinpointing and analyzing the deviations from the project plans, and taking corrective actions if needed. To put formally, a productive system needs to set the rule for the following policies: (a) monitoring policy: "what, how, where, when and by whom to monitor" and (b) control policy: what, how, where, when and by whom to prevent, intervene and correct (Hazır 2015).

Colin and Vanhoucke (2015) pointed out that the main goal of the control process is to accomplish the construction works, while respecting a preset budget and agreed duration. The level of detail accessible for the project manager during project controls depends on the effort exerted during the control process (Colin et al. 2015). Colin and Vanhoucke (2015) considered that a bottom-up approach starts with a complete and thorough control on the activities at the lowest level of the work breakdown structure (WBS); leading to a consistent forecast of the total duration of the project, and corrective actions can be consequently taken in order to respect a project milestone. On the other hand, a top-down approach considers a particular collective performance metric computed at the top level of the WBS. Only if needed, more effort can be exerted by examining those activities that require corrective actions, to assure that the project will be finished on time, within budget and according to the set quality standards spelled out in the specification requirements (Colin and Vanhoucke 2015).

2.5.1 *Internal and External Project Control*

Internal project control involves the contractor's measures and methods for monitoring work, recording status, and taking the corresponding corrective actions. External project control is the supplementary procedures enforced on the contractor by the client. Examples of external project control include governmental contracts that require inspection of the contractor's invoices by governmental auditors or client's own project manager. External project control is usually a basis of frustration to the contractor, due to the additional administration costs and bureaucratic chaos. However, it is a considered as a tool to protect the client's benefits, particularly in cost plus contracts (Nicolas and Steyn 2008).

2.5.2 ***Factors Affecting the Selection of Project Controls Methods***

Many factors affect the choice of management systems and thus the method of project controls, the most important ones are:

2.5.2.1 Project Size and Duration

Antvik (1998) claimed that the longer the duration of the project, the higher the risks associated with the foreign exchange rate and/or purchasing prices of material are. Projects having a long duration are typically more complex than smaller projects with shorter duration. Long projects need at least six months to develop a detailed project plan for executing the work and thus achieving the project targets. This does not mean that smaller projects require no plan, but they will have less elaborate project plan showing the same requirements. Moreover, it is not feasible to establish detailed monthly reports with variance analysis and corrective action strategies because the project will be finished before the system is appropriately recognized. Variances shall be interpreted and corrective actions shall be taken if needed, but in an informal way, with less bureaucracy in documentation (Humphreys 2011).

2.5.2.2 Technical, Schedule and Cost Risks

Risk is directly related to the maturity of the type of technology used in the project. If the project were in a long list of many similar projects, simple progress indicators are only required. However, if the project involved the development of new technology, more elaborate and detailed plan is needed to monitor the progress of the project towards the objective (Humphreys 2011).

2.5.2.3 Project Contract Environment

The project contract environment plays a major role in the weight of project controls. On a fixed-price type of contracts (i.e. lump sum), the client does not lay a lot of emphasis on cost monitoring and assessment. On the other hand, the contractor is very cautious in monitoring and assessing cost because he is the main entity accountable of any cost overrun when he signed such type of contract. From the client's point of view, schedule and technical requirements are very critical especially in the case of multiple prime contractors. Productivity is also a concern, as it is an indicator of whether the schedule can be achieved. In a cost plus type of contract, cost control is a major concern to the client since the contractor can increase revenues by increasing the number of manhours needed to execute the work. The detail level for cost and schedule control will fluctuate in detail consequently (Humphreys 2011).

2.5.2.4 Management Involvement Level

The management involvement level is a key factor in the selection of project controls. In the majority of projects, clients and contractors will have different systems for monitoring and assessing project status. The contractor, who is liable for executing the work, will call for an elaborate reporting system. Conversely, the owner does not need this level of detail to assess the progress and determine the project status. However, this is not always the case; if the owner is supplying the labor and working in a "hands-on management" condition, then a thorough reporting system is required in the owner's organization (Humphreys 2011).

2.5.3 *Measures of Effectiveness of Control*

As mentioned earlier, control process involves making measures, comparing them with the planned values, and taking any corrective actions if needed. Thus, the effectiveness of control is an aggregation of the effectiveness of each step in the process. As such, there are many ways used for indicating the effectiveness of the control system. First of all, the control system must alert the project manager of any possible problems. The level of detail and reliability that any control system can provide is also an indication of its effectiveness. For instance, a system that can indicate a project loss or a gain is less effective than a system that shows that carpenters are working below estimated on slab formwork.

The project control process should also consider the level of detail needed in reports, which depends on the level of management for which reports are sent. Normally, top management will be concerned about the global picture of the project performance, however, project managers will need more detailed reports, but not as detailed as requested by the site engineer. The cost control system must offer the required data with the purpose of assessing variations, in order to help the contractor to build the new rates depending on this information. To end with, control corrective actions will depend on the information given by the control system and consequently the information should be flawless and accurate at revealing to the different levels of management any deviation from the estimated performance (Al-Jibouri 2003).

2.5.4 *Achieving Project Control Success*

Kerzner (2013) described project control consists of monitoring, evaluating, and making corrective actions if needed. Likewise, Angus et al. (1997) mentions that “monitoring and controlling of a project must be done very carefully”. Moreover, Jackson (2010) considered that an efficient reporting system is instrumental for the effectiveness of the project control system. To this effect, a good project control system should allow an easy access of information when needed (Jackson 2010). Frigenti and Comninos (2002) claimed that “project information needs to be measured through meaningful control systems in an economical manner and systems need to be appropriate for the size and complexity of the project”. Thus, a good understanding of the influencing factors is highly recommended for the effective implementation of project control in any construction project. For instance, Robert et al. (2006) mentions that it is important to learn what information technology (IT) software and knowledge are needed to apply control measures in construction projects. Moreover, there is a necessity to learn the required skills that should be acquired by the project control team during the different phases of the control cycle, i.e., monitoring, evaluating, and initiating corrective actions (Jackson 2010). To this effect, Dunna and Burela (2008) enumerated several requirements used for enhancing the project control process in any construction project. These included: (a) data collection approaches, (b) time consumed on data collection and investigation, (c) use of information technology (IT) in the control system, (d) required skills for control process, (e) reporting system used, and (f) construction business process.

2.6 Genesis, Evolution, and Standardization of EVM

The “Earned Value” (EV) notion has been around for several years dating back to the early time of the nineteenth century. In 1957, the U.S. Navy developed the program evaluation and review technique (PERT) for its Polaris missile platform to create “a logic network of dependent sequential events" (Fleming and Koppelman 2006). In the early 1960's, before being adopted by the management market, the U.S. Air Force enhances PERT by including cost variances and then, the fundamental concept of earned value was accepted (Brandon and Daniel 1998). Nevertheless, PERT did not persist, but the basic concept of EV did (Brandon and Daniel 1998). In 1963, the U.S. government dispensed the Department of Defense (DOD) and NASA Guide to PERT/Cost, which is a simplified designation of earned value (Fleming and Koppelman 2006). Instead of comparing the planned costs with the actual costs, PERT/Cost compared the physical work achieved with the actual costs in order to assess the efficiency of money spent; which was a totally new and innovative technique in project management (Fleming and Koppelman 2006). In the mid-1960, the DOD withdraws the PERT/Cost; however, it kept the concept of earned value (Fleming and Koppelman 2006). The U.S. Air Force defined 35 statements involving minimal prerequisites of a satisfactory project management system (Brandon and Daniel 1998; Fleming and Koppelman 2006; Hernández et al. 2013).

With the issuance of Cost/Schedule Control Systems Criteria (C/SCSC) in 1967, the concept of EVM was officially adopted (Fleming and Koppelman 2006). Many ideas within the Department of Defense (DOD) have emerged to minimize extreme inefficient constituents of the C/SCSC (Brandon and Daniel 1998). In 1996, after the acceptance of the DOD, the private industry rewrites the 35 C/SCSC criteria and reduces their number to 32, under a new label "the Earned Value Management System (EVMS)" (Fleming and Koppelman 2006).

The new terminology replaced the expressions of "budgeted cost of work scheduled" (BCWS), "budgeted cost of work performed" (BCWP), and "actual cost of work performed" (ACWP), with respectively "planned value" (PV), "earned value" (EV), and "actual cost" (AC), to facilitate the understanding of the concept without referring to an expert (Fleming and Koppelman 2006). Subsequently, the Department of Defense allowed graduate students at the "Air Force Institute of Technology" to access its broad database, including hundreds of contracts. These students produced remarkable research studies, improving EVM concepts and enhancing its use by defense acquisition managers (Abba 2000). In 1998, the National Defense Industrial Association (NDIA) received approval of the EVM in the form of the American National Standards Institute, designated as the ANSI/EIA-748 Standard (Hernández et al. 2013). Table 1 summarizes the main milestones of the genesis, evolution, and standardization of EVM.

Table 1. Genesis, Evolution, and Standardization of EVM

Year	Event(s)
1957	The U.S. Navy developed The "Program Evaluation and Review Technique (PERT). PERT is a method to analyze the activities in a project by determining the time required to finish the activities and thus conclude the minimum duration to execute the project.
1962	US Department of Defense introduces the Work Breakdown Structure (WBS) Approach. Before being adopted by the management market, the U.S. Air Force enhances PERT by including cost variances and then, the fundamental concept of earned value was accepted.
1963	U.S. government dispensed the Department of Defense (DOD) and NASA Guide to PERT/Cost, which are a simplified designation of earned value. PERT/Cost compared the physical work achieved with the actual costs in order to assess the efficiency of money spent.
1965	The U.S. Air Force defined 35 statements involving minimum prerequisites of a satisfactory project management system, as minimum prerequisites for a satisfactory project management system.
1967	With the issuance of Cost/Schedule Control Systems Criteria (C/SCSC) in 1967, the concept of earned value management was officially adopted.
1987	The PMBOK Guide has an outline of Earned Value Management (EVM) then detailed in recent versions.
1989	EVM leadership was promoted to the "Undersecretary of Defense for Acquisition", therefore mandating EVM as a necessary part of project management.
1996	The private industry rewrites the 35 C/SCSC criteria and reduces their number to 32, under a new label "the Earned Value Management System (EVMS).
1998	The American National Standards Institute (ANSI) identifies PMBOK as a standard, and then by the Institute of Electrical and Electronics Engineers (IEEE) (i.e. "EVM Standard ANSI/EIA-748")

2.6.1 *EVM Method as a Project Controls Tool*

Due to the market pressure and the high global competition in the construction market, a critical need for rougher and stronger management information system had emerged, giving rise to the implementation of EVM method as a management requirement to control project cost and duration. As such, a wide agreement is spread among academicians, researchers and practitioners (Christensen 1998; Christensen 1999; Anbari 2003; Cioffi 2006; Valle and Soares 2006; Lipke et al. 2009; Naderpour and

Mofid 2011; Bhosekar and Vyas 2012; Moreira and Figueiredo 2012; Czemplik 2014; Kim 2014; Narbaev and De Marco 2014; Hazır 2015; Willems and Vanhoucke 2015; Chen et al. 2016) about the effectiveness of EVM as a main project monitoring and controls platform in construction projects with broad research on the extensions and applications of EVM in the recent literature.

Ballard and Koskela (1998) described EVM as a project management method, established within the conversion view, in order to control project performance and progress. As a step further, Cioffi (2006; as cited in Khamooshi and Golafshani (2014)) stated the main basic requirements for the effective implementation of EVM in a project to be a well-detailed scope, a complete schedule and a comprehensive budget. The plan, constituting the budget and schedule, is to be conceived for the bottom levels of WBS, for it to be effectively monitored and controlled (Cioffi 2006).

The Project Management Institute (2008) defined the EVM technique as "a method for integrating scope, schedule, and resources, and for measuring project performance. It compares the amount of work that was planned with what was actually earned with what was actually spent to determine if cost and schedule performance are as planned." By the same token, Chou et al. (2010) defined EVM as a project performance measurement that controls the progress of the project in an objective manner.

According to Chou et al. (2010), EVM has become an important project controls technique for project managers (PM) to evaluate performance and perceive problems early enough for corrective actions to be taken, due to its ability to consolidate cost, schedule and technical performance. Likewise, EVM is considered as the most adequate and precise monitoring and controlling method to keep an eye on the project status and to provide approaches and tools to infer final duration of the project (Moreira and Figueiredo 2012). As such, project managers should not wait until the end of the project to be informed if cost overruns or schedule delays are within the probabilistic expected levels or not (Acebes et al. 2013).

Lately, Naderpour and Mofid (2011) defined earned value as a recognized project management methodology that integrates cost, schedule and scope into a unique measurement system. EVM provides an early warning signal of any problem, which creates a chance to initiate corrective actions. Similarly, Vanhoucke (2012) stated that earned value management method provides an efficient check for the project manager on the control account level or at higher levels of the WBS. Recently, Czemplik (2014) considered the EVM as a worldwide standard for monitoring and controlling project performance and measurement. In the same way, Hazır (2015) defined earned value analysis (EVA) as a management tool used to monitor, evaluate, and control the progress of the project, by comparing "the actual and budgeted values of the work performed, the time taken, and the costs incurred", which permits the computation of cost and schedule variances in order to track the progress and forecast the total cost and duration of the project. Per se, Chen et al. (2016) stated that EVM produces performance measures (i.e., variances and indices) for project costs and schedules, and consequently forecasts project final cost and time at completion, proposing prompt signs of anticipated project performance outcomes.

However, using EVM as a standard practice may be an encumbrance, mainly since collecting significant data and information needs a lot of effort by the project team. Several companies may firstly discard applying the essential "best practices" (Humphreys and Visitacion 2009). For those firms that insist, using EVM provides a high probability to deliver effectively the project. Moreover, the traditional EVM performance indicators (i.e. CPI, SPI and SPI(t)), cannot be used to create accurate projections early in the project life due to their instability (Gardoni et al. 2007). Furthermore, even though EVM variances and indicators designate whether a project suffers from cost or time overruns, they do not notify the project manager about whether these deviations stand within the acceptable bounds of the project's estimated variability (Pajares and López-Paredes 2011).

2.6.2 *EVM Metrics*

Principally, the EVM entails a static reference point, determined by the project baseline schedule and the budget at completion (BAC), with the purpose of frequently monitor and control the project performance throughout the project lifecycle. Monitoring performance related to time and cost is done by comparing the three pillars of EVM, namely the planned value (PV), actual costs (AC) and earned value (EV), generating performance variances such as cost variance and schedule variance and performance indexes, for instance the schedule performance index and the cost performance index (Hernández et al. 2013). As shown in Figure 2, the horizontal axis (x-axis) of the EVM diagram represents time, whereas the vertical axis (y-axis) might represent the budgeted cost of work scheduled (planned costs), actual cost of work performed (actual costs) and work packages checked and paid for (or earned) having the adequate quality (Chou et al. 2010).

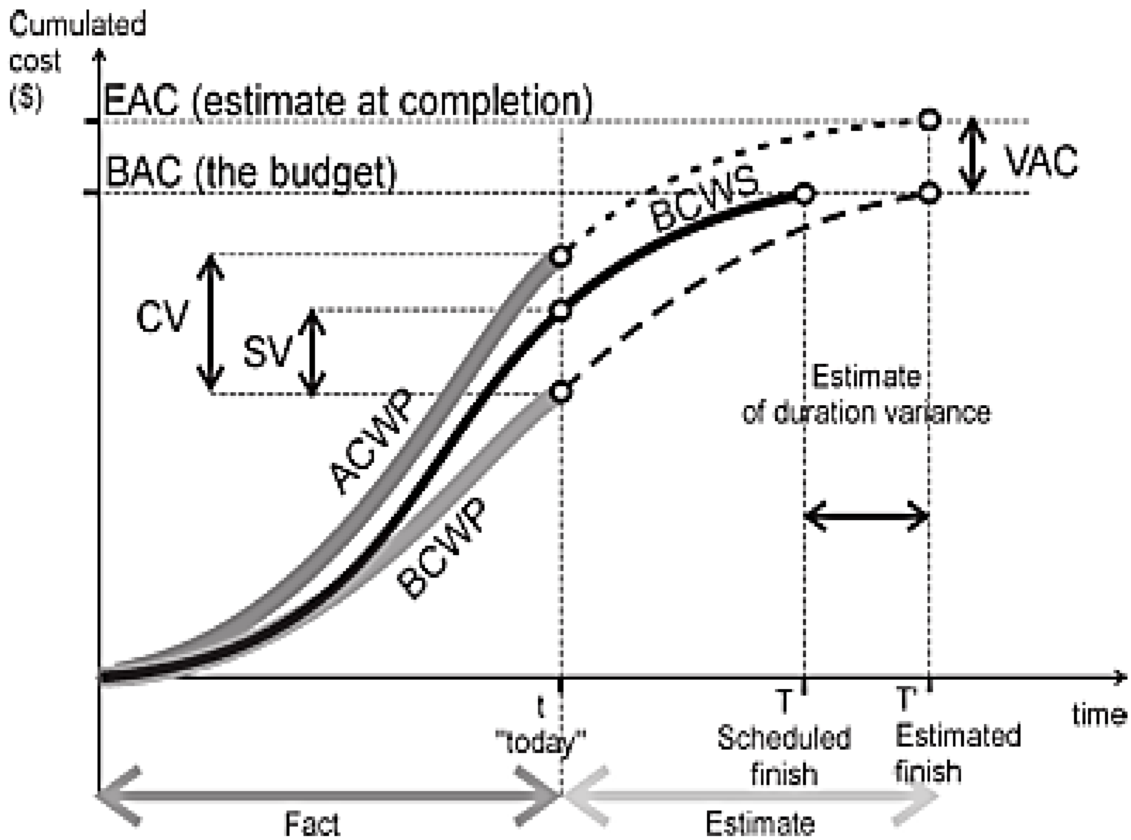

Figure 2. EVM fundamentals (Czarnigowska 2008)

The PV is defined as the share of the budget that is planned to be spent at a given instant of time (Lukas 2010). In other words, BCWS is the "permissible budgeted cost for accomplishing project plan workload at some stage during project implementation" (Zhong and Wang 2011). However, the AC is the money spent for a completed work package at some stage of the project (Lukas 2010). Last but not least, the EV is the share of the total budget actually achieved at a given instant of time (Lukas 2010). To this effect, EV is a measure of the project's "physical progress" actually completed (Henderson 2003), in other words, EV is defined as the "calculating cost" of the achievement of the work package and quota budget price. In fact, it is a quantitative measure of the execution of the project (Zhong and Wang 2011). To this effect, Hajdu et al. (2013) analyzed the three parameters of EVM and concluded the following scenarios:

- AC > EV > PV: if the task will be executed with the same power, it could be completed before the scheduled time, yet, cost overrun is anticipated.
- PV > EV > AC: if the task will be executed with the same power, it could be completed after the scheduled time, yet, cost saving is anticipated.
- AC > PV > EV: if the task will be executed with the same power, it could be completed after the scheduled time; likewise, cost overrun is anticipated.
- EV > PV > AC: if the task will be executed with the same power, it could be completed before the scheduled time, additionally, cost saving is anticipated.
- EV >AC > PV: if the task will be executed with the same power, it could be completed before the scheduled time, additionally, cost saving is anticipated.
- PV > AC > EV: if the task will be executed with the same power, it could be completed after the scheduled time, additionally, cost overrun is anticipated.

When the three main EVM key parameters (i.e., PV, EV and AC) are appropriately determined along the lifecycle of the project, the project manager is capable of calculating two types of performance measures: variances and indices. Whereas variances are used to highlight the difference between the actual project status and its baseline in monetary units, indices represent how well the performance of the project is, as compared with the baseline. As these variances and indices are interconnected, they both contribute to the critical task of forecasting the expected at-completion figures for the duration and cost of the project, as shown in Table 2.

2.6.3 *Why EVM method Does Not Work on All Projects?*

Lukas (2010) states ten reasons why EVM method does not work on all construction projects, and proposes some recommendations on how to solve each problem. The following is a summary of the reasons and their proposed solutions:

- No tangible requirements: requirements delineate the final product used by the client; and without requirements, the bond to establishing a WBS is destroyed. Hence, the project team shall coordinate with the owner to properly document the requirements of the project.
- No complete requirements: in many circumstances, the owner does not have enough project expertise. In this case, the project owner may develop the "how" as a replacement for of the "what" in the request for proposal (RFP). The project team shall spend enough time to cooperate with the owner in order to guarantee that the requirements exactly mirror what is required to achieve the project goals.
- Work breakdown structure (WBS) not used or not accepted: in the absence of a comprehensive WBS, the schedule and budget will not precisely reveal the true figures for a successful project completion. The other concern is when the project manager organizes the WBS and the project team actually does not appreciate its importance and offers slight collaboration. The project manager shall clearly state the importance of using the WBS and clarify that this WBS is the "foundation" project document for the project. Or else, the WBS will not be sustained and rapidly turn out to be outdated.
- WBS not complete: evidently, incomplete requirements lead to an incomplete WBS. The other side is having comprehensive requirements, however the WBS is

not tested against the requirements and thus some requirements are omitted. To prevent this, it is advisable to use a WBS dictionary and containing a section stating the requirements enclosed by each WBS component.

- Plan not combined: The project manager should ensure that the scheduler and/or estimator are involved in the construction of the WBS and in alignment with preparing the budget and schedule estimates to be consistent with the WBS elements. The schedule of the project contains tasks relating back to each WBS work package. The project estimate should contain a statement of work for each WBS work package, in addition to an authorized budget. It is also crucial to allocate to each work package a performance responsibility given to an individual; thus, a complete project plan that integrates cost, time and WBS is established. Once the progress is then measured, earned value analysis is easily implemented on the project.
- Wrong Schedule and/or budget: most of the cases, the schedule contains errors, such as hangers, inadequate relationships, and abuse of constraints. Moreover, budget mistakes may occur for several causes such as poor communication, mistakes in estimating quantities or use of incorrect rates. Thus, a quality control process allows an assessment and checking of the schedule and budget estimate by experts and professionals before the final project plan is issued.
- “Change management” not used or unsuccessful: change management should be taken into account in the project plan, and contains the processes for controlling change orders, assessing change requests, the review and approval procedures for changes, and the process to guarantee variations are integrated into the project

plan, and thus the earned value computations continue to be applicable. Designers may improve the final product by adding some new features, and they do not recognize that this change will cause extra money or time during construction. The project manager should work with the design team to identify which items are changing the project scope. The project PV curve must reveal the subtotal excluding contingencies or inflation. The change management process is used to allot contingencies to work packages. Once the change is authorized, the plan and the PV curve should be changed using any computer software.

- Poor cost collection methodology: EVM method does not work without tracking down the precise AC for the project. Enterprises having many cost systems transform the process of cost collection and reporting to a very hard job. A main drawback of cost systems is that they simply reveal AC for bills received and/or paid. Bills lagging by a month or more from the date the work was fully completed are not shown. Thus, using data from the cost system for earned value computations is deceptive. To solve this issue, an "adjusted actual cost" column is used to register the AC. Adjusted actual cost contains the AC from the cost system, plus a forecast for outstanding bills for work completed (i.e. accruals).
- Wrong progress measurement: EVM method is a quantitative tool used for assessing the performance of the project. Nonetheless, it actually depends on the method of measurement adopted for assessing project progress. It works better when the method used is quantitative, for example, milestones, units complete, etc. However, if the method used is qualitative, this allows for a subjective

measure in the registered progress. The project manager should make sure that the progress is reported well.

Management effect and/or control: the last problem that may be encountered when implementing EVM method is the management pressure to affect the reported outcomes for several reasons. It can be company objectives that should be achieved associated to project motivations, or the typical human comportment of being optimistic and preventing “bad news” wishing that the problem might be upturned.

Table 2. EVM Metrics

Category	Acronym	Description	Formula	Interpretation
EVMS Key Parameters	BCWS (PV)	Budgeted Cost of Work Scheduled (Planned Value)	Work Load × Budget at Completion (BAC)	PV is the share of the budget that is planned to be spent at a given instant of time, known as the performance measurement baseline.
	BCWP (EV)	Budgeted Cost of Work Performed (Earned Value)	% Completed Work × Budget at Completion (BAC)	EV is a measure of the project's "physical progress" actually completed (i.e. authorized work).
	ACWP (AC)	Actual Cost of Work Performed (Actual Cost)	---	AC is the money spent for a completed work package at some stage of the project.
EVMS Project Status Indicators (Performance Measures)				
Variances	CV	Cost Variance	BCWP-ACWP	It measures the conformance of the budget to the actual cost of work executed (CV<0 is over budget; CV>0 is under budget)
	SV	Schedule Variance	BCWP-BCWS	It mesures the conformance of project progress to the schedule (SV<0 is behind schedule; SV>0 is ahead of schedule)
Indices	CPI	Cost Performance Index	BCWP/ACWP	It compares the planned and actual value of works" accomplished
	SPI	Schedule Performance Index	BCWP/BCWS	It "compares the planned cost of work done with planned cost of work planned
EVMS Forecasting Parameters	EAC	Cost Estimate At Completion	ACWP + Planned Cost of Work Remaining (PCWR) where PCWR= [(BAC-BCWP) / PF]	It is a prediction of probably the total project costs at a given project performance, which might be different from the Budget At Completion (BAC).
	ETC	Estimate to Complete	EAC-ACWP	This is the expected extra cost to execute the project at a given point in time.
	VAC	Variance at Completion	BAC-EAC	It expresses the amount by which the project will be over or under budget.
	EAC (t)	Duration Estimate At Completion	Actual Time (AT) + Planned Duration of Work Remaining (PDWR)	It is a prediction of the final project duration at the current status date, at a given project performance, which might be different from the Planned Duration (PD).
	PF	Performance Factor	---	It indicates the amount in which the increase in ACWP or BCWP is dependent on the assumption of the performance of the remaining work to be done.
			PF=1	Future performance is likely to follow the baseline schedule.
			PF= CPI	Future performance is likely to follow the existing cost performance.
			PF= SPI	Future performance is likely to follow the existing time performance.
			PF= SCI	Future performance likely to follow the existing time and cost performance where SCI=SPI × CPI
			PF= w1×CPI+ w2×SPI	w1=0.8 and w2=0.2

CHAPTER 3

RESEARCH MOTIVATIONS, OBJECTIVES AND CONTRIBUTIONS

3.1 Preamble

This chapter summarizes the research statement, motivation, objectives, and contributions of the conducted research work. In addition, the various steps of the followed methodology are thoroughly explained and detailed.

3.2 Research Statement and Motivation

It has seldom been reported that the project was completed "on time, to budget and at the required quality". There is an excess of reports on cost and time overruns of projects stating that 50% of construction projects in the UK and approximately 63% of all information systems projects suffer from large cost overrun, where overrun values range from 40 to 200 percent"(Morris and Hough 1987). However, the main dilemma is that the project stakeholders recognize that the project is behind schedule and/or over budget, but do not identify the most suitable method to handle the problem.

One of the major requirements in the construction industry is that projects are typically required to be executed within the specified timeframe and the allocated budget. however, there are several uncertain factors that have the potential influence on time and cost during project execution, thus, calling for the need for effective management controls. In a project context, control is one of the major aspects of project management;

this is obviously specified in most widely recognized definitions of project management, namely those related to the Association for Project Management (APM 2012) and Project Management Institute (PMI 2018).

"Project control can be defined as the application of processes to measure project performance against the project plan, to enable variances, to be identified and corrected, so that project objectives are achieved" (APM 2012). In the construction industry, time and cost are the two major aspects that "stand out" when talking about control (Cooke and Williams 2013). Thus, in construction projects, which usually include a significant amount of cost and time investment; it is undeniably significant to control cost and time in the interest of both the provider and the customer.

As such, the EVM method is a recognized management technique that is used for monitoring, evaluating, and controlling the progress of projects. The method's employability challenges have consistently been addressed in the literature along with proposed enhancements that aim at improving its application. To this effect, the current literature has presented a significant volume of research work pertaining to improvements and enhancement proposed to this project control tool, that aim at improving its application. However, none of the previous research efforts has designed a framework that can systematically guide in promoting the employability of this control method on construction projects of various organizational and contractual structures, while making use of and benefiting from the enhanced capabilities of the technique that are widely spread in the archived literature.

3.3 Research Questions

Following the thorough review and inspection of the archived literature, and after examining several case studies related to construction projects experiencing cost and schedule overruns, numerous research questions arose that this study is intended to find answers. Consequently, the proposed research questions are:

1. What are the core factors leading project success and avoiding cost and budget overruns in construction projects?
2. What are the main impediments preventing the widespread implementation of EVM method by the construction contract engineer as an effective project monitoring and control technique in the construction industry?
3. What are the key proposed enhancements to the EVM basic set of parameters, leading to an enhanced “state-of-the-art” project controls tool?
4. What are the influencing/threshold factors for effective implementation of EVM in construction projects, given the gap between the practical application of these improvements and the capability of the available software and medium of analysis used for project controls?
5. What are the main purposes justifying the use of the proposed enhancements to the EVM in construction projects?

3.4 Research Goals and Contributions

The construction industry is huge, unpredictable, and needs remarkable capital expenditures. However, client satisfaction during project execution is threatened due to cost overrun and/or schedule slippage (Kaliba et al. 2009). To this end, successful projects have all common characteristics; they have a well-defined scope of work, achievable schedule, and a realistic budget. Although these characteristics are the core of a successful project, project monitoring and controls is a main critical success factor for construction projects. As such, the EVM is a well-established tool intended for monitoring, evaluating, and controlling the progress of projects of several types and sizes. However, the literature has steadily revealed limitations related to the employability of this technique, as perceived by key players in a number of industries, and more so in the construction industry. The overall objective of the research is to investigate these EVM limitations and to pursue prospects and recommendations that could serve in instilling a widespread implementation of EVM as an effective project monitoring and control method in the construction industry.

Therefore, the conducted research aims to:

1. examining the significance of project controls as a critical success factor (CSF), in order to validate the continued need for improving on the current practices related to putting in place effective project control processes;
2. exploring the shortcomings and challenges reported to be incumbering EVM's employability as a project controls tool;
3. investigating the main encountered improvements, with the aim of gaining discernment on how the reported EVM shortcomings may probably be overcome
4. developing several EVM-based frameworks, which shall be of value to the construction contract engineer, through stipulating an integrated set of methods and metrics with the purpose of widening its applicability in construction projects.

The outcomes of the research include:

1. an overview and a thorough classification of the various challenges and limitations that are said to be hindering the employability of EVM in construction projects;
2. a comprehensive understanding of the spectrum of the improvements encountered in the reviewed literature in connection with the EVM key parameters and the corresponding performance and forecasting parameters based on the project lifecycle stages (i.e., preconstruction and construction);
3. an in-depth understanding of the practical implication of the encountered improvements according to the purposes that can be regarded as justifying their use, including those in respect of (a) the "monitoring and control" function and (b) the satisfaction of construction contract administration requirements;
4. the development of design-aid frameworks that can systematically guide the construction contract engineer in promoting the employability of this control method on construction projects, while making use of and benefiting from the enhanced capabilities of the technique that are widely spread in the archived literature.

3.5 Methodology

In view of the myriad projects suffering from cost overrun and/or schedule slippage, the aim of the work presented in this research aimed at investigating several decision-aid frameworks that can systematically guide the construction contract engineer in making the EVM tool better accustomed and suited for exercising project controls and administrating construction contracts, while making use of and benefiting from the enhanced capabilities of the technique that are widely spread in the archived literature. To this effect, the adopted multi-step methodology, as shown in Figure 3, included: (1) the verification of the degree of importance of project controls in relation to project success, in order to establish the continued need for improving on the current practices related to putting in place effective project control processes; (2) the classification of the shortcomings and challenges reported to be incumbering EVM's employability as a project controls tool; and (3) the compilation and synthesis of the encountered improvements, with the aim of gaining discernment on how the reported EVM shortcomings may probably be overcome.

As depicted in Figure 3, the enhancements encountered in the reviewed literature in connection with the EVM sets of metrics; (i.e. key parameters, performance measures and forecasting parameters) were mapped and classified based on the project lifecycle stages (i.e., preconstruction and construction). To this effect, The main research outcomes involved developing several EVM-based frameworks, which shall be of value to the construction contract engineer, through stipulating an integrated set of methods and metrics used for: (i) checking the analytical schedule-based cash flow S-curve (i.e., planned value) submitted by the contractor, (ii) dealing with interim-payment valuations and certifications, and (iii) forecasting and updating the remaining duration for the construction project on hand. Finally, these outcomes revealed an opportunity for developing a number of particular provisions that can be adopted by contract administration practitioners when deciding on or drafting the construction contract conditions. As such, the developed particular conditions clarify and set out the related requirements to be met by contractors and the types of authority to be entrusted with the engineer for facilitating the employability of the proposed frameworks, thereby potentially minimizing the likelihood of conflicts and disputes to arise between owners and contractors on construction projects.

3.5.1 *Project Controls as a Main CSF*

Research work on construction project success has been of steadily considerable interest to a number of industries, including that of engineering and construction. The objective of the first stage of this research work was to investigate the significance of project controls as a CSF, with the aim of validating the continued need for improving on the current practices related to putting in place effective project control processes. The research methodology involved undertaking a scrutinized review of project controls research studies reported on—over the last three decades—in the related reputable literature, followed by a synthesis of the factors cited as critical to the success of several types of projects. A lower limit (i.e. 1987) for this study period is set to limit the number of the older publications in this research area. The reviewed studies were searched for using the “Google Scholar,” “Science Direct,” and “ASCE” databases search engines, based on the semantics and keywords-based methods. Accordingly, the search resulted in filtering a total number of 65 relevant publications, which were classified based on their year of publication, the methodologies adopted, the types of projects, the semantics encountered and deemed to be associated with project controls, and the inferred rankings of “effective project monitoring and controls methods” as a CSF.

3.5.2 *Stage 2: EVM Limitations*

Given the importance of the project controls as a CSF, this track of analysis was instigated by an explorative and scrutinized review of the current literature concerned with project controls and EVM, published in the last three decades. Accordingly, the adopted research studies were obtained through an extensive search of online libraries and databases search engines (e.g., Web of Science, Google Scholar and Science Direct) of published articles and conference proceedings in the construction management field, by using semantics and keywords-based methods. The search resulted in adopting a total of 81 relevant studies that dealt with EVM limitations and challenges reported to be hindering the use of this project control method in the construction industry.

3.5.3 *Stage 3: Encountered EVM Improvements*

The objective of this track of analysis is to present the results of the scrutinized review of the adopted research studies concerned with the identification and classification of the main tracks along which reported improvements can be categorized, in order to tackle the already encountered EVM limitations, as perceived by key players in a number of industries, and more so in the construction industry. The enhancements encountered in the reviewed literature in connection with the EVM sets of metrics; (i.e. key parameters, performance measures, and forecasting parameters) were mapped and classified based on the project lifecycle stages (i.e., preconstruction and construction) and from the perspective of the various project participants (i.e. customer and provider) in numerous project organizational structures.

3.5.3.1 Inclusion and Exclusion Criteria

The initial steps in this research involved a close examination of the inclusion/exclusion criteria in order to decide whether to include or exclude the study in the reviewed literature. The current literature was searched in order to include papers reporting three types of studies (inclusion criteria): (1) studies that tackled the extensions and improvements addressing the main shortcomings of EVM project control methodology, (2) studies that considered the EVM as a main platform for new methods and tools for project controls, and (3) empirical studies (i.e. real life projects and case studies), theoretical studies and literature reviews related to the contributions to literature that have attempted to deal with the reported limitations of the EVM methodology. However, studies having these characteristics are omitted from the research (exclusion criteria): (1) written in a language other than English, (2) not available on the Worldwide Web, and (3) keynote speeches, workshop papers, PowerPoint presentations, drafts, master's theses, and doctoral dissertations.

3.5.3.2 Research Studies Selection

Snowball and keyword searches are both used to collect the relevant studies. To this effect, the reviewed studies were searched for using main electronic digital libraries or databases, for instance Scopus, IEEE Xplore, ScienceDirect, Web of Science, ABI/Informs, ProQuest, Emerald Insight, and the search engine Google Scholar, based on the semantics and keywords-based methods. The search resulted in filtering 188 relevant studies in total, after determining the research period to be between 2000 and 2017. For backward snowballing searches, we instigated with Willems and Vanhoucke (2015) as being the latest comprehensive overview of the current literature on project controls and earned value management and extracted eligible studies from its reference list. Sequentially, the filtered research studies retrieved from the Willems and Vanhoucke (2015) research paper mentioned above were consulted to explore more papers, up until no more new studies popped in, resulting in a total of 60 research studies.

The selection of the shortlisted papers in each search phase (i.e., keyword and snowball search) follows two main steps: pre-selection and selection, as shown in Figure

1, to cover the latest studies (i.e., increase the sensitivity of the search) in order to assure that as many as possible of the necessary and relevant studies are included in the review process. In the pre-selection process, the studies resulting from the keyword search were separately analyzed by reading the tile and the abstract and thus removing all those that are not relevant to the research study. The same procedure is repeated in the second phase of the search, which is the snowball search.

In the selection process, the inclusion and exclusion criteria are applied on each prequalified research study after reading the abstract, introduction and conclusion of each hypothetically relevant research study approved from the pre-selection process. After removing duplicates through the inclusion/exclusion criteria, along with the results from the snowball search, the final selection consisted of 248 relevant studies that dealt with reporting on EVM proposed improvements. Accordingly, the shortlisted EVM research studies focus on the main enhancements proposed with the aim of achieving a wider future use of EVM in the construction industry. Consequently, the collected research studies were scanned and synthesized into a classification framework in order to draw interpretations on the current research trends and postulate areas that merit additional examination.

3.5.4 *Interim Progress Payment Valuation and Certification*

Interim progress payment valuations and certifications signify a central contract administration function in the construction industry. If not attended to by the involved contract administrators in accordance with prescribed provisions, this critical function could end up being a primary cause for disputes to arise between owners and contractors.

To this effect, there are several scenarios as to why work estimated by contractors to have been completed end up being denied certification by the engineer, thus causing the deferral of receipt, if not temporary or complete rejection, of payment to the contractor.

The aim of this step is therefore to address the situations that could justify the potential withholding or setting-off by the engineer of amounts that are otherwise viewed as due by the contractor. The adopted methodology relied on three sources of information pertaining to payment reduction practices. These included: (1) a review of relevant standard contract conditions governing payment certification by the contract engineer, (2) an examination of the payment certification records on three building construction project cases, and (3) a synthesis of several techniques, encountered in the reviewed literature, tackling progress measurement assessments and earned value (EV) adjustments. The first two sources led to the compilation of an initial set of reasons for, and corresponding means of, effectuating payment reductions in practice. These deduced methods, together with those synthesized from the reviewed literature, fed into the formulation of a framework that comprehensively incorporates the reasons that can potentially drive the effectuation of EV reductions.

The outcomes of this step shall be of value to project participants involved in administrating construction contracts, through stipulating transparent practices for dealing with interim-payment certifications. The ultimate implication is intended to be one that helps in avoiding probable payment-related conflicts and disputes between owners and contractors on construction projects.

3.5.5 *Comparative Analyses of Construction Cash Flow Predictions Using Empirical S-Curves*

Following the contract award and soon upon receiving the notice of commencement with the works, the contractor is normally required to submit to the construction contract engineer a baseline schedule for review and possible consent. To this effect, such a schedule is needed by the engineer for progress tracking and monitoring purposes and by the owner and contractor to plan the project and construction financing requirements, respectively. As such, it is necessary to obtain an early – yet realistic – basis that estimates the project-level cash flow prior to the start of construction, against which the reasonableness of the contractor's PV curve, which is generated from the baseline schedule and serving owner's cash flow requirements, can be checked.

That said, the objective of the research work is therefore concerned with the investigation, from the perspective of the project owner, of the prediction properties of the literature-proposed planned work progress estimation models. To achieve this, the adopted methodology included the following: (a) a thorough review and synthesis of the several techniques that were encountered in the reviewed literature as tackling the forecasting of the project-level cash flow in the preconstruction stages, and (b) an examination of the applicability and prediction accuracy of the proposed techniques using actual earned value figures achieved on a completed residential project. The performed examination was further supported by comparative and sensitivity analyses, in order to determine those ranges of the input factors that satisfy an acceptable degree of prediction accuracy.

The outcomes of this step shall be of value to the contract engineer involved in administrating construction contracts, through stipulating a reasonable approach for checking the schedule-based S-curve (i.e. planned value curve) submitted by the contractor. The ultimate implication is intended to be one that better helps in owners' initial financial planning and more objectively judging the analytical schedule-based cash-flow estimate, thereby serving the ultimate critical task of conducting project monitoring and control.

3.5.6 *Schedule Performance Measurement and Assessment*

Schedule monitoring and control is considered as one of the most crucial functions of project management that continues to receive considerable research attention. To this effect, the EVM method is a well-established project performance technique, originally established as a cost management and control tool and later extended to track schedule performance. While there are many shortcomings to the use of EVM data for the purpose of schedule performance measurement and analysis, the literature has proposed duration forecasting methods to supplement and enhance the effectiveness of schedule analysis for the construction project.

That said, the objective of this research work is to investigate and propose a framework that can systematically guide the construction contract engineer in measuring and controlling project schedule performance. The adopted methodology included the following: (1) a synthesis of the several techniques that were encountered in the reviewed literature as serving the critical task of forecasting and updating the EAC(t) figure for the duration of a construction project on hand, (2) a compilation of a number of additionally emergent extensions, involving variant metrics that are proposed in complement to other proposed EVM-compatible methods, in order to offer better means for studying the project schedule performance and measuring the total expected delays, and (3) an examination of the applicability and prediction accuracy of the proposed techniques and metrics using a hypothetical project demonstrated through scheduling software.

The outcomes of this step shall be of value to the contract engineer involved in administrating construction contracts, through stipulating an integrated set of methods and metrics for more reasonably forecasting the remaining project duration. The ultimate implication is intended to be one that helps in justifying a fair initiation of the recovery of liquidated damages (LD) in case of schedule delays, thereby minimizing the likelihood of conflicts and disputes to arise between owners and contractors on construction projects as a result of such LD-enforcement actions.

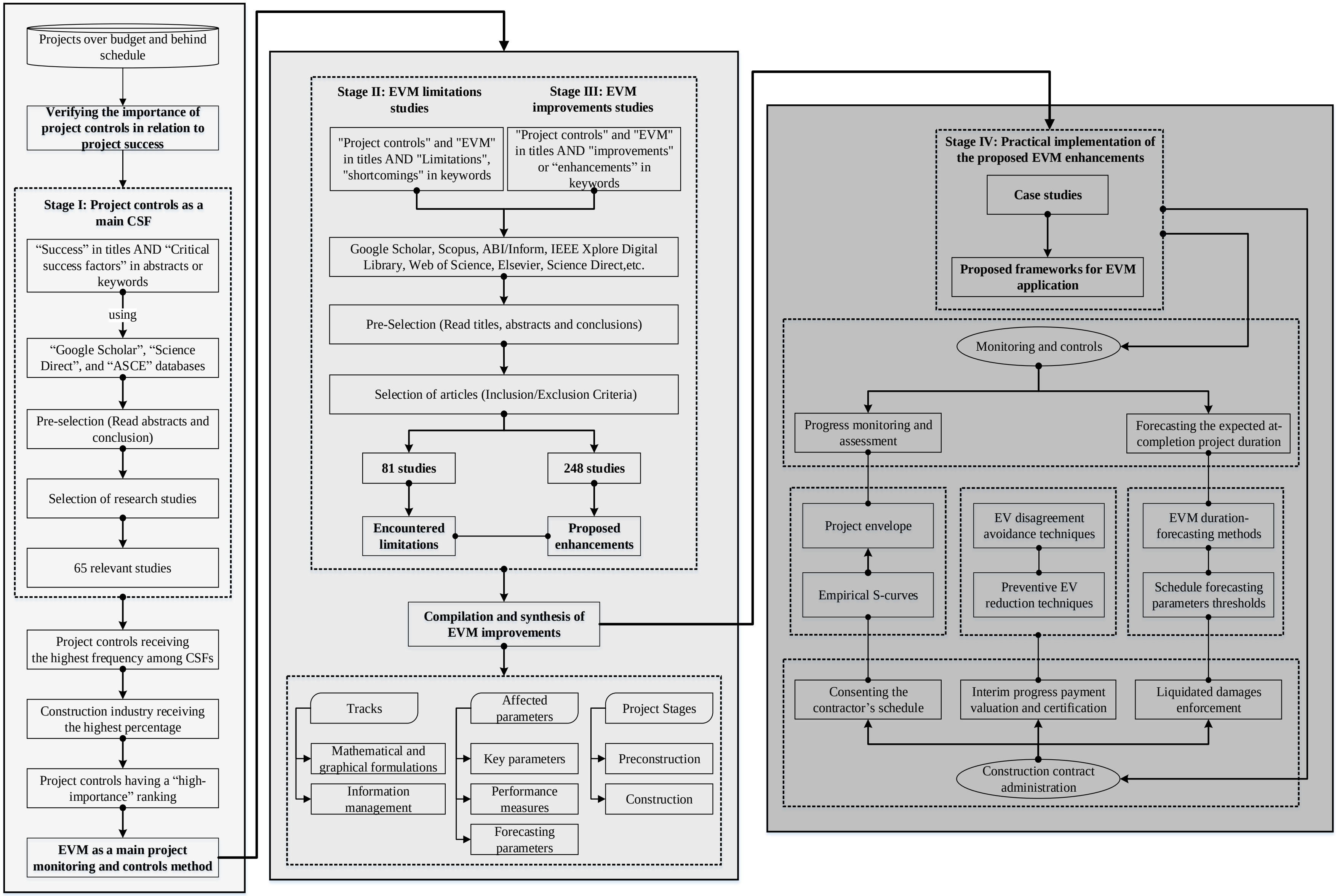

Figure 3. Research methodology

CHAPTER 4

DEGREE OF CRITICALITY OF PROJECT MONITORING AND CONTROL TO PROJECT SUCCESS

4.1 Preamble

Research work on construction project success has been of steadily considerable interest to a number of industries, including that of engineering and construction. To this effect, this chapter investigates the significance of project controls as a critical success factor (CSF), with the aim of validating the continued need for improving on the current practices related to putting in place effective project control processes.

4.2 Introduction

The major challenge for launching a new product depends on the manager's capability to exercise control on the project development process (Langford and Franck 2008), while clients are nowadays demanding to accomplish the project in "record time" (Kog et al. 1999). Through control, managers and planners allocate resources, adjust investments, monitor performance, identify corrective actions, and regulate the flow of human capital (Langford and Franck 2008).

In construction projects, the main purpose of project control is to finish the project within the allocated time and the preset budget and in accordance with the set quality standards. To this end, this is a difficult task undertaken by the project managers, by way of continually measuring progress, assessing plans and deciding on corrective actions when needed (Kerzner 2013).

Factors such as organizational rules, executive procedures, and environmental conditions have been identified as being critical to the success of projects of various types (Pinto and Covin 1989). Al-Jibouri (2003) reported that "a project is highly unlikely to proceed in all respects entirely according to plan, particularly when the plan has been expressed in some detail." Chan et al. (2004) mentioned that the main factors leading to the success of construction projects, referred to as critical success factors (CSFs), can be categorized into main classes related to project, procurement, project management, and project participant. Moreover, Torp et al. (2004) conducted a survey on large public projects in Norway and stated that "project planning and control" ranked third among the identified CSFs for project performance after "project organization" and "contract strategy." Likewise, Toor and Ogunlana (2009) stated that "effective project planning and control" is a top critical success factor for construction projects.

4.3 Analysis and Results

This section presents the research findings concerned with the identification of the perceptions that contractors, owners, and researchers have vis-a-vis the essential factors contributing to the success of projects. Based on the in-depth review of the filtered 65 research papers, the frequencies associated with the reported CSFs were of main interest, coupled with the question of where “project control” stands relative to the rankings of other CSFs.

4.3.1 *General Screening and Findings*

The adopted research papers were ordered and grouped according to their years of publication, as shown in Figure 4. The depicted distribution clearly reveals that significant volume of work pertaining to project success factors has been performed in the last three brackets starting early 2000’s and on, the time at which the use of earned value management system was introduced as a contemporary project performance control platform. The 65 garnered publications made reference to a wide range of factors found to be connected to project success. As expected, such reference lacked consistency in respect of the semantics used.

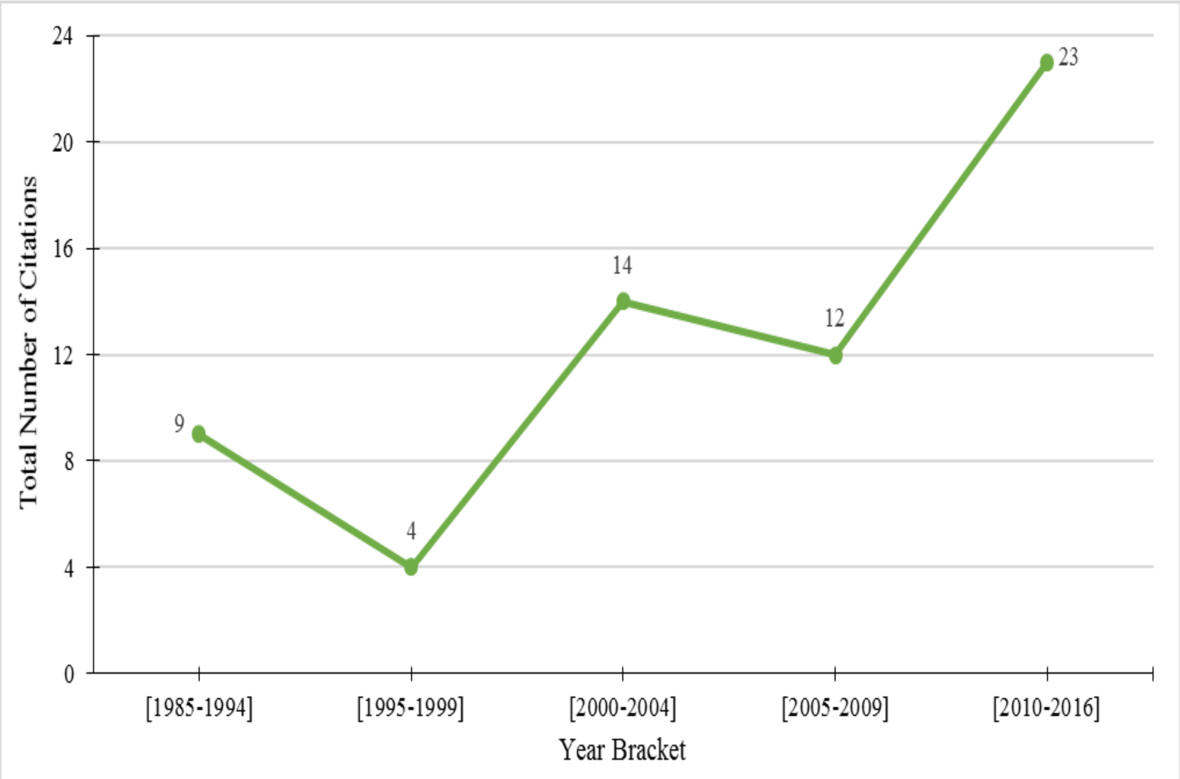

Figure 4. Distribution and spans of research studies

A thorough review and inspection of all encountered factors allowed their grouping into general headings that offer clearer representations of what is reported to be critical to project success. Table 3 lists fifteen of the generated headings that were found to have citation frequencies of more than 10.

Table 3. CSFs Encountered in the Reviewed Literature

Critical Success Factors (CSFs)	**Count of citations**
Effective Project Monitoring and Controls Methods	62
Good leadership (i.e. PM) and Competent Project Team	51
Effective Coordination, Communication, and Commitment	48
Realistic Project Requirements and Goal	45
Owner Involvement, Consultation and/or Commitment	42
Effective Planning and Scheduling	37
Top Management Support	36
Clear and Deliberate Project Organization Structure	32
Adequacy of an Up-to-date Risk Management Plan	29
Availability of Resources (Human, financial, materials and facilities)	28
Technical Advancement and Innovation	27
Realistic Project Cost and Time Estimates	26
Standards for Change Control and Quality Control	24
Design Management	22
Effective Crisis Management (i.e. Disputes Resolution Procedures)	12

The listed headings are presented in a decreasing order of occurrence frequency, with the adopted heading of "effective project monitoring and controls methods" receiving the highest citation frequency of 62, thereby confirming the exceptional significance of implementing proper control mechanisms for achieving project success.

To be noted here is that the 62 reviewed studies that cited "project controls" as a CSF were found to have employed several methodologies for seeking the perceptions of industry professionals regarding what they view to be critical for achieving project success. These included case studies (CS), questionnaires (Q), interviews (I) literature reviews (LR), or a combination of such methods, as per the frequencies reported in Figure 5. It can be seen that a total of 42 of the encountered investigations relied on questionnaires, either wholly (30 studies) or partially (12 studies), for soliciting insights and perceptions on CSFs for projects in various industries. This could have a positive bearing as to the credibility of the inputs given by professionals, being first-reaction opinions expressed at the will of respondents and without external influences.

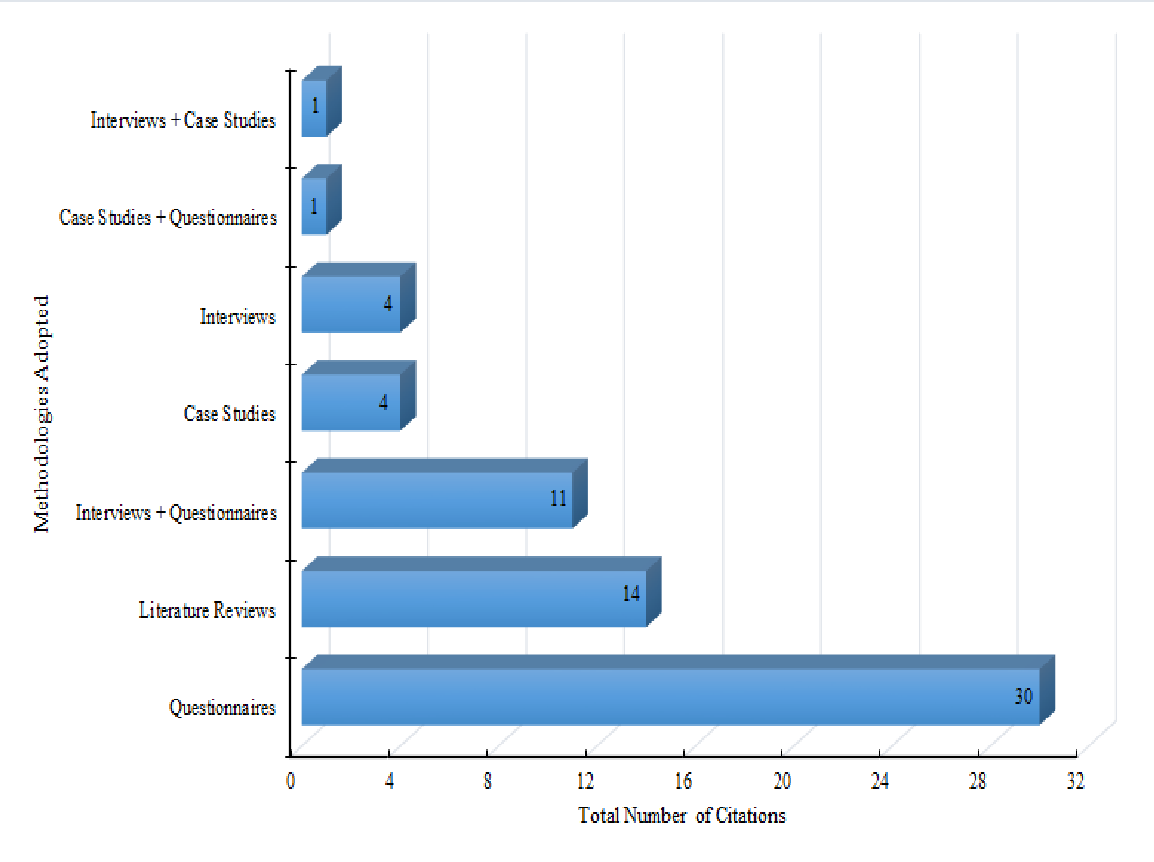

Figure 5. Distribution of research studies by adopted methodologies

4.4 Project Control Semantics

This section sheds light on the various terms and semantics used in the reviewed studies for making reference to factors related to the project controls CSF. The purpose is to unveil the spectrum of expressions reflecting what may be viewed by industry and research professionals to be falling under the umbrella of project controls. As such, the expressions extracted from the adopted 62 studies that cited "project controls" as a CSF were grouped into six main classes that are shown in Figure 6. Furthermore, Table 4 provides some examples of the exact semantics encountered in the reviewed studies citing “project controls” as a CSF. It can be deduced that the majority of the used semantics are found to be in connection with the efforts, systems, or mechanisms needed for implementing effective planning, monitoring, reporting, and control.

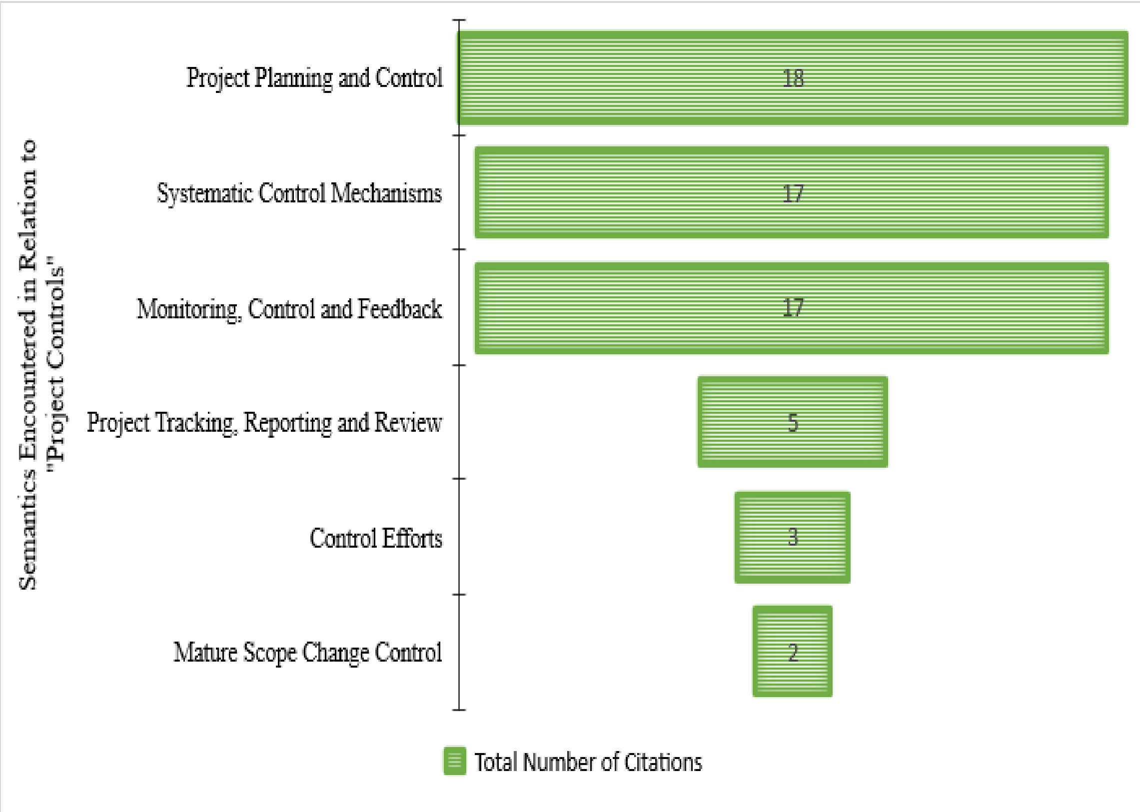

Figure 6. Frequency of semantics encountered in relation to project controls

Table 4. Semantics Encountered in Relation to "Project Controls"

Semantics Groups	Authors	Semantics Reported in the Literature
Project Planning and Control	De Wit (1988) Westerveld (2003) Ogwueleka (2011) Chipulu et al. (2014) Babatunde et al. (2016)	Effective project controls Sound operational project control Project planning and control Project controls Effective management control
Systematic Control Mechanisms	Ashley et al. (1987) Parfitt and Sanvido (1993) Chua et al. (1999) Adnan et al. (2012) Wai et al. (2013)	Control systems Control mechanisms Monitoring and control mechanisms Monitoring and control mechanisms Control systems
Monitoring, Control, and Feedback	Pinto and Covin (1989) Park (2009) Tabish and Jha (2011) Gingnell et al. (2014) Shatat (2015)	Monitoring and feedback Control and monitoring External monitoring and control Project monitoring Monitoring and evaluation of performance
Project Tracking, Reporting and Review	Cash and Fox II (1992) Chow and Cao (2008) Siddiqui et al. (2016)	Control and reporting Good project progress tracking Project tracking and reviews
Control Efforts	Jaselskis and Ashley (1991) Pollalis and Hanson Frieze (1993)	Control efforts Control abilities
Mature Scope Change Control	Cooke-Davies (2002) Hutchings and Christofferson (2005)	Allowing changes to scope only through a mature scope change control Cost control and control of change orders

4.5 Industry-Based Analysis

A more detailed track of analysis tackled the prominence of the above-mentioned findings from the perspective of the various industries investigated as part of the reviewed published work. To this effect, Figure 7 shows the breakdown of the reviewed project success studies by the type(s) of industry that were the subjects of investigations. It was found that 53 percent of the examined studies citing "project controls" as a CSF were concerned with the construction-type projects, whereas only 3 percent dealt with the success of research and development projects. Given the fact that the three other types involving "project management and organizational" projects, "all" projects, and "infrastructure" projects can also be considered to be related to the construction industry, the above general findings can then be construed to be of greatest pertinence to the construction industry, among the other investigated ones.

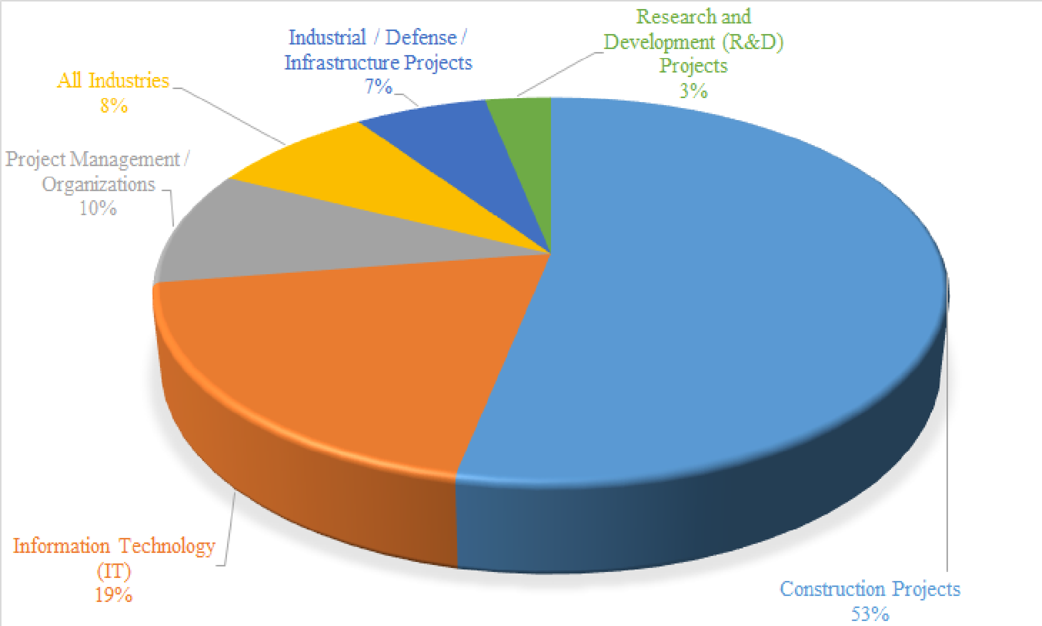

Figure 7. Distribution of research studies by types of projects

This dominant pertinence of the deduced CSFs to the construction-type projects is further confirmed through the distribution on a heading-by-heading basis of the encountered citations according to types of projects, as depicted in Figure 8. As it can be inferred, eight out of the 15 adopted CSF headings are found to be encountered in all six categories of projects, while four, two, and one of the synthesized headings are found to be applicable to five, three, and two categories of projects, respectively. Furthermore, the heading that embeds all the semantics related to "effective project monitoring and controls methods" is shown to have received the highest citation frequencies in four of the investigated project types, including that related to the construction sector with a total of 33 citations. In brief, project participants and stakeholders seem to have equivalent perceptions towards "project controls" as a leading CSF with similar positive impacts for projects of different industries.

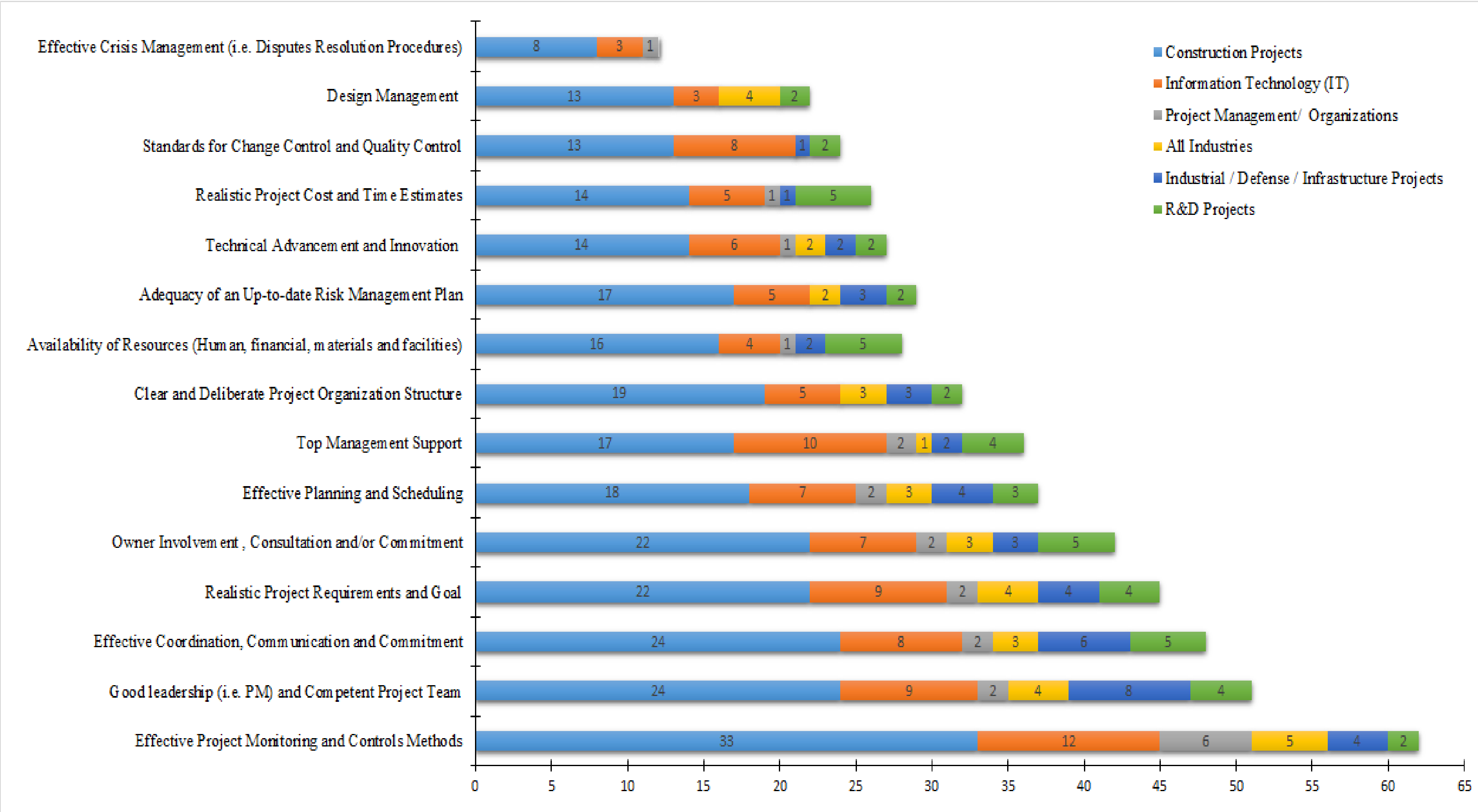

Figure 8. Distribution of Critical Success Factors (CSFs) by types of project

4.6 Ranking of "Project Controls" as a CSF

The relative importance of "project controls" as a CSF was further investigated in order to infer the ranking, if any, assigned to it under the 62 reviewed studies. As clearly evident from Figure 9, 31 of the adopted studies (50 percent) did not state any ranking for this highest-frequency factor. Conversely, the other 50 percent provided ranking information, albeit not always using an explicit or a unified way for doing that. Of these, 15 and 13 studies were considered to have ranked "project controls" to be of high and medium criticality, respectively.

To this end, in instances where an exact ranking is not stated, the inherent ranking was inferred, given each study's context, based on the location of the "project controls" factor relative to those of other factors. A high-importance ranking was assigned if it happens to fall above the 75th percentile, whereas medium- or low-importance rankings were adopted if falling between the 75th and 25th percentiles or below the 25th percentile, respectively.

Table 5 shows the distribution of the adopted studies, which cited "project controls" as a CSF, according to the inferred rankings and the types of projects. It can be readily noticed that the studies dealing with construction-type projects contributed to 11 of the 15 high-importance rankings encountered for the "project control" CSF. Moreover, more than fifty percent (18 studies) of the construction-specific studies (33 ones) revealed an importance ranking of at least medium.

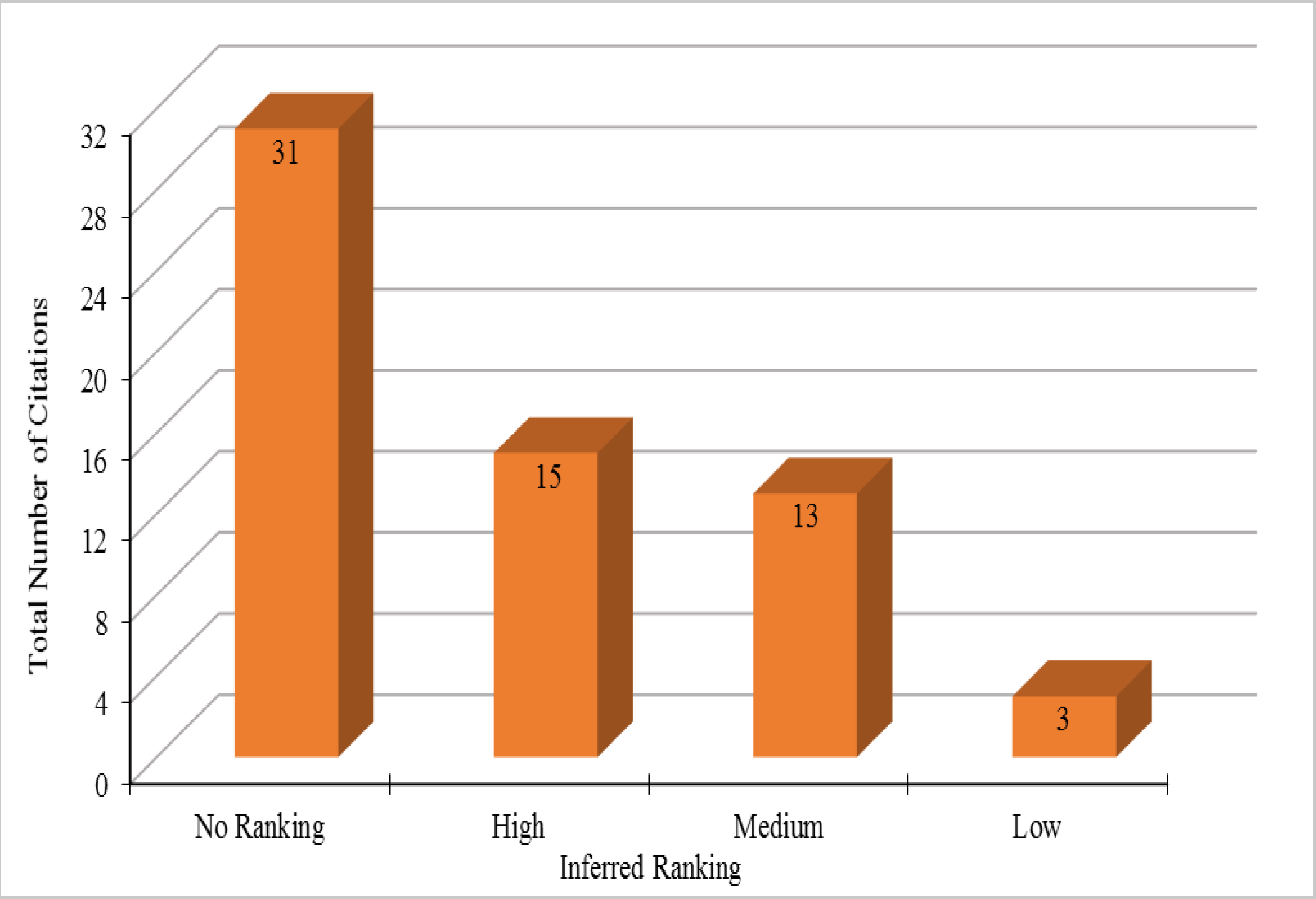

Figure 9. Inferred rankings of "Project Controls" as a CSF

Table 5. Types of Projects and Inferred Ranking of "Project Controls"

Inferred Ranking	**Types of Projects**						
	Construction Projects	***IT***	***R&D Projects***	***Industrial/Defense/ Infrastructure Projects***	***Project Management/ Organizations***	***All***	**Total**
No Ranking	12	7	2	4	3	3	31
High	11	2	0	0	2	0	15
Medium	7	3	0	0	1	2	13
Low	3	0	0	0	0	0	3
Total	33	12	2	4	6	5	**62**

CHAPTER 5

TECHNICAL AND IMPLEMENTATION BARRIERS OF EVM AS THE UNDERLYING PLATFORM FOR PROJECT CONTROLS

5.1 Preamble

The EVM method is undoubtedly a well-established technique offering an integrated approach for controlling a project's cost and schedule targets. Nevertheless, the literature has increasingly reported limitations hindering the use of this tool, as perceived by key players in a number of industries, and more so in the construction industry. As such, this chapter presents the research findings concerned with the delineation of the limitations that are said to be hindering the employability of EVM as a project control tool.

5.2 Introduction

The construction industry is huge, unpredictable, and requires immense capital expenditures (Kaliba et al. 2009). Nevertheless, it has seldom been reported that the project was completed on time, to budget and at the required quality (Morris and Hough 1987). As such, client satisfaction during project execution is threatened due to cost overrun and/or schedule slippage (Kaliba et al. 2009). However, there are many uncertain factors that have probable bearing on project time and cost during project execution (Olawale and Sun 2015). To this effect, Barraza et al. (2004) stated the common uncertain factors that may occur in construction projects to include: (a) unanticipated cost fluctuations, (b) material shipment delays, (c) scope deviation, (d) variations in the project execution plan, and (e) poor subcontractor performance. Yet, the inferior performance of projects, leading to the disappointment of project stakeholders, appears to have become "the rule and not the exception" in the construction industry (Ika et al. 2012).

Research work on construction project success has been of increasingly substantial interest to various industries, including that of engineering and construction. Factors such as organizational rules, executive procedures, and environmental conditions have been recognized as being critical to the success of projects of all types and sizes (Pinto and Slevin 1989). Jaselskis and Ashley (1991) defined project success as a construction exertion perceived by the project manager, and therefore by his company, to obtain outstanding outcomes for key project participants. Similarly, Parfitt and Sanvido (1993) defined project success as the complete accomplishment of project objectives and expectations, related to a variety of factors, namely "technical, financial, educational, social, and professional issues". Al-Jibouri (2003) stated that "a project is highly unlikely to proceed in all respects entirely according to plan, particularly when the plan has been expressed in some detail." Additionally, Torp et al. (2004) conducted a survey on public projects in Norway and reported that "project planning and control" ranked third among the recognized critical success factors for project performance after "project organization" and "contract strategy". Furthermore, Chan et al. (2004) mentioned that the key factors leading to the success of construction projects, referred to as critical success factors (CSFs), can be classified into four essential groups, mainly related to: project, procurement, project management, and project participants. Likewise, Shtub et al. (2005) mentioned that effective monitoring and control system is an essential requirement in project-based organizations. Toor and Ogunlana (2009) stated that "effective project planning and control" is a top critical success factor for construction projects. To this effect, Demachkieh and Abdul-Malak (2018) confirmed the continued need for improving the efforts, systems, or mechanisms related to putting in place effective project control processes for achieving success in all industries and more critically for projects in the construction industry.

As such, the delivery of construction projects under the pressure of respecting the agreed completion time and contract price, and while being in accordance with the set quality standards, serves the interests of all project participants (Bubshait and Almohawis 1994; Gorse and Emmitt 2003; Aliverdi et al. 2013). Accordingly, this calls for the need of innovative planning, scheduling, and control mechanisms (Abeyasinghe et al. 2001; Azimi et al. 2011; Chen et al. 2012; Colin et al. 2015; Hazır 2015; Olawale and Sun 2015), intended to: (1) specifying the performance standards, (2) measuring actual cost and progress and comparing them with the planned values, (3) reporting the project status of the project, (4) pinpointing and analyzing the deviations from the project plans, and (4) implementing prompt corrective measures in case of unsatisfactory actual status outcomes so that project targets are achieved (Nicolas and Steyn 2008; Kerzner 2013; Acebes et al. 2014; Hazır 2015; Willems and Vanhoucke 2015). In a project context, Reschke and Schelle (1990) defined project control as "the skill required to bring a project from the start to the end without jeopardizing pre-defined goals". As reported by Görög (2009), planning and control are "twin brothers" during project delivery; adequate control processes cannot be efficiently applied without sufficient planning.

Hoffman et al. (2007) found that 72% of 332 projects sponsored by the US Air Force were not finished within the baseline planned duration. In addition, Shehu et al. (2014) conducted a survey of 359 projects in Malaysia and revealed that 55% of those projects experienced cost escalations. To this effect, time and cost are two of the essential areas that need to be controlled in construction projects (Cooke and Williams 2013). Ruskin and Estes (1994) found that project cost control is confirming that project work packages are executed within their corresponding budget (Ruskin and Estes 1994). Therefore, it is critical to control cost in construction projects, which usually comprise a substantial amount of capital investment, to serve the interests of both the owner and the contractor (Olawale and Sun 2015). On the other hand, schedule control involves assessing the project schedule status, assessing whether changes have taken place or must have, and dealing with schedule changes (Heldman 2010).

One of the most well-known techniques to evaluate a project's performance is the earned value management (EVM) method (Fleming and Koppelman 2009). EVM is undeniably one of the most straightforward and most extensively disseminated tools for monitoring and controlling construction projects at regular time intervals (Willems and Vanhoucke 2015). The Project Management Institute (2008) defined EVM as "a method for integrating scope, schedule, and resources, and for measuring project performance." This control tool adopts a set of key parameters and provides the user with a set of performance measures used for evaluating the project status and forecasting the expected-at-completion figures for the duration and cost given the project performance-to-date (Vanhoucke 2018). According to Chou et al. (2010), EVM is an important project controls technique for project managers to evaluate performance and perceive problems early enough for corrective actions to be taken, due to its ability to consolidate cost, schedule and technical performance under the same framework. Recently, Czemplik (2014) considered EVM as a worldwide standard for monitoring and controlling project performance. Similarly, Willems and Vanhoucke (2015) reported that EVM was developed with the purpose of integrating cost, time, and scope to effectively and proficiently monitor and control a project during construction. In fact, a wide agreement is spread among academicians, researchers, and practitioners about the effectiveness of EVM as a main project monitoring and controls tool throughout the life of the project with broad research on the extensions and applications of this tool in the recent literature (Bhosekar and Vyas 2012; Vanhoucke 2012; Khamooshi and Golafshani 2014; Kim 2014; Hazır 2015; Chen et al. 2016; Chang and Yu 2018).

Although EVM is gaining a lot of importance among project managers, many researchers and practitioners have proclaimed various shortcomings associated with implementing this technique in practice, some are found to be related to EVM technical aspects (Moslemi-Naeni et al. 2011; Hall 2012; Narbaev and De Marco 2014; Babar et al. 2016; Najafi and Azimi 2016), whereas others are found to be concerned with EVM practical implementation issues (Valle and Soares 2006; Bell 2009; Luis Felipe Cândido et al. 2014). In light of the backdrop stated above, the work presented in this research has been motivated by the need to emphasize the significant importance of applying adequate project controls processes in order to achieve project success and to identify the main shortcomings hindering the employability of EVM as a main project control tool, with the aim of gaining discernment on how the reported EVM shortcomings may probably be overcome as a way to lessen the magnitude of cost and time overruns and improve the construction project control process in practice.

5.3 EVM Limitations

This section provides a review of the historical genesis, evolution, and standardization of the EVM technique, along with a thorough in-depth analysis of the limitations and challenges reported to be hindering EVM application, which was used as the foundation for mapping the improvements encountered in the literature, as a step towards better packaging the enhanced capabilities of the technique for extending its employment on construction projects of various organizational deliverance structures and contractual frameworks.

5.4 Temporal Distribution and General Screening

The frequencies related to the encountered EVM limitations were disseminated according to their years of publication, as shown in Figure 10. It is found that a large volume of research work related to EVM has been performed in the last three decades, and especially from 1998 and so on, the year during which the American National Standards Institute (ANSI) and the Institute of Electrical and Electronics Engineers (IEEE) identified Project Management Body of Knowledge (PMBOK) as a standard, (i.e. EVM Standard ANSI/EIA-748"). To be noted is that although EVM was first initiated and endorsed by the U.S. Department of Defense in the early 60's, research concerned with its limitations is much more contemporary, with a total of 80 citations found to be occurring in the current decade.

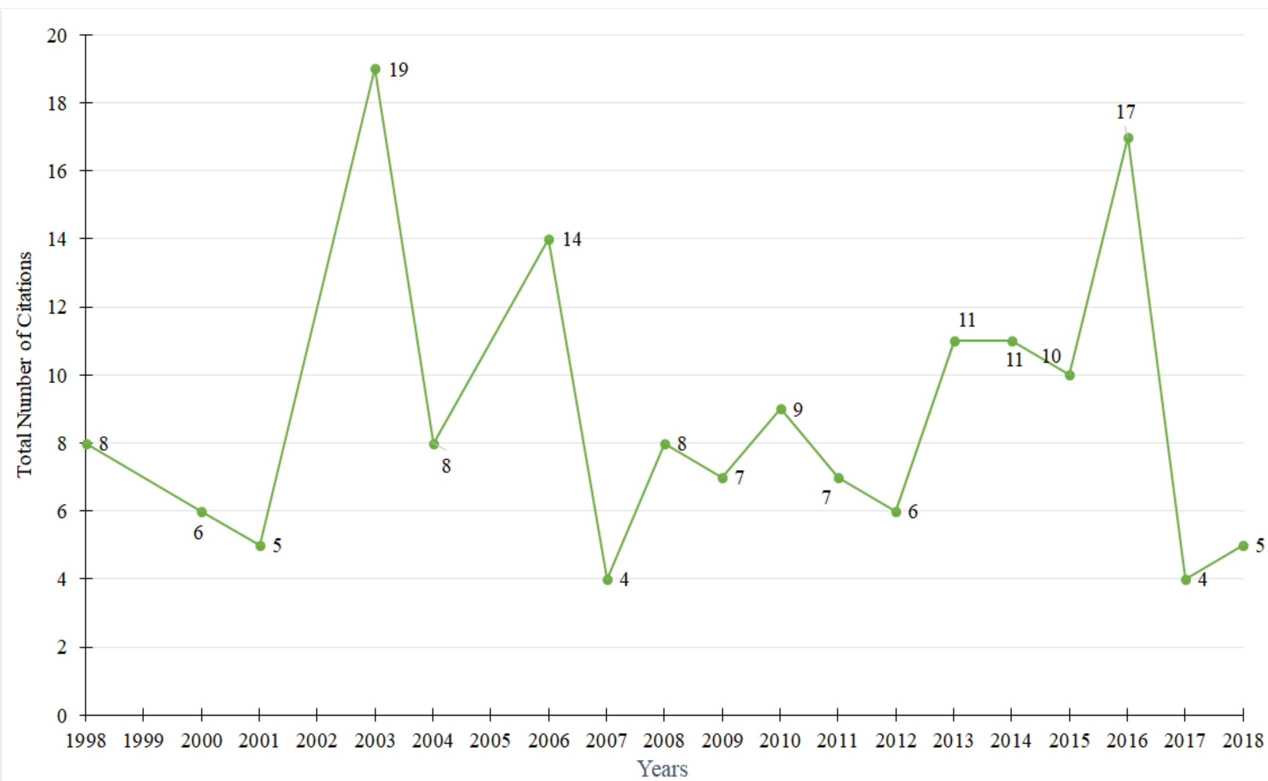

Figure 10. Distribution of encountered EVM limitations

To this end, the 81 reviewed studies made reference to various shortcomings said to be hindering the applicability of this project controls tool. An in-depth analysis and examination of the reported limitations allowed their sorting and classification into broad headings or classes describing the main hindrances deemed to be limiting the employability of EVM. Accordingly, the generated sixteen headings, as shown in Figure 11, were classified in an increasing order of occurrence frequency. It can be safely deduced that the two headings related to the quality of inputs (namely, faulty results in calculating the percent complete) and outputs (i.e., mistaken results of duration estimate-at-completion figure), have received the highest citation frequencies of 24 and 21 respectively, compared to other human and process-related EVM limitations, such as poor understanding of EVM method, excessive rules and formulas, and employee and contractor resistance.

To this effect, various technical related challenges, including inaccurate results of SV and SPI at the final stages of the project and use of deterministic tools, were shown to have been cited significantly in the reviewed literature. Furthermore, Table 6 provides some examples of the exact semantics encountered in the reviewed research studies describing a variety of EVM limitation classes covering the technical and practical employment of this project controls tool. The list of all references used to retrieve the main difficulties deemed to have prevented the method’s applicability in the construction industry is shown in Table 7.

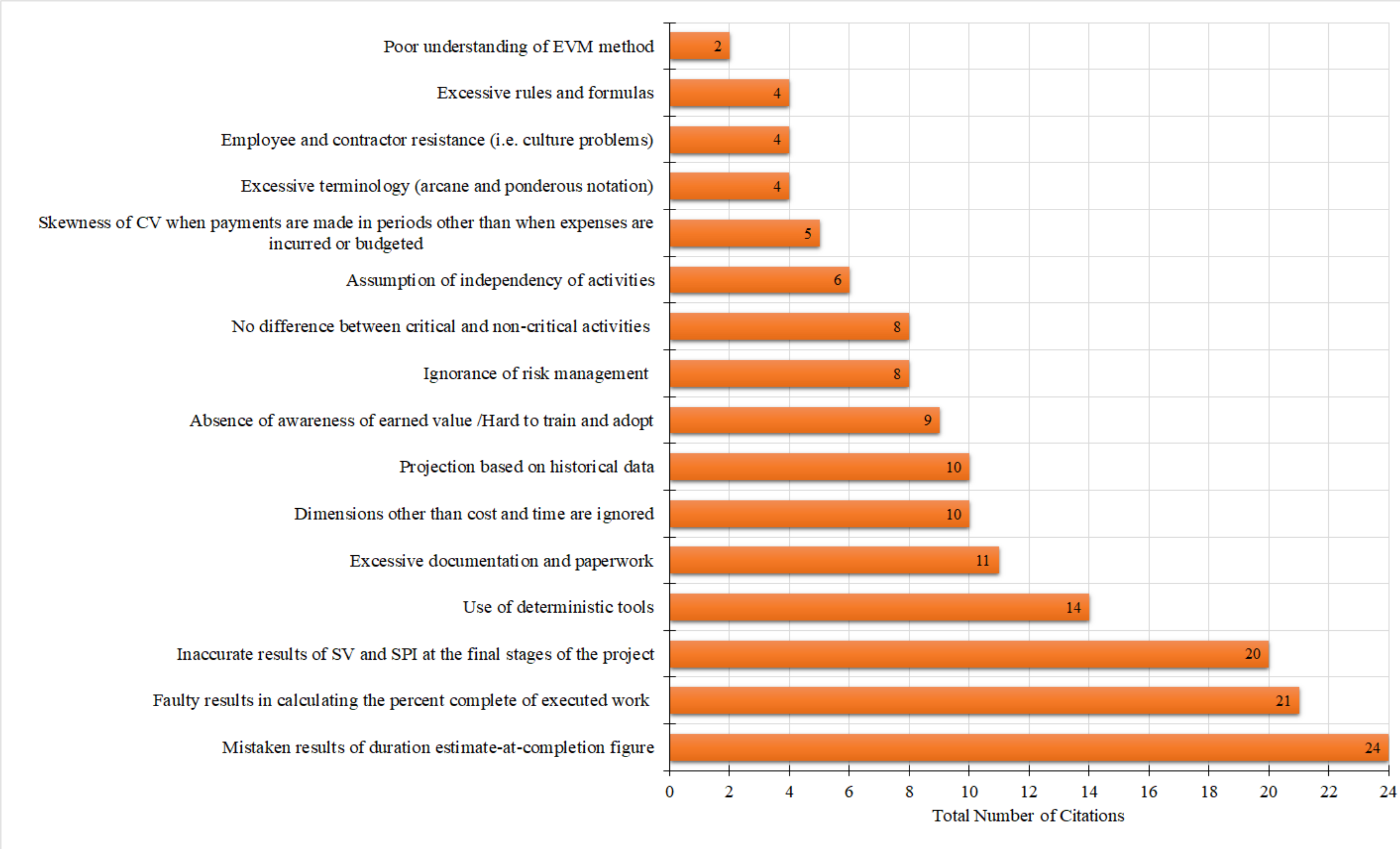

Figure 11. Frequency of reported EVM limitations classes

Table 6. Semantics Encountered in Relation to EVM Limitations

Authors	Reported EVMS Limitations	EVM Limitation Class
Czarnigowska (2008)	As there are usually both critical and non-critical tasks in the schedule, a delay of a single task does not necessarily mean that the project finish date is going to be affected. The earned value model does not allow for this fact and each task deviation is reflected in the project's SV and SPI.	No difference between critical and non-critical activities
Vanhoucke and Shtub (2011)	The main disadvantage of the Earned Value system is its inability to distinguish between critical and non-critical activities.	
Zhong and Wang (2011)	The traditional EV ignored the difference between critical and non-critical activities of work items and ignored the restraints of the critical activities in the whole project.	
Hall (2012)	EV does not distinguish between critical and noncritical activities, although time variance is clearly a more serious concern for critical activities.	
El-Shaer (2013)	Forecasting accuracy of ESM by removing/decreasing the false warning effects caused by the non-critical activities.	
Najafi and Azimi (2016)	SPI and SV ignore critical path and precedence relations between activities.	
Kim and Ballard (2000)	Where cost risk has been contractually shifted to others, EVM is less popular.	Ignorance of risk management
Solomon (2004)	EVMS was not designed to manage risk and does not even mention the subject.	
Acebes et al. (2013)	EVM variables and variances talk about what happened in the past, whereas risk management is concerned about the future.	
Hernández et al. (2013)	EVM contains no guidelines on risk management.	
Czemplik (2014)	EVM should be modified, taking into account also the future risks, in order to be successfully used for project time management.	
Babar et al. (2016)	EVM forecasts are still influenced by project risks and uncertainties, leading to inconsistency between EAC results obtained through standard formulae.	

Table 7. List of Authors of Reported EVM Limitations Classes

Limitations of EVM	Research Studies
Mistaken results of duration estimate-at-completion figure	(Kim and Ballard 2000); (Al-Jibouri and Mawdesley 2001); (Anbari 2003); (Corovic 2006); (Vandevoorde and Vanhoucke 2006); (Gardoni et al. 2007); (Czarnigowska 2008); (Lipke et al. 2009); (Kim and Reinschmidt 2010); (Caron et al. 2013); (Elshaer 2013); (Hernández et al. 2013); (Luis Felipe Cândido et al. 2014); (Chen 2014); (Czemplik 2014); (Narbaev and De Marco 2014); (Kim et al. 2015); (Babar et al. 2016); (Borse and Biswas 2016); (Chen et al. 2016); (Caron et al. 2016); (Warburton and Cioffi 2016); (Batselier and Vanhoucke 2017); (Chang and Yu 2018)
Faulty results in calculating the percent complete of executed work	(Brandon and Daniel 1998); (Anbari 2003); (Kim et al. 2003); (Ruskin 2004); (Solomon 2004); (Czarnigowska 2008); (Langford 2008); (Nicolas and Steyn 2008); (Lukas 2010); (Kim and Reinschmidt 2010); (Naderpour and Mofid 2011); (Moslemi-Naeni et al. 2011); (Hernández et al. 2013); (Turkan et al. 2013); (Luis Felipe Cândido et al. 2014); (Bosché et al. 2015); (Willems and Vanhoucke 2015); (Salehipour et al. 2015); (Babar et al. 2016); (Forouzanpour et al. 2016); (Nkiwane et al. 2016)
Inaccurate results of SV and SPI at the final stages of the project	(Lipke 2003); (Henderson and Lipke 2006); (Corovic 2006); (Vandevoorde and Vanhoucke 2006); (Buyse et al. 2006); (Czarnigowska 2008); (Vanhoucke and Vandevoorde 2008); (Christensen-Day 2010); (Rodrigues 2010); (Warburton 2011); (Pajares and López-Paredes 2011); (Lipke 2012); (Hernández et al. 2013); (Khamooshi and Golafshani 2014); (Batselier and Vanhoucke 2015); (Willems and Vanhoucke 2015); (Borse and Biswas 2016); (Borges Jr and Mário 2017), (Chang and Yu 2018); (Hammad et al. 2018)
Use of deterministic tools	(Barraza et al. 2000); (Kim and Ballard 2000); (Kim et al. 2003); (Barraza et al. 2004); (Barraza and Bueno 2007); (Bagherpour et al. 2010); (Kim and Reinschmidt 2010); (Moslemi-Naeni et al. 2011); (Caron et al. 2013); (Azeem et al. 2014); (Willems and Vanhoucke 2015); (Borse and Biswas 2016); (Du et al. 2016); (Wood 2016)
Excessive documentation and paperwork	(Brandon and Daniel 1998); (Christensen 1998); (Al-Jibouri and Mawdesley 2001); (Al-Jibouri 2003); (Kim et al. 2003); (Buyse et al. 2006); (Fleming and Koppelman 2006); (Bell 2009); (Lukas 2010); (Hall 2012); (Willems and Vanhoucke 2015)
Dimensions other than cost and time are ignored	(Ballard and Koskela 1998); (Kim and Ballard 2000); (Rozenes et al. 2004); (Solomon 2004); (Hall 2012); (Hernández et al. 2013), (Luis Felipe Cândido et al. 2014); (Hazır 2015); (Dodson et al. 2015); (Babar et al. 2016)
Projection based on historical data	(Al-Jibouri and Mawdesley 2001); (Al-Jibouri 2003); (Anbari 2003); (Kim et al. 2003); (Solomon 2004); (Cioffi 2006); (Gardoni et al. 2007); (Kim and Reinschmidt 2009); (Czemplik 2014); (Khamooshi and Abdi 2016)
Absence of awareness of earned value /takes too much time to train/ Hard	(Brandon and Daniel 1998); (Christensen 1998); (Al-Jibouri and Mawdesley 2001); (Anbari 2003); (Al-Jibouri 2003); (Kim et al. 2003); (Solomon 2004); (Valle and Soares 2006); (Bell 2009)

to adopt	
No difference between critical and non-critical activities	(Vanhoucke and Vandevoorde 2007); (Czarnigowska 2008); (Vanhoucke and Shtub 2011); (Zhong and Wang 2011); (Hall 2012); (Elshaer 2013); (Najafi and Azimi 2016); (Vanhoucke 2018)
Ignorance of risk management	(Kim and Ballard 2000); (Solomon 2004); (Acebes et al. 2013); (Hernández et al. 2013); (Czemplik 2014); (Babar et al. 2016); (Moradi et al. 2017); (Tereso et al. 2017)
Assumption of independency of activities	(Ballard and Koskela 1998); (Kim and Ballard 2000); (Hall 2012); (Kim et al. 2015); (Najafi and Azimi 2016); (Vanhoucke 2018)
Skewness of CV when payments are made in periods other than when expenses are incurred or budgeted	(Anbari 2003); (Czarnigowska 2008); (Nicolas and Steyn 2008); (Bell 2009); (Lukas 2010)
Excessive terminology (arcane and ponderous notation)	(Al-Jibouri 2003); (Cioffi 2006); (Buyse et al. 2006); (Luis Felipe Cândido et al. 2014)
Employee and contractor resistance (i.e. culture problems)	(Brandon and Daniel 1998); (Kim et al. 2003); (Valle and Soares 2006); (Bell 2009)
Excessive rules and formulas	(Al-Jibouri and Mawdesley 2001); (Al-Jibouri 2003); (Kim et al. 2003); (Cioffi 2006)
Poor understanding of EVM method	(Kim et al. 2003); (Bell 2009)

5.5 EVM Time-Phased Limitations

A more detailed track of analysis tackled the significance of the above-mentioned research findings dealing with EVM limitations from the perspective of the chronological evolvement explored as part of the reviewed published work. To this effect, Figure 12 shows the breakdown of the EVM citations according to their years of publication. It is found that a number of EVM shortcomings were prevailing in the first years of EVM adoption, corresponding to limitations No. 1 to 6, shown in Figure 12. However, various technical-related shortcomings, corresponding to limitations No. 1, 7, 8, and 15, are more dominant in the current decade, as per the frequencies shown in Figure 12.

To this effect, some human- and process-related shortcomings, such as poor understanding of EVM method, too much rules and formulas, employee and contractor's resistance and absence of awareness of earned value /hard to train and adopt, are no longer perceived as significant challenges over the last five years. It can be argued that this is probably due to the fact that EVM is reaching greater acceptance as a result of many improvements and extensions associated with mutually lessening EVM deficiencies and improving its potentials as a main project controls tool in the construction industry.

As it can be inferred from Figure 12, the highest number of new encountered EVM limitations and reported citations (i.e. 19 citations) are found to have been occurring in 2003, the year during which an extensive number of improvements dealing with ways and means that can improve the representation, usage, and measurements of the basic EVM traditional metrics have been proposed (Anbari 2003; Jacob 2003; Lipke 2003). Furthermore, it is shown that starting year 2009 and on, no new EVMS limitations were found in the reviewed literature. In brief, industry professionals and researchers seem to have full-fledged perceptions towards the main challenges hindering the wide employability of this technique in construction projects.

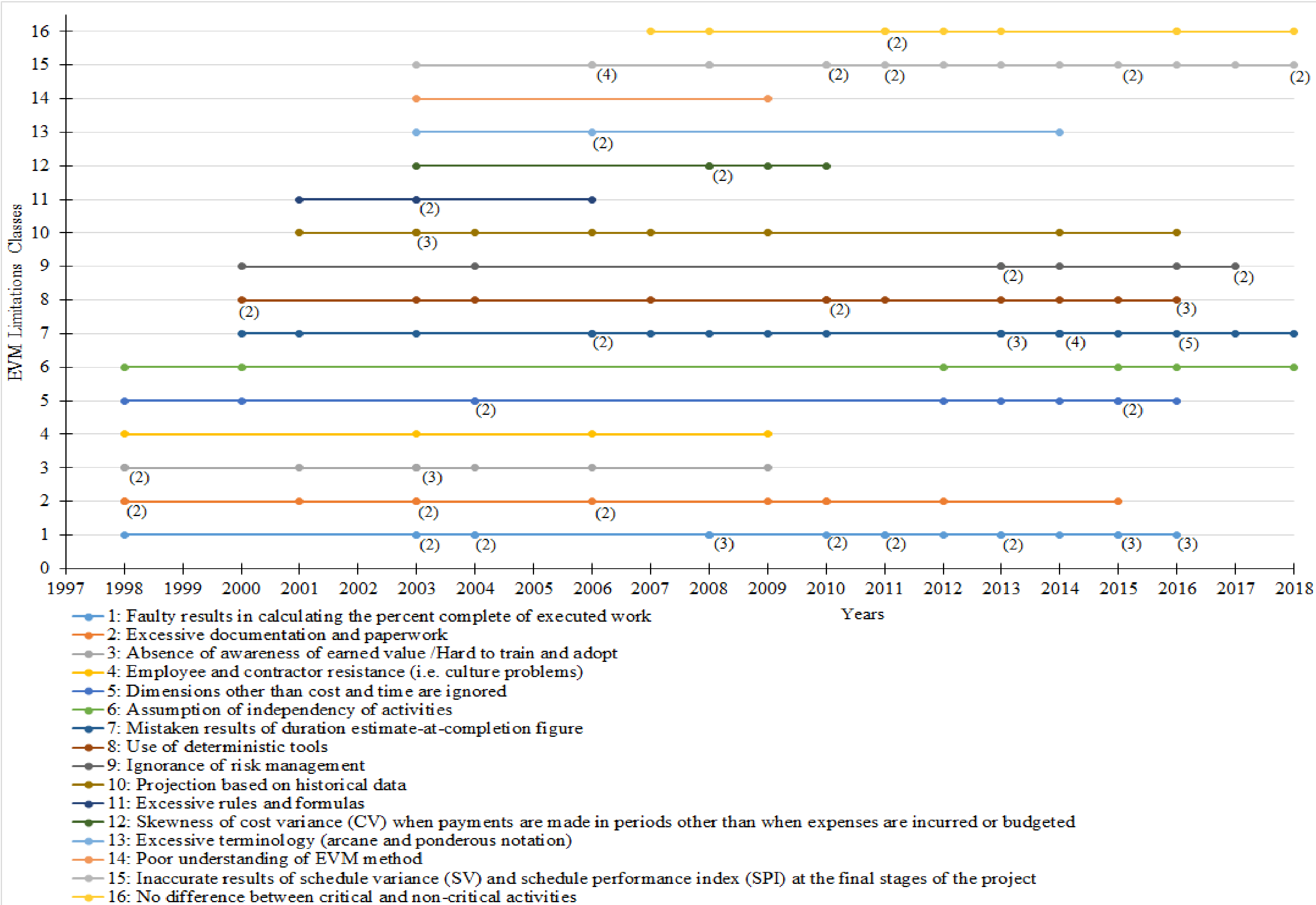

Figure 12. Chronological listing of reported EVM limitations

5.6 EVM Limitations Classification Framework

As revealed in the previous sections, the in-depth review of all encountered shortcomings allowed their classification into sixteen general headings describing the main obstacles reported to be hindering the applicability of this tool. Accordingly, Figure 13 presents a proposed classification of the gleaned literature-based limitations into six broad classes of barriers, four of which are found to be related to EVM technical aspects, whereas the other two are found to be concerned with EVM practical implementation issues, providing richer depiction of what is reported to be encumbering the use of this methodology. It can be seen that the technical-related heading, namely the accuracy of metrics, has received the highest citation frequencies of 67, compared to those in relation to human- and process-related shortcomings, as shown in Figure 13. However, a significant volume of research work dealing with approaches that can improve the acceptability of this technique and contribute to the learning of EVM concepts and their application has been performed in order to lessen the impact of EVM shortcomings related to practical implementation issues. Moreover, it is found that the number of technical barriers is about four times that of practical barriers, showing the significant prominence of technical over implementation barriers, thus shedding light on prospective research areas for extensions and practical applications of EVM method for monitoring and controlling project cost and schedule in order to conquest the much-reported EVM limitations.

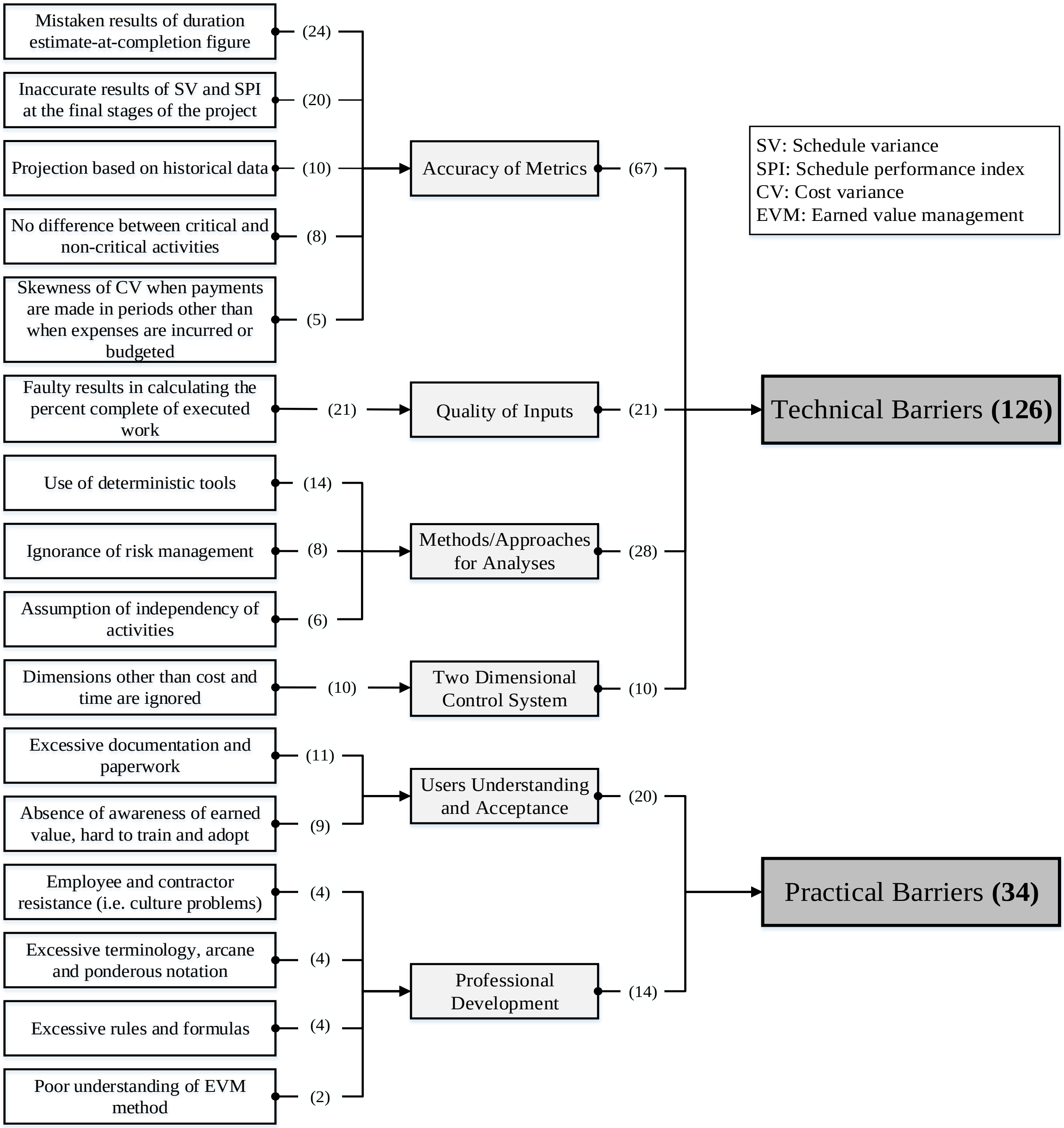

Figure 13. Technical and practical classification of EVM limitations

CHAPTER 6

SYNTHESIS OF IMPROVEMENTS TO EVM METRICS REPRESENTATION

6.1 Preamble

This chapter presents the findings concerned with the identification and classification of the main tracks along which encountered enhancements can be classified, with the aim of gaining discernment on how the reported EVM limitations may have probably been resolved.

6.2 Introduction

The execution of “complex, large scale, resource intense projects” relies on project management tools and methods to help better plan, control, monitor, and predict the project’ diverse performance indicators. To this end, the earned value management (EVM) method is considered as the most adequate monitoring and control tool used for tracking the project status and providing approaches and tools to infer the expected final figures for a project’s duration and cost (Moreira and Figueiredo 2012). Similarly, Vanhoucke (2012) considered the EVM as an early “warning signal system”, spotting problems and identifying opportunities in a straightforward way. It is further added that, in combination with the project schedule, this method permits to take corrective actions on troubled activities, especially those on the critical path. Likewise, Chou et al. (2010) defined EVM as a project performance measurement tool that helps control the progress of a project in an objective manner. Due to its ability to consolidate cost, schedule and technical performance, EVM has become an important project control technique for project managers to evaluate performance and perceive problems early enough for corrective actions to be taken (Chou et al. 2010). Extensive research has also been dedicated to the extensions and applications of EVM for monitoring and controlling project cost and schedule. In that regard, some studies have tried to conquest the much reported earned value limitations, examples of which are found to relate to enhancements proposed in respect of the traditional use of deterministic EVM tools, including the introduction of fuzzy indices (Moslemi-Naeni et al. 2011; Ponz-Tienda et al. 2012; Aliverdi et al. 2013; Hajali-Mohamad et al. 2016; Wood 2016), stochastic S-curves (Barraza et al. 2004), and statistical tools (Colin and Vanhoucke 2015; Rubio et al. 2015). As such, this chapter summarizes the research findings dealing with the identification and categorization of the essential tracks along which the reported improvements can be classified, with the purpose of gaining perspicacity on how the encountered EVM shortcomings may have possibly been resolved.

6.3 EVM Improvement Studies: Classification Database Summary

As mentioned earlier-on, the search of the improvement studies yielded a total of 248 research studies. To this effect, 137 research studies were categorized into six classes, forming the database developed from the selection process. To be noted is that 111 studies relevant studies, tackling the automation of data collection and progress tracking in construction sites, are not included in the analysis provided in this chapter and are thoroughly explained in the following section. The objective of the classification database is to categorize all the encountered improvements research studies in explanatory classes. These included: year of publication, author(s), subject, main improvement(s), reported limitations(s) and reported future research area(s), as described in Table 8. That being said, this database is used to deduce the main contributions proposed in the existing literature and to make recommendations for wide employment of this technique in monitoring, evaluating, and controlling the progress of construction projects.

Table 8. Classification Database Template

Data	Description
Year	Year of publication of the paper
Author(s)	Names of all authors
Subject	Main topic of the paper
Main Improvement(s)	Main theoretical and/or empirical improvement or contribution to the traditional EVMS
Reported Limitation(s)	Possible design features or weaknesses that are generally out of the authors' control (i.e. limited funding, choice of research design, statistical model constraints, or other factors)
Reported Future Research Area(s)	New perception and innovative tactics for exploring the research problem based on the outcomes of the study

6.4 Temporal Distribution of Improvement Studies

The reviewed 137 research studies were grouped and organized according to their years of publication, as shown in Figure 14. It is obvious that the last three years (i.e., 2015-2018) included a large number of research studies concerned with the proposed main improvements to the EVM technique as a main project control in the construction industry. To be noted is that about 60 percent (81 studies) of the 137 filtered research studies were achieved in the current decade, highlighting on the importance of the reported enhancements studies on preventing the effects of EVM shortcomings hindering the employability of this tool, with the purpose of achieving wider applicability of this technique for project controls.

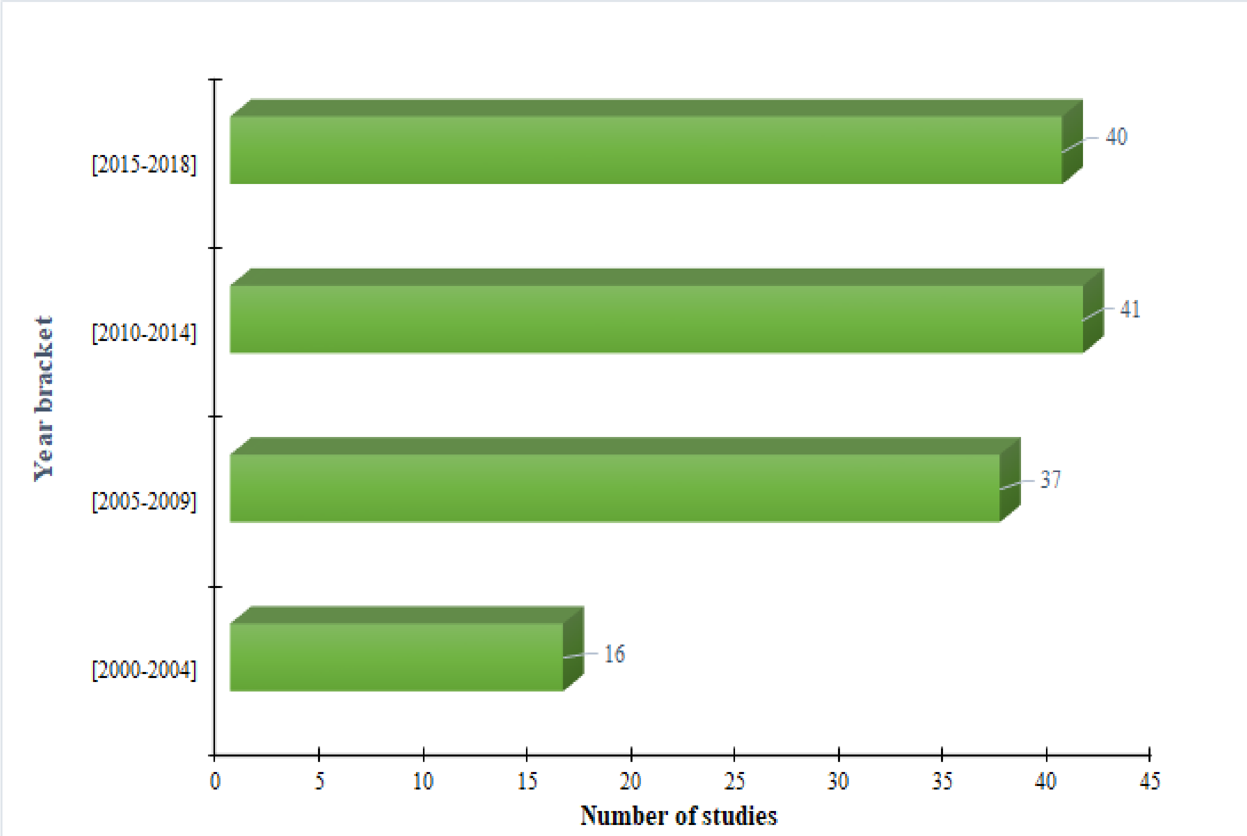

Figure 14. Temporal distribution of encountered EVM improvements

6.5 Breakdown of Improvements by EVM Limitations

A more detailed analysis track dealt with the implication of the above-mentioned research findings from the viewpoint of the several limitations as part of the reviewed improvements-related studies. As such, Table 9 shows the distribution of the 137 encountered studies spread over the already-generated EVM challenges. To be noted is that some of the EVM limitations headings deduced from Figure 11 were consequently joined as part of this analysis, after identifying that a number of encountered studies were found to have each tackled more than one class. This has produced a revised total of thirteen EVM shortcomings classes, as listed under Figure 15. It can be deduced that the research effort associated with EVM enhancements is found to be following the same rate as to the occurrence frequencies of EVM limitations. That being said, it is obvious that the top three frequencies (19, 16 and 12 percent) of encountered enhancements (totaling 47 percent) are found to have been connected with the three top-ranked EVM shortcomings, associated with technical barriers, and more specifically to the accuracy of metrics and quality of inputs, corresponding to slices 1, 2 and 3 in Figure 15.

Table 9. Distribution of Enhancements for Each Limitation Class

EVM Limitations	Improvement studies
Faulty results in calculating the percent complete of executed work	(Paquin et al. 2000), (Lipke 2004), (Noori et al. 2008), (Moslemi-Naeni and Salehipour 2011), (Moslemi-Naeni et al. 2011), (Cheng et al. 2011), (Lipke 2011), (Turkan et al. 2012), (Lin et al. 2012), (Hernández et al. 2013), (Mortaji et al. 2013), (Vanhoucke 2013), (Turkan et al. 2013), (Naeni et al. 2014), (Chen 2014), (Kim et al. 2015), (Dodson et al. 2015), (Forouzanpour et al. 2016), (Chen et al. 2016), (Moradi et al. 2017), (Demachkieh and Abdul-Malak 2018)
Excessive documentation and paperwork & Employee and contractor resistance (i.e. culture problems) & Poor understanding of EVM method	(Songer and Hays 2003), (Cheung et al. 2004), (Moselhi et al. 2004), (Moselhi et al. 2004), (Warhoe 2004), (Fermilab 2006), (Fleming and Koppelman 2006), (Fleming and Koppelman 2006), (Ghanem and AbdelRazig 2006), (Czarnigowska 2008), (Humphreys and Visitacion 2009), (Ju and Xu 2017), (Orgut et al. 2018)
Absence of awareness of earned value /Hard to train and adopt	(Kim et al. 2003), (Valle and Soares 2006), (Czarnigowska 2008), (von Wangenheim et al. 2012), (Virle and Mhaske 2013), (Chen et al. 2015)
Dimensions other than cost and time are ignored	(Paquin et al. 2000), (Lipke 2004), (Hernández et al. 2013), (Dodson et al. 2015), (Tatlari and Kazemipoor 2015), (Kim et al. 2015)
Assumption of independency of activities	(Howes 2000), (Kim et al. 2015)
Mistaken results of duration estimate-at-completion figure	(Barraza et al. 2000), (Anbari 2003), (Jacob 2003), (Lipke 2003), (Barraza et al. 2004), (Henderson 2004), (Jacob and Kane 2004), (Vandevoorde and Vanhoucke 2006), (Henderson and Lipke 2006), (Vanhoucke and Vandevoorde 2007), (Barraza and Bueno 2007), (Iranmanesh et al. 2007), (Vanhoucke and Vandevoorde 2007), (Lipke 2009), (Pewdum et al. 2009), (Rujirayanyong 2009), (Kim and Reinschmidt 2009), (Lipke et al. 2009), (Kim and Reinschmidt 2010), (Caron et al. 2013), (Aliverdi et al. 2013), (Mortaji et al. 2014), (Wauters and Vanhoucke 2014), (Khamooshi and Golafshani 2014), (Azeem et al. 2014), (Batselier and Vanhoucke 2015), (Batselier and Vanhoucke 2015), (Batselier and Vanhoucke 2015), (Batselier and Vanhoucke 2015), (Khamooshi

	and Abdi 2016), (Warburton and Cioffi 2016), (Caron et al. 2016), (Batselier and Vanhoucke 2017), (Borges Jr and Mário 2017), (Chang and Yu 2018)
Use of deterministic tools	(Lipke 2002), (Nassar et al. 2005), (Gardoni et al. 2007), (Kim and Reinschmidt 2009), (Lipke et al. 2009), (Kim and Reinschmidt 2010), (Feng et al. 2010), (Kim and Reinschmidt 2011), (Aliverdi et al. 2013), (Caron et al. 2013), (Kim and Kim 2014), (Mortaji et al. 2014), (Azeem et al. 2014), (Colin and Vanhoucke 2015), (Kim 2015), (Khamooshi and Abdi 2016), (Wood 2016), (Lipke 2016)
Ignorance of risk management	(Moslemi-Naeni et al. 2011), (Pajares and López-Paredes 2011), (Lipke 2011), (Moslemi-Naeni and Salehipour 2011), (Ponz-Tienda et al. 2012), (Maravas and Pantouvakis 2012), (Mortaji et al. 2013), (Caron et al. 2013), (Salari et al. 2014), (Czemplik 2014), (Naeni et al. 2014), (Colin and Vanhoucke 2014), (Salehipour et al. 2015), (Rubio et al. 2015), (Acebes et al. 2015), (Hajali-Mohamad et al. 2016), (Wood 2016), (Vanhoucke and Colin 2016), (Moradi et al. 2017), (Martens and Vanhoucke 2018)
Projection based on historical data	(Cioffi 2005), (Mavrotas et al. 2005), (Blyth and Kaka 2006), (Chao and Chien 2009), (Chao and Chien 2010), (San Cristóbal et al. 2015), (Chao and Chen 2015), (Wang et al. 2016), (San Cristóbal 2017)
Skewness of cost variance (CV) when payments are made in periods other than when expenses are incurred or budgeted	(Park et al. 2005), (Lipke 2009), (Lipke 2009), (De Marco and Narbaev 2013), (Subramani et al. 2014), (de Souza et al. 2015), (Kim 2015), (Picornell et al. 2016),
Excessive terminology (arcane and ponderous notation) & Excessive rules and formulae	(Cioffi 2006)
Inaccurate results of schedule variance (SV) and schedule performance index (SPI) at the final stages of the project	(Lipke 2003), (Nassar et al. 2005), (Corovic 2006), (Cioffi 2006), (Lipke 2007), (Leu and Lin 2008), (Warburton and Kanabar 2008), (Noori et al. 2008), (Kim 2009), (Fleming and Koppelman 2009), (Lipke 2009), (Rodrigues 2010), (Lipke 2011), (Moslemi-Naeni et al. 2011), (Moslemi-Naeni and Salehipour 2011), (Warburton 2011), (Lipke 2012), (Mortaji et al. 2013), (Colin and Vanhoucke 2014), (Kim 2014), (Kim and Kim 2014), (Salari et al. 2014), (Naeni et al. 2014), (Vanhoucke et al. 2015), (Moradi et al. 2017), (Lipke 2017), (Hammad et al. 2018), (Vanhoucke 2018)
No difference between critical and non-critical activities	(Lo 2007), (Vanhoucke and Vandevoorde 2008), (Vanhoucke 2010), (Zhong and Wang 2011), (Kesheh 2012), (Elshaer 2013), (Lipke 2015), (Vanhoucke and Colin 2016), (Najafi and Azimi 2016)

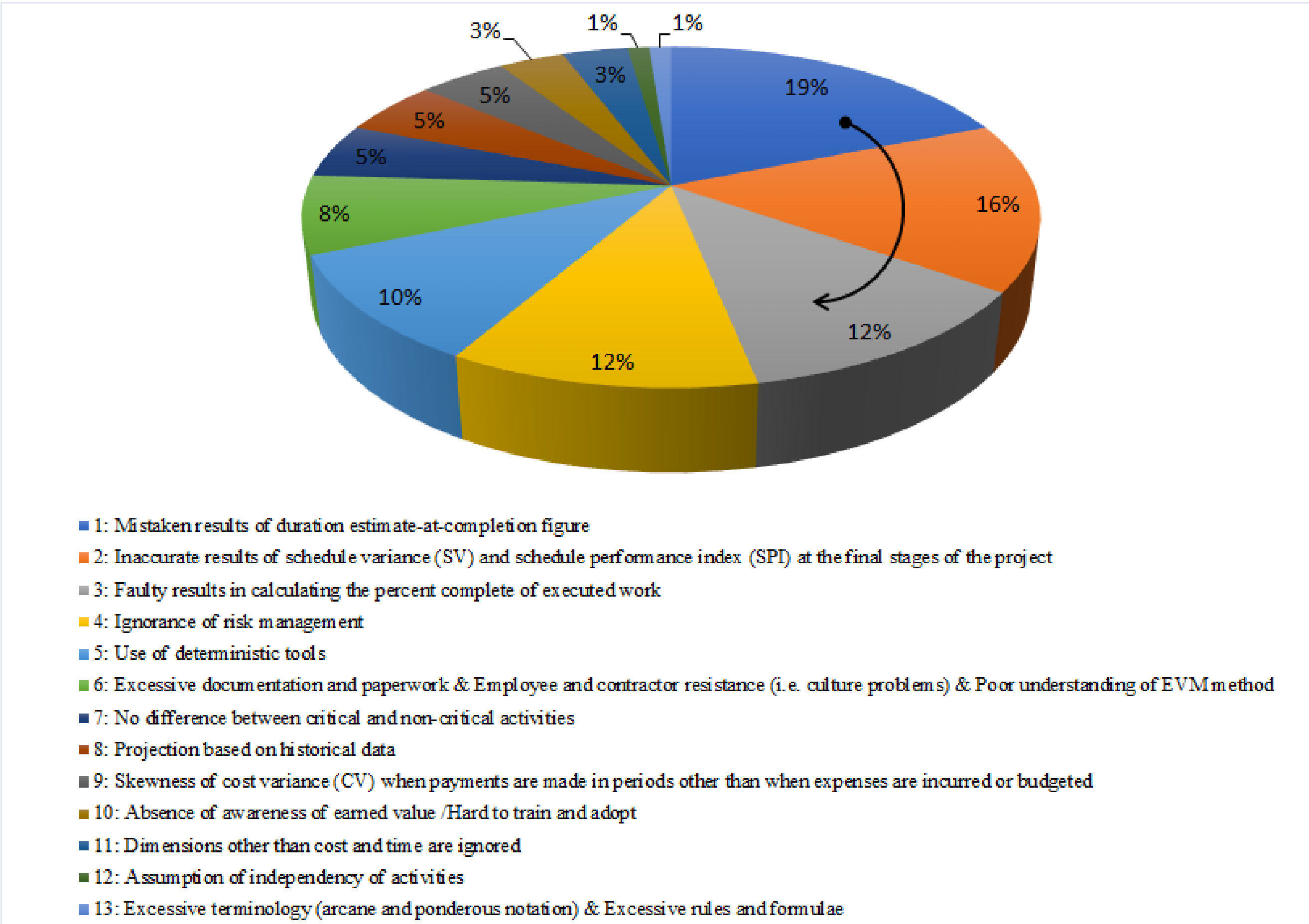

Figure 15. Percent share of enhancements for each limitation class

6.6 Affected Sets of Metrics

When the three main EVM parameters (i.e., PV, EV and AC), as defined in Table 10, are appropriately determined along the lifecycle of the project, the project manager is capable of calculating two types of performance measures: variances and indices. Whereas variances are used to highlight the difference between the actual project status and its baseline in monetary units, indices represent how well the performance of the project is, as compared with the baseline. As these variances and indices are interconnected, they both contribute to the critical task of forecasting the expected at-completion figures for the duration and cost of the project. The improvements encountered in the reviewed literature in connection with the EVM key parameters and the corresponding performance and forecasting parameters were mapped and classified, with the aim of developing novel integrated sets of metrics for this methodology. Table 11 shows the corresponding authors along with the year of publication for all improvement studies distributed over the EVM set of metrics. To this effect, Figure 16 shows the breakdown of the encountered research studies based on the three groups of EVM basics (i.e., metrics), including: key parameters, performance measures, and forecasting parameters. It can be safely inferred that the studies tackling EVM performance measures amounted to 40 percent of the reported enhancements.

Table 10. EVM Set of Metrics

Category	**Acronym**	**Description**
Key Parameters	BCWS (PV)	Budgeted Cost of Work Scheduled (Planned Value)
	BCWP (EV)	Budgeted Cost of Work Performed (Earned Value)
	ACWP (AC)	Actual Cost of Work Performed (Actual Cost)
Performance Measures		
Variances	CV	Cost Variance
	SV	Schedule Variance
Indices	CPI	Cost Performance Index
	SPI	Schedule Performance Index
Forecasting Parameters	EAC	Cost Estimate at Completion
	ETC	Estimate to Complete
	VAC	Variance at Completion
	EAC (t)	Duration Estimate at Completion

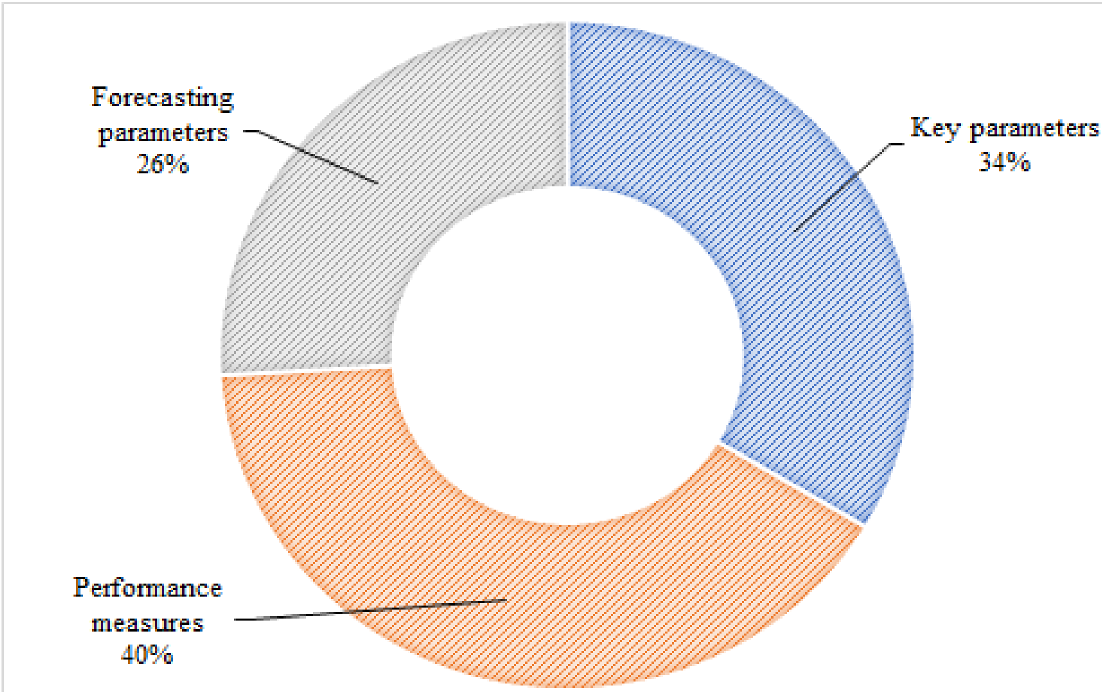

Figure 16. Number of shared improvements per affected EVM set of metrics

Table 11. Distribution of Improvements per Affected EVM Set of Metrics

EVM set of metrics	Improvement studies
Key parameters	(Vanhoucke and Colin 2016), (Kim et al. 2015), (Hernández et al. 2013), (Lipke 2004), (Dodson et al. 2015), (Paquin et al. 2000), (Barraza et al. 2000), (Barraza et al. 2004), (Barraza and Bueno 2007), (Blyth and Kaka 2006), (Cioffi 2005), (Chao and Chien 2009), (San Cristóbal 2017), (Chao and Chen 2015), (Chao and Chien 2010), (Moslemi-Naeni et al. 2011), (Moslemi-Naeni and Salehipour 2011), (Naeni et al. 2014), (Mortaji et al. 2013), (Moradi et al. 2017), (Forouzanpour et al. 2016), (Noori et al. 2008), (Park et al. 2005), (San Cristóbal et al. 2015), (Hajali-Mohamad et al. 2016), (Picornell et al. 2016), (Gardoni et al. 2007), (Chen 2014), (Lin et al. 2012), (Cheng et al. 2011), (Chen et al. 2016), (Lo 2007), (Ponz-Tienda et al. 2012), (Wang et al. 2016), (Feng et al. 2010), (Maravas and Pantouvakis 2012), (Lipke 2011), (Vanhoucke 2013), (Mavrotas et al. 2005), (Tatlari and Kazemipoor 2015), (Howes 2000), (Turkan et al. 2012), (Turkan et al. 2013), (Demachkieh and Abdul-Malak 2018)
Performance measures	(Hammad et al. 2018), (Warburton 2011), (Kim 2014), (Vanhoucke 2018), (Wood 2016), (Salari et al. 2014), (Moslemi-Naeni and Salehipour 2011), (Naeni et al. 2014), (Mortaji et al. 2013), (Moradi

	et al. 2017), (Forouzanpour et al. 2016), (Noori et al. 2008), (Acebes et al. 2015), (Picornell et al. 2016), (Kim 2009), (Lipke 2011), (Lipke 2002), (Rubio et al. 2015), (Lipke 2011), (Lipke 2011), (Lipke 2004), (Lipke 2009), (Lipke 2017), (de Souza et al. 2015), (Rodrigues 2010), (Lipke 2003), (Lipke 2012), (Warburton and Kanabar 2008), (Najafi and Azimi 2016), (Vanhoucke and Vandevoorde 2008), (Lipke 2016), (Cioffi 2006), (Lipke 2007), (Subramani et al. 2014), (Lipke 2009), (Vanhoucke 2013), (Henderson 2004), (Chang and Yu 2018), (Colin and Vanhoucke 2015), (Leu and Lin 2008), (Vanhoucke 2010), (Kim 2015), (Czemplik 2014), (Zhong and Wang 2011), (Martens and Vanhoucke 2018), (Colin and Vanhoucke 2014), (Elshaer 2013), (Nassar et al. 2005), (Pajares and López-Paredes 2011), (Salehipour et al. 2015), (Aliverdi et al. 2013), (Corovic 2006), (Fleming and Koppelman 2009)
Forecasting parameters	(Batselier and Vanhoucke 2015), (Lipke et al. 2009), (Batselier and Vanhoucke 2015), (Vandevoorde and Vanhoucke 2006), (Borges Jr and Mário 2017), (Batselier and Vanhoucke 2015), (Khamooshi and Abdi 2016), (Kim and Reinschmidt 2009), (Mortaji et al. 2014), (Kim and Kim 2014), (Caron et al. 2013), (Aliverdi et al. 2013), (Kim and Reinschmidt 2011), (Iranmanesh et al. 2007), (Henderson and Lipke 2006), (De Marco and Narbaev 2013), (Kesheh 2012), (Lipke 2015), (Henderson 2004), (Vanhoucke and Vandevoorde 2007), (Batselier and Vanhoucke 2015), (Chang and Yu 2018), (Azeem et al. 2014), (Vanhoucke et al. 2015), (Khamooshi and Golafshani 2014), (Caron et al. 2016), (Kim and Reinschmidt 2010), (Anbari 2003), (Batselier and Vanhoucke 2017), (Wauters and Vanhoucke 2014), (Jacob 2003), (Jacob and Kane 2004), (Vanhoucke and Vandevoorde 2007), (Pewdum et al. 2009), (Rujirayanyong 2009), (Warburton and Cioffi 2016)

6.7 Affected Project Stage

Table 12 shows the corresponding authors along with the year of publication for all improvement studies distributed over the project lifecycle stages. As it can be inferred from Table 12, numerous studies were concerned with the EVM improvements applied during the preconstruction stages. For instance, thirteen studies have been found to tackle the forecasting of the project-level cash flow in the preconstruction stages. However, the majority of the research studies were dealing with the EVM enhancements applied during the project construction stage.

For instance, several research studies account for various emergent extensions, involving variant metrics that have been developed in complement to other proposed EVM-compatible methods, in order to offer better means for studying the project schedule performance and measuring the total expected delays during the project execution stage.

Table 12. Distribution of Improvements per Project Stage

Project stage	Improvement studies
Preconstruction stage	(Blyth and Kaka 2006), (Cioffi 2005), (Chao and Chien 2009), (San Cristóbal 2017), (Chao and Chen 2015), (Chao and Chien 2010), (Gardoni et al. 2007), (Hajali-Mohamad et al. 2016), (Chen 2014), (Lin et al. 2012), (Cheng et al. 2011), (Chen et al. 2016), (Mavrotas et al. 2005)
Construction stage	(Batselier and Vanhoucke 2015), (Lipke et al. 2009), (Batselier and Vanhoucke 2015), (Vandevoorde and Vanhoucke 2006), (Hammad et al. 2018), (Warburton 2011), (Borges Jr and Mário 2017), (Batselier and Vanhoucke 2015), (Khamooshi and Abdi 2016), (Kim and Reinschmidt 2009), (Kim 2014), (Kim and Kim 2014), (Vanhoucke 2018), (Wood 2016), (Vanhoucke and Colin 2016), (Kim et al. 2015), (Hernández et al. 2013), (Lipke 2004), (Dodson et al. 2015), (Paquin et al. 2000), (Barraza et al. 2000), (Barraza et al. 2004), (Barraza and Bueno 2007), (Caron et al. 2013), (Aliverdi et al. 2013), (Moslemi-Naeni et al. 2011), (Moslemi-Naeni and Salehipour 2011), (Naeni et al. 2014), (Salari et al. 2014), (Mortaji et al. 2013), (Moradi et al. 2017), (Forouzanpour et al. 2016), (Noori et al. 2008), (Kim and Reinschmidt 2011), (Acebes et al. 2015), (Park et al. 2005), (San Cristóbal et al. 2015), (Picornell et al. 2016), (Lo 2007), (Ponz-Tienda et al. 2012), (Wang et al. 2016), (Feng et al. 2010), (Maravas and Pantouvakis 2012), (Kim 2009), (Lipke 2011), (Lipke 2002), (Rubio et al. 2015), (Lipke 2011), (Lipke 2011), (Lipke 2009), (Lipke 2017), (de Souza et al. 2015), (Rodrigues 2010), (Iranmanesh et al. 2007), (Lipke 2003), (Lipke 2012), (Henderson and Lipke 2006), (Warburton and Kanabar 2008), (Najafi and Azimi 2016), (Vanhoucke and Vandevoorde 2008), (Lipke 2016), (Cioffi 2006), (De Marco and Narbaev 2013), (Lipke 2007), (Kesheh 2012), (Lipke 2015), (Subramani et al. 2014), (Lipke 2009), (Henderson 2004), (Vanhoucke 2013), (Vanhoucke and Vandevoorde 2007), (Batselier and Vanhoucke 2015), (Chang and Yu 2018), (Azeem et al. 2014), (Colin and Vanhoucke 2015), (Vanhoucke et al. 2015), (Leu and Lin 2008), (Vanhoucke 2010), (Khamooshi and Golafshani 2014), (Kim 2015), (Czemplik 2014), (Zhong and Wang 2011), (Martens and Vanhoucke 2018), (Colin and Vanhoucke 2014), (Caron et al. 2016), (Elshaer 2013), (Nassar et al.

	2005) (Kim and Reinschmidt 2010), (Pajares and López-Paredes 2011), (Salehipour et al. 2015), (Aliverdi et al. 2013), (Anbari 2003) , (Batselier and Vanhoucke 2017), (Wauters and Vanhoucke 2014), (Jacob 2003), (Jacob and Kane 2004), (Corovic 2006), (Vanhoucke and Vandevoorde 2007), (Fleming and Koppelman 2009), (Pewdum et al. 2009), (Rujirayanyong 2009), (Tatlari and Kazemipoor 2015), (Warburton and Cioffi 2016), (Howes 2000), (Turkan et al. 2012), (Turkan et al. 2013), (Demachkieh and Abdul-Malak 2018)

6.8 Information Management Technologies for Improving Earned Value Quantification

Real-time progress tracking of construction activities is critical for successful project monitoring and control. As such, the application of modern information technologies for progress tracking are proclaimed to overcome the limitations of manual approaches and hence contribute to the automated acquisition of onsite data for the computation of the earned value of progressed work. To this end, this section presents a thorough review of the 111 studies dealing with automated data collection and progress tracking on construction sites, 62 percent of which were published over the last eight years. The adopted research studies were evaluated and categorized in relevant groups, allowing the identification of the main ICT areas proposed for use on construction sites for achieving more accurate earned value computations.

6.8.1 *Introduction*

Construction projects are nowadays more challenging in terms of time and budget constraints, thereby calling for devising better control and monitoring platforms (Chen et al. 2012). To this effect, and due to market pressure and global competition in the construction industry, a critical need for advanced management information systems had emerged. This need gave rise to the implementation of EVM method to limit projects' cost and duration overruns (Hunter et al. 2014). According to Naderpour and Mofid (2011), the EVM method is a recognized project management methodology that integrates cost, schedule, and scope into a unique measurement system, providing an early warning signal of project deviations from the plan, thus creating a chance to initiate timely corrective actions.

However, numerous researchers and practitioners have proclaimed that the main shortcoming associated with EVM is the difficulty in obtaining the percent complete of executed work. Ruskin (2004) considered "eyeball estimates" as personal and bias estimates of the percent complete of the executed works and are thus exposed to intended or unintentional biases. Consequently, they are hard to repeat, and they may comprise huge errors (Ruskin 2004). Likewise, Humphreys and Visitacion (2009) assumed that using EVM as a standard practice may be an encumbrance, mainly since collecting significant data and information in construction sites needs a lot of effort by the project team. Moreover, Omar and Nehdi (2016) consider that construction progress tracking is not a simple task and involves challenges due to the large amounts of information in construction sites, mainly related to a diversity of functions, for instance, "scheduling, construction methods, cost management, resources, quality control, and change order management".

In recent years, construction information management has significantly benefited from developments in information and communications technology (ICT), by enhancing the speed of information flow and improving the effectiveness of information communication. As such, existing ICT has shown great potentials in enhancing on-site collection and retrieval of data (Chen and Kamara 2011).

6.8.2 ***Results and Analysis***

6.8.2.1 Temporal Distribution of Research Studies

The 111 research studies were ordered and grouped according to their years of publication, as shown in Figure 17. It can be noticed that starting 2005 there seems to be a jump in the number of encountered studies, with the two middle ranges reflecting an average of seven publications per year. The last eight years (i.e., 2010-2017) encompassed a large number of publications (around 11 per year), showing the rapid evolvement of research tackling automated data acquisition technologies that have the potential to be used on construction sites.

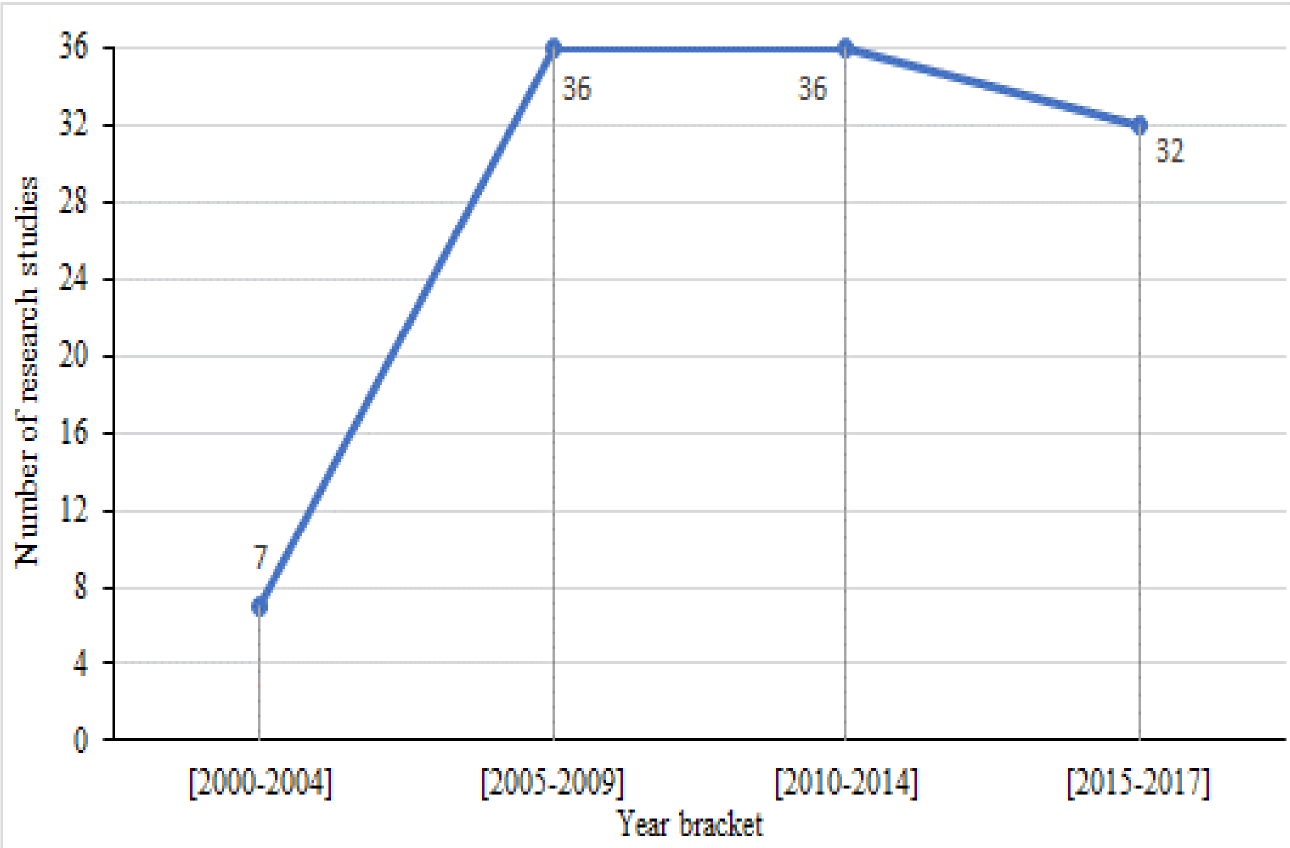

Figure 17. Temporal distribution of research studies

6.8.2.2 General Screening and Findings

Figure 18 provides a general classification of the encountered relevant technologies for managing information on construction sites, classified according to four categories, mainly “enhanced IT”, “geo-spatial”, “imaging” and “augmented reality”, following the classification of Omar and Nehdi (2016), along with the frequencies deduced in connection with each sub-class. To this effect, the various IT-based technologies included multimedia tools (i.e., digital camera and video) (Bohn and Teizer 2009), voice-based tools (Cheng et al. 2017), email and short message services (SMS) (Hegazy et al. 2014), and mobile computing tools (El-Omari and Moselhi 2011). Those inexpensive tools are said to enable the daily automated progress tracking of construction activities, leading to better schedule and cost control through enhanced communication.

Moreover, Geo-spatial-based tools, including barcoding, radio frequency identification (RFID) (Khoury et al. 2015), ultra-wide band (UWB) tags (Shahi et al. 2014), geographic information systems (GIS) (Bansal and Pal 2009), and global positioning systems (GPS) (Behnam et al. 2016) are used to visualize on-site construction objects. Example applications include real-time 3D material, labor and equipment tracking. Furthermore, progress tracking based on imaging technologies has been focusing on using digital images to produce 3D information about various objects on a construction site in order to be used in project controls (Golparvar-Fard et al. 2011; Golparvar-Fard et al. 2012). Finally, augmented reality (AR), defined as "the combination of real and virtual scenes" (Wang et al. 2014), is mainly used for the comparison of different project status (Omar and Nehdi 2016). The most efficient AR application that is successively employed on construction sites is BIM (Han et al. 2017).

That being said, it can be noted that the highest frequency (i.e. 57) of reported technologies is found to be related to the AR applications group. This is explained by the fact that AR has a great potential to address a plethora of challenges throughout the project execution, by providing a "radical shift in human–computer interaction" (Omar and Nehdi 2016), thus receiving growing attention by researchers and industry practitioners. With an enduring technological evolvement of these applications, AR applications are progressively becoming more cost-effective with improved capabilities to deliver exhaustive data on various project activities. The evolvement of these data acquisition tools was further investigated, by providing the temporal distribution of the corresponding research work in the 111 reviewed studies. As shown in Figure 19, research on progress tracking using imaging technologies has been speedily growing over the years. Moreover, it can be seen that 42 of the 57 studies (74 percent) that employ AR applications for automated data collection were published in the last eight years (i.e. during 2010-2017). However, although work pertaining to AR technologies for construction projects has noticeably increased in the most recent years, as revealed in Figure 19, these applications are said to be still in the research phase and their complete capabilities have not yet been fully realized (Omar and Nehdi 2016).

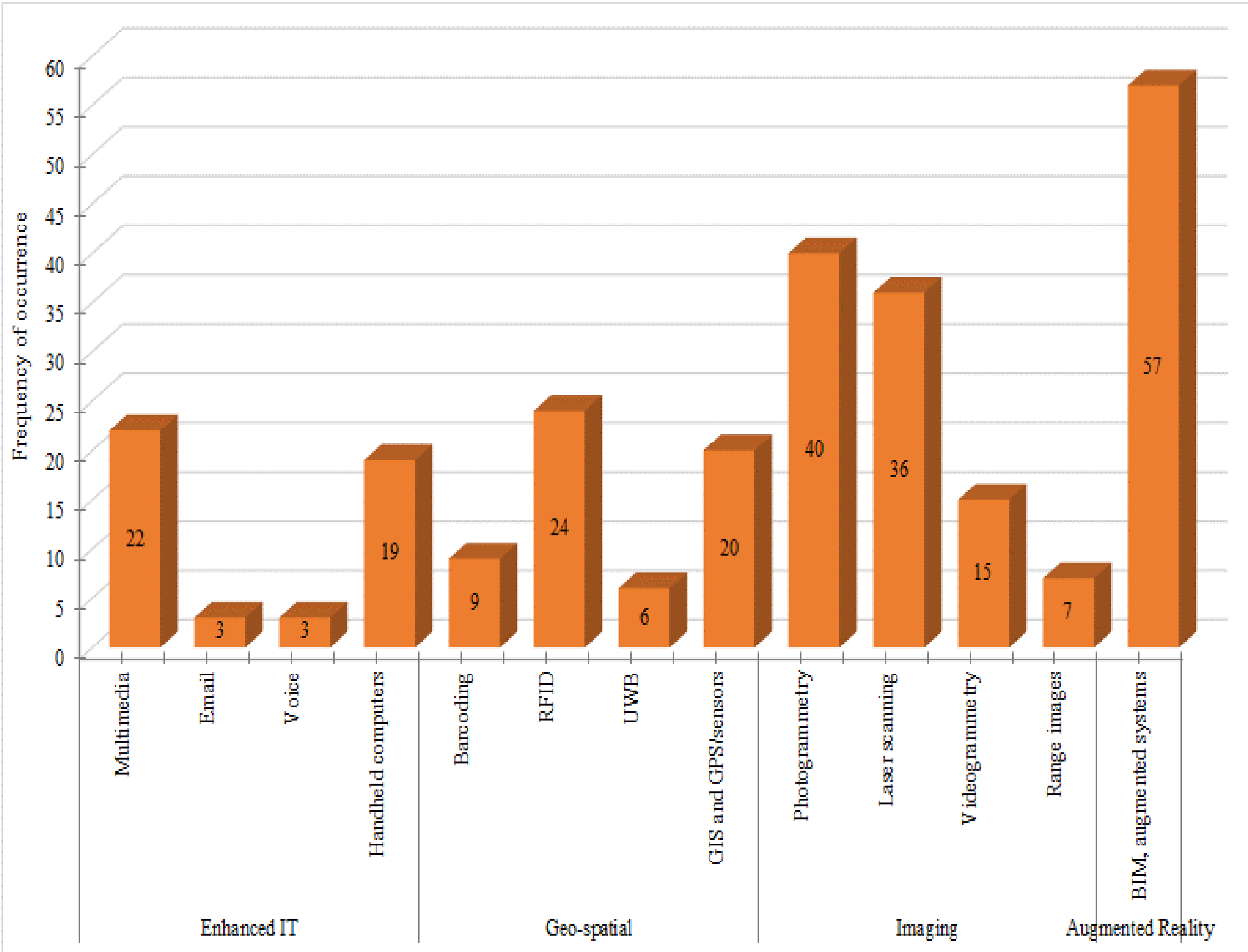

Figure 18. Frequencies of technologies for construction site data acquisition

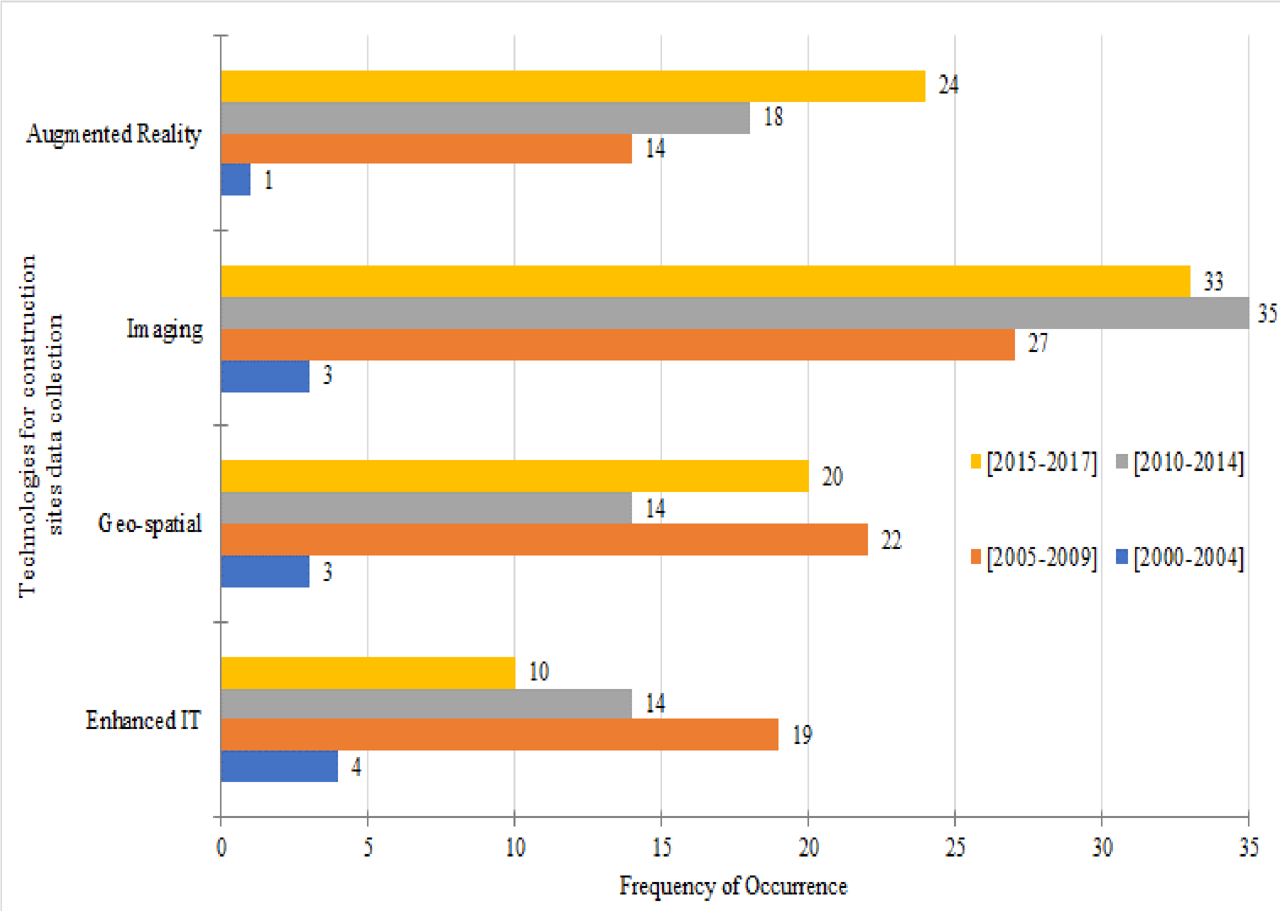

Figure 19. Temporal distribution of encountered technologies.

6.8.2.3 Areas of Application in Construction

A more detailed track of analysis tackled the significance of the above-mentioned findings from the perspective of the various areas of applications investigated as part of the reviewed published work. To this effect, Table 13 shows the breakdown of the filtered studies by the areas of application that were the subjects of investigation. It was found that 69 studies (63 percent) out of the examined studies (111, in total) were concerned with all kinds of project activities, whereas only one percent dealt with off-site construction activities. The more specific applications areas are found to include concrete and steel elements, MEP elements, indoor elements, and outdoor elements, among other similarly common on-site activities.

6.8.2.4 Benefits of Data Acquisition Technologies

Current methods for progress tracking on construction sites are mostly manual, labor-intensive, and time-consuming, and they are often based on abstruse and unreliable rules (Golparvar-Fard et al. 2011; Turkan et al. 2013; Montaser and Moselhi 2015). A considerable number of advanced automated data acquisition technologies, offering real-time on-site progress tracking, have been identified in this study. The encountered technologies are reported to significantly decrease labor hours and the time needed for progress monitoring. They allow this jobsite task to be achieved remotely and help in keeping track of the material used on construction site. It is found that real-time automated data collection on construction activities progress facilitates the generation of status reports and permits the early detection of deviations between the as-planned and current project statuses, thus allowing the timely flow of information between all interested parties. To this end, espousing such a variety of automated progress-tracking technologies can offer decision makers with prompt information in order to track the project progress more efficiently. The ultimate implication is the ability to produce accurate schedule updates and forensic delay analyses, and to better conceive suitable corrective measures. The research studies used in the analysis of this chapter are summarized in Table 14.

Table 13. Distribution of Technologies by Areas of Application in Construction.

Specific application in construction	Number of research studies
General (any type)	69
Workers, materials and/or equipment	15
Infrastructure/Industrial	7
Concrete elements	6
MEP elements (cylindrical pipes and pipes spools)	3
Indoor elements	3
Structural steel elements	2
Earthwork	2
Outdoor elements	2

Secondary and temporary elements	1
Off-site construction elements	1

Undeniably, the main obstacles for adopting the proposed technologies in construction include the excessive cost of procurement and maintenance of those emerging technologies, the necessity for extensive users training and the complexity of integration of these technologies with current applications. Data acquisition technologies that have the potential to be used on construction sites are hastily developing; thus, it is highly suggested that decision makers carefully research their availability in order to get the up-to-date applications serving the purpose of achieving better monitoring and control of construction progress.

Table 14. Research Lines Related to Information Management Technologies

#	Research Studies	Technologies for construction sites data collection													Specific Application in Construction
		Enhanced IT				Geo-spatial				Imaging				Augmented Reality	
		Multimedia	*Email*	*Voice*	*Handheld computers*	*Barcoding*	*RFID*	*UWB*	*IS and GPS/Sensors*	*Photogrammetry*	*Laser scanning*	*Videogrammetry*	*Range images*		
1	(Cheok et al. 2000)								1		1				Any type
2	(Cheng and Chen 2002)	1				1			1						Precast elements
3	(Abeid et al. 2003)	1													Any type
4	(Moselhi et al. 2004)				1										Any type
5	(Perera and Imriyas 2004)				1										Any type
6	(Trucco and Kaka 2004)									1					Any type
7	(Bayrak and Kaka 2004)									1				1	Any type
8	(Memon et al. 2005)									1					Any type
9	(Shehab and Moselhi 2005)					1									Any type
10	(Zhao et al. 2005)								1	1	1	1		1	Any type
11	(Chin et al. 2005)						1							1	Any type
12	(Navon and Shpatnitsky 2005)								1						Equipment
13	(Bosche et al. 2006)									1					Any type
14	(Shih and Huang 2006)										1				Any type
15	(Akinci et al. 2006)						1				1			1	Any type
16	(Ghanem and AbdelRazig 2006)				1		1								Any type
17	(Fard and Peña-Mora 2007)									1				1	Any type
18	(Teizer et al. 2007)												1		Workers and equipment
19	(Rabbani et al. 2007)										1				Industrial elements
20	(Navon and Sacks 2007)	1		1	1	1	1		1						Any type
21	(Lukins and Trucco 2007)									1					Any type
22	(Tsai et al. 2007)	1			1										Any type
23	(Jung and Kang 2007)				1	1	1		1						Any type
24	(Hammad and Motamedi 2007)						1							1	Any type

25	(Bosche and Haas 2008)										1		1		Any type
26	(El-Omari and Moselhi 2008)									1	1				Any type
27	(Rebolj et al. 2008)	1												1	Outdoor elements
28	(Leung et al. 2008)	1			1										Any type
29	(Chin et al. 2008)				1		1							1	Structural steel elements
30	(Kiziltas et al. 2008)				1		1		1		1				Infrastructure
31	(Dai and Lu 2008)									1					Precast elements
32	(Chin et al. 2008)									1					Any type
33	(El-Omari and Moselhi 2009)	1			1	1	1				1				Any type
34	(Ibrahim et al. 2009)	1												1	Any type
35	(Zhang et al. 2009)	1												1	Any type
36	(Golparvar-Fard et al. 2009)									1				1	Any type
37	(Golparvar-Fard et al. 2009)									1				1	Any type
38	(Tsai 2009)	1				1	1								Any type
39	(Zhu and Brilakis 2009)									1	1	1	1		Infrastructure
40	(Bosche et al. 2009)										1			1	Any type
41	(Bansal and Pal 2009)								1					1	Any type
42	(Dong et al. 2009)				1										Any type
43	(Motamedi and Hammad 2009)						1							1	Any type
44	(Bosché 2010)										1			1	Any type
45	(Brilakis et al. 2010)	1									1	1	1	1	Any type
46	(Wu et al. 2009)									1				1	Any type
47	(AbouRizk 2010)													1	Any type
48	(Tang et al. 2010)										1			1	Any type
49	(Yang et al. 2010)	1										1			Workers
50	(Bohn and Teizer 2009)	1													Any type
51	(Moon and Yang 2009)				1		1								Concrete Pouring Operation
52	(Son and Kim 2010)									1				1	Outdoor elements
53	(Jung and Lee 2010)						1		1		1				Any type
54	(Golparvar-Fard et al. 2011)									1				1	Any type
55	(Golparvar-Fard et al. 2011)										1			1	Any type

56	(El-Omari and Moselhi 2011)	1			1	1	1			1	1				Any type
57	(Liang et al. 2011)	1												1	Any type
58	(Razavi and Haas 2011)				1		1		1						Materials
59	(Chi and Caldas 2011)									1		1			Workers and equipment
60	(Fathi and Brilakis 2011)											1			Infrastructure
61	(Bhatla et al. 2012)	1								1					Infrastructure
62	(Hegazy and Abdel-Monem 2012)		1												Any type
63	(Turkan et al. 2012)										1			1	Any type
64	(Shahi et al. 2012)							1							Indoor elements
65	(Weerasinghe et al. 2012)									1					Workers
66	(Memarzadeh et al. 2012)											1			Workers and equipment
67	(Kim et al. 2013)	1									1			1	Any type
68	(Turkan et al. 2013)						1	1		1	1			1	Any type
69	(Shahi et al. 2013)							1							Welding and inspection
70	(Memarzadeh et al. 2013)											1			Workers and equipment
71	(Liu et al. 2013)				1		1		1						Earth-rock dams
72	(Xiong et al. 2013)										1			1	Indoor elements
73	(Hegazy et al. 2014)		1												Massive linear and repetitive projects
74	(Costin et al. 2014)						1							1	Workers, materials and equipment
75	(Ahmed et al. 2014)										1				Cylindrical elements
76	(Wang et al. 2014)													1	Industrial elements
77	(Turkan et al. 2014)									1	1			1	Secondary and temporary elements
78	(Rankohi and Waugh 2014)	1								1	1			1	Any type
79	(Nahangi and Haas 2014)										1			1	Fabricated pipe spools
80	(Shahi et al. 2014)						1	1	1	1	1			1	Any type
81	(Johansson et al. 2015)													1	Any type
82	(Braun et al. 2015)													1	Any type
83	(Bosché et al. 2015)										1			1	Cylindrical elements
84	(Montaser and Moselhi 2015)	1			1	1	1		1					1	Any type

85	(Pătrăucean et al. 2015)									1	1			1	Any type
86	(Son et al. 2015)				1		1	1		1	1			1	Infrastructure
87	(Han and Golparvar-Fard 2015)									1				1	Materials
88	(Arashpour et al. 2015)													1	Off-site construction elements
89	(Khoury et al. 2015)						1		1						workers
90	(Zhang et al. 2015)									1				1	Workers
91	(Kopsida et al. 2015)						1			1	1			1	Any type
92	(Braun et al. 2015)									1				1	Any type
93	(Lin et al. 2015)								1	1				1	Any type
94	(Lin et al. 2015)									1				1	Any type
95	(Jrade and Lessard 2015)													1	Any type
96	(Behnam et al. 2016)	1							1						Linear infrastructure
97	(Lee et al. 2016)													1	Any type
98	(Omar and Nehdi 2016)	1	1	1	1	1	1	1	1	1	1	1	1	1	Any type
99	(Martínez-Rojas et al. 2015)								1					1	Any type
100	(Bueno et al. 2017)										1				Indoor elements
101	(Chen and Wang 2017)											1			Any type
102	(Cheng et al. 2017)	1		1											Equipment
103	(Zhu et al. 2017)									1		1			Workers and equipment
104	(Rausch et al. 2017)										1			1	Construction assemblies
105	(Rebolj et al. 2017)									1		1	1	1	Materials
106	(Soman et al. 2017)								1						Any type
107	(Tuttas et al. 2017)									1				1	Any type
108	(Bügler et al. 2017)									1		1			Earthwork
109	(Sharif et al. 2017)										1			1	Any type
110	(Hamledari et al. 2017)													1	Any type
111	(Han et al. 2017)										1			1	Any type

CHAPTER 7

COMPARATIVE ANALYSES OF CONSTRUCTION CASH FLOW PREDICTIONS USING EMPIRICAL S-CURVES

7.1 Preamble

The S-curve is the common tool used for depicting the project cumulative progress during execution. Numerous studies have been found to tackle the forecasting of the project-level cash flow in the preconstruction stages, using prediction techniques involving neural network and regression analyses as well as third-degree polynomial and sigmoid functions. The encountered models rely on an array of input variables, including the type of work and location, degree of project simplicity, team competence, curve slope and inflection point, and specific time-money milestones, among others. This chapter is concerned with the investigation of the applicability and prediction accuracy of the proposed planned progress estimation models from the perspectives of construction project owners and their appointed contract engineers.

7.2 Introduction

Cash is the most significant resource in the construction industry (Askew et al. 1997; Park et al. 2005). Appropriate cash flow management is critical for the delivery of construction projects, under the pressure of respecting the agreed completion time and allocated contract price, and while producing an acceptable profit (Kaka 1990; Chen and Chen 2000; Görög 2009; Samer Ezeldin and Ali 2017). To this effect, the common reasons for the increase in the rate of business bankruptcy in construction projects include:

a. the competitive nature of the business (Khosrowshahi and Kaka 2007),

b. the uncertainties involved (Khosrowshahi and Kaka 2007; Cheng and Roy 2011; Kishore et al. 2011), and
c. the financial-related reasons, displayed in low returns, losses, and even liquidation (Touran et al. 2004; Khosrowshahi and Kaka 2007).

Producing reliable cash flow estimates has long been recognized as a critical, if not challenging, task for projects in all industries and more critically for those in the construction industry (Chen et al. 2005). This is so since projects are nowadays mostly complex and take longer time to be executed, compared to other industries, and – correspondingly – progress payments are usually large (Makarfi Ibrahim 2010; Kishore et al. 2011). As such, releasing regular interim payments to contractors is considered vital to provide revenues for the execution of construction activities (El-adaway et al. 2013; Samer Ezeldin and Ali 2017), and contractors should be completely aware of the provisions for interim payment applications administration with the aim of suitably supporting their construction cash flow analyses (El-adaway et al. 2013). To this effect, an accurate cash flow estimate is crucial for several reasons, including:

a. calculating working capital requirements,
b. determining project cost-benefit analysis,
c. assessing project financing requirements, and
d. conducting earned value analyses (Maravas and Pantouvakis 2012).

As such, the construction industry has used one or more ad-hoc approaches for cash flow management (Khosrowshahi and Kaka 2007). Typically, in such approaches, past case projects are gathered and categorized based on various attributes (i.e., contract amount, project duration, project type) into groups, and the average input parameters for each group are adopted to generate a standard S-curve, in order to form the basis for cash flow estimation for a new project categorized in the same group (Balkau 1975; Bromilow and Henderson 1977; Miskawi 1989; Evans et al. 1996). However, the systematic and scientific tools adopted for project cash flow estimate models are based on the use of S-curves to predict a project's expenditure cash flow (Blyth and Kaka 2006; Khosrowshahi and Kaka 2007; Chao and Chien 2010; Maravas and Pantouvakis 2012). As defined by the American Association of Cost Engineers (AACE) (AACE International Recommended Practice No. 10S-90), an S-curve, in the context of project control, is defined as "a cumulative distribution of costs, labor hours, progress, or other quantities plotted against time." As such, the S-curve is a graphical display showing the cumulative progress of a construction project from start to end, with the horizontal axis representing time and the vertical axis showing the cumulative progress in dollars value or percent complete (Chao and Chien 2009; Chao and Chien 2010; Chao and Chen 2015). When plotted against time, collected project efforts or costs usually take the form of an S-curve, normally with a smaller slope at the beginning and near the end and a larger slope in the middle (Cioffi 2005; Mattos 2013), indicating that the progress is slow in mobilization and demobilization phases but quicker when the majority of the tasks takes place (Sweis et al. 2008; Chao and Chien 2009). As such, and even though the S-shape is usually applicable to all projects of various industries, each individual project is unique, thus having an S-curve with different geometric properties (e.g., the relative length and rise of each section of the curve) (Chao and Chien 2009). Figure 20 shows an example of typical S-curves with early and late dates, depicting the planned progress of a construction project.

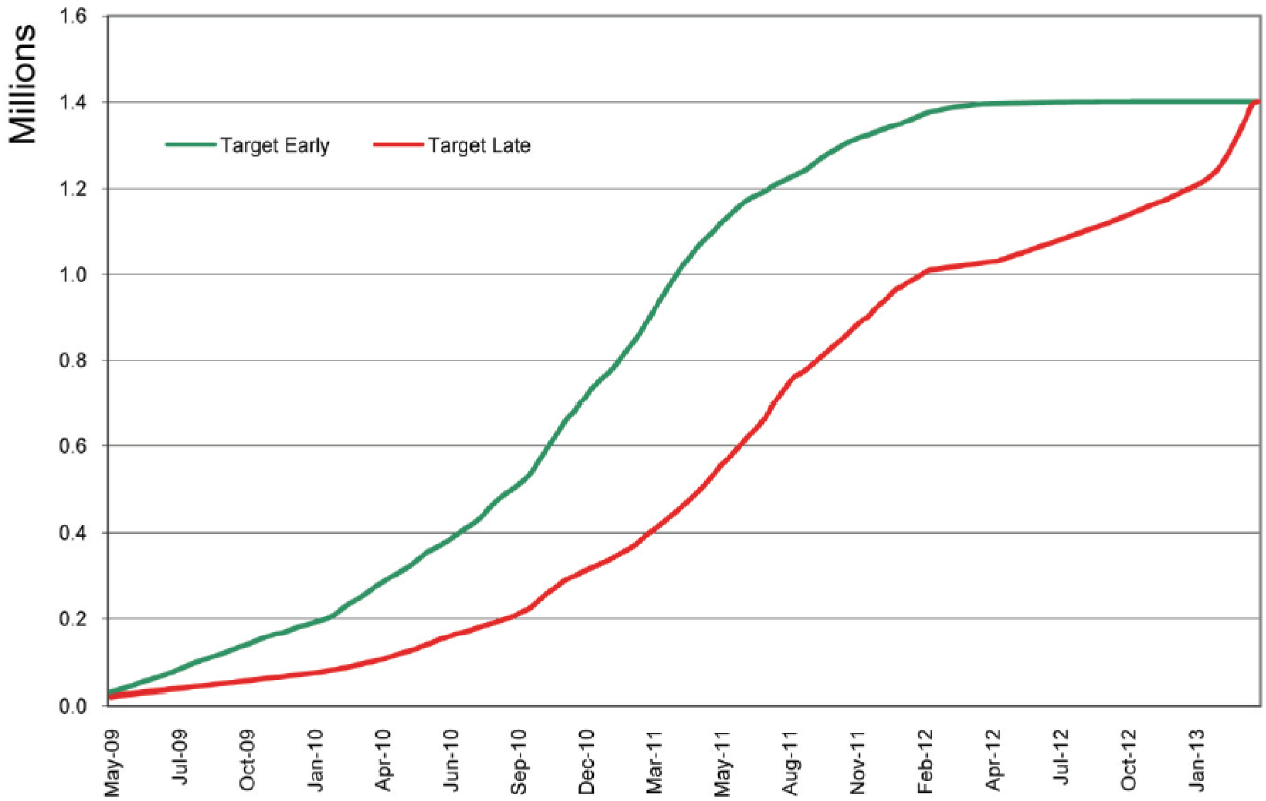

Figure 20. Typical S-Curves with early and late dates (AACE International Recommended Practice No. 55R-09)

To this effect, estimated cash flow S-curves are used by owners as:

a. a baseline for assessing, during the preconstruction stages, the cash flows for establishing financial requirements (Chao and Chien 2009), and

b. a basis against which the project actual progress at any point in time can be assessed, with the purpose of evaluating the project status and quantifying the amount of delay, if any, in the execution stage of a construction project (Cioffi 2005; Blyth and Kaka 2006; Chao and Chien 2009).

Additionally, the S-curve estimate will assist the engineer in the determination of violation of the construction contract in case of an incurred delay by the contractor and the corresponding penalty (Chao and Chien 2009). However, some modern schools of thought (namely, lean construction) have questioned the use of the S-curve to evaluate the overall progress with the purpose of monitoring and controlling the project status, since contractors, under the risk of liquidated damages getting levied, likely resort to accelerating nonurgent activities in order to compensate delays of earned value in critical activities (Kim and Ballard 2000). As such, the S-curve, being able to establish the project progress in a single figure, has the essential benefit of easiness and remains convenient to be used in construction projects (Chao and Chien 2009). On balance, the embracing of the S-curve for financial management is unquestionable; however, it seems undeniable that the complete reliance on it as the main control tool during execution may give reason for concern because of its oversimplification (Chao and Chien 2009; Chao and Chien 2010).

Accordingly, cash flow estimation in the preconstruction stages, when only sketchy project information is available, adopted historical-data-based empirical tools and mathematical formulas to forecast progress as a function of time (Chao and Chien 2009). However, when detailed project information is handy and accessible, the most adequate method for estimating an S-curve is analytical, in other words, based on the planned schedule of activities (AACE International Recommended Practice No. 55R-09 ; Chao and Chen 2015). In practice, following the contract award and soon upon receiving the notice of commencement with the works, the contractor is required to develop and submit a detailed network and/or bar chart schedule for review by the project owner (Farzad Moosavi and Moselhi 2014; Wang et al. 2016), in order to ensure its compliance with contractual provisions and documents, as regards to “technical accuracy, reasonableness, and representativeness” (Moosavi 2012). The project construction consented schedule (i.e., as-planned contractual schedule) is then used to develop an as-planned progress S-curve as the baseline against which the actual project progress at any point in time is assessed in order to evaluate whether the project is behind or ahead of schedule (Chao and Chien 2009). To this effect, the schedule provides the foundation for:

a. project execution, monitoring, and progress reporting,
b. administration of construction claims and disputes,
c. effective application of earned value technique, and
d. computation of the expected at-completion figures for the project duration (Moosavi 2012).

Hence, it is vital to confirm the reasonableness of the schedule for its intended uses (Farzad Moosavi and Moselhi 2014). According to Songer et al. (2001), construction schedules are usually reviewed for correctness and rationality prior to their implementation by the management team. As such, owners and/or their agents (e.g., owner's representatives, contract engineers, project managers, etc.) should assess schedules based on the rationale of job logic and accuracy of activities duration (Douglas 2009; Avalon and Foster 2010; O'brien and Plotnick 2010). Moreover, they should evaluate the critical path(s) and near critical path(s) to check their reasonableness. To this effect, Russell and Udaipurwala (2000) presented a number of measures used for assessing schedule quality. These included:

a. aligning the schedule with the contract and other planning documents,
b. maintaining strategy integrity under all date scenarios,
c. accomplishing work continuity, learning curve effects, and stable production rates, and
d. preventing congested work areas.

In addition, Dzeng et al. (2005) claimed that the engineer, while reviewing the schedule submitted by the contractor, may emphasize on:

a. finding the distorted component of the schedule (e.g., irrational float or critical paths),
b. emphasizing on the coherence of schedule format and content,
c. providing a basis for schedule integration and earn value calculations.

Similarly, Farzad Moosavi and Moselhi (2014) considered that owners usually review and evaluate the schedule according to various considerations, which are frequently subjective and differ from one organization to another.

In light of the backdrop stated above, the work presented in this chapter has thus been motivated by the need to have clear and rationalized basis that can be relied upon, together with such other evaluations as previously stated, by the construction contract engineer when deciding to perform an objective review and effective assessment of the schedule-based S-curve submitted by the contractor. More specifically, the work is concerned with checking the reasonableness of contractor's planned value (i.e., PV) that serves the project owner's cash flow requirements. As such, this chapter is intended to assess the reliability, accuracy, and applicability of cash flow prediction models, proposed to be used during the preconstruction stages of the project delivery process, from the owner's viewpoint.

7.3 Planned Work Progress: Owner's Perspective

For over four decades, the earned value management (EVM henceforth) method is undoubtedly a well-established method offering an integrated approach for controlling a project's cost and schedule targets (Demachkieh and Abdul-Malak 2018). According to the Project Management Institute (PMI 2018), EVM is a method that "integrates the scope baseline with the cost baseline, along with the schedule baseline, to form the performance measurement baseline, which helps the project management team assess and measure project performance and progress." Moreover, the AACE (AACE International Recommended Practice No. 10S-90) defines the EVM system "as a project progress control system that integrates work scope, schedule, and resources to enable objective comparison of the earned value to the actual cost and the planned schedule of the project". As such, EVM has three key metrics or parameters, including the planned value (PV), actual cost (AC), and earned value (EV). To this effect, Figure 21 is a graphical form showing various analysis types that can be performed using the EVM method.

The PV, known as the budgeted cost of work scheduled (BCWS), is defined as the authorized budget assigned to scheduled work at a given reporting period. The AC is the total cost actually incurred and recorded in completing an activity or a work package. These two parameters (PV and AC) are usually considered in traditional cost management (AACE International Recommended Practice No. 10S-90). On the other hand, the AACE (Amos 2004) defines EV as "the periodic, consistent measurement of work performed in terms of the budget planned for that work". To calculate the EV for a certain work item, its total budget is multiplied by its percent complete. Alternatively, it can also be calculated by multiplying the quantity installed for an activity by its agreed unit rate or price. Aside from that, PV is the predictor for EV and AC prior to the execution of a project. Accordingly, the relationship between the three main parameters (i.e., PV, AC and EV) allows for both cost and time control using a set of integrated metrics (i.e., performance measures and forecasting parameters) (Anbari 2003; Fleming and Koppelman 2006; PMI 2011).

In this research study, it is the owner's cash flow projection curve that is of relevance. This curve is developed by loading the activities of the contractor's schedule with the work items' costs, reflected by the contract's agreed unit rate for an item in question multiplied by the quantity of that item that is planned to be executed in each of the schedule's activities. Such a computed PV amount, which is the authorized time-phased budget representing the expected rate at which the project work is to be accomplished (i.e., expected EV), is significant for control purposes. That is, it is compared with the value that is earned, with the aim of frequently monitoring and controlling the project performance during construction and generating cash flow estimates updates.

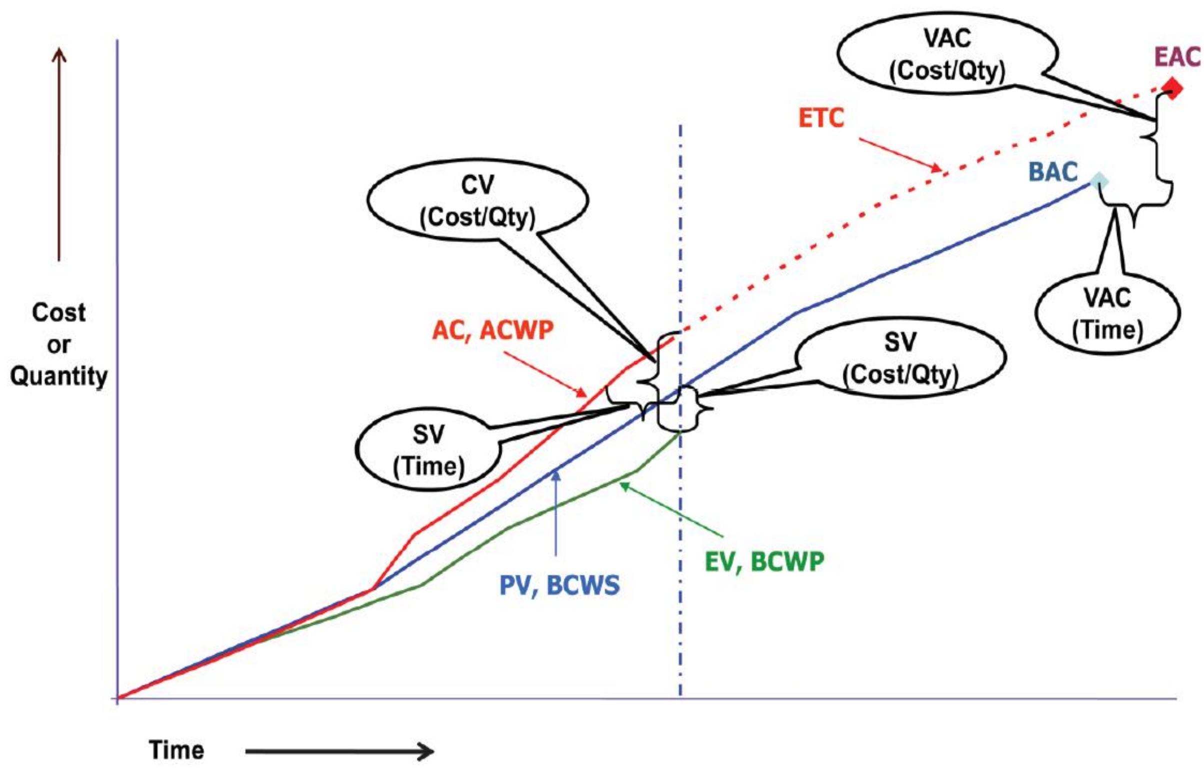

Figure 21. Earned Value S-curve basic analysis (AACE International Recommended Practice No. 55R-09)

7.4 Consenting the Contractor's Schedule

The construction schedule is a graphical representation of the contractor's best intent or plan for the execution of the works, developed in such a manner that respects the contractual project duration, indicates the critical paths, reflects activities' sequencing and other constraints, and depicts the loading of resources and costs. To this effect, the schedule is a convenient tool used by the construction contract engineer to monitor progress and for the owner and the contractor to plan their project and construction financing commitments, respectively. Accordingly, both the owner and engineer are entitled to arrange the personnel requirements during work execution, based on the schedule submitted by the contractor (Booen 2000).

In practice, subsequent to the contract award and soon after receiving the notice of commencement with the works, the contractor is usually required to submit to the engineer a high-level preliminary schedule reflecting enough details for the activities that are planned to be executed in the first 90 days of the project duration. A full-fledge schedule is later submitted before the end of the first 90-day period, incorporating adequate details for all activities intended to be executed during the contractual construction duration. The Gantt chart in Figure 22 shows an example of a project baseline schedule for a notional project, assuming a linear distribution of the activities' cost.

ACTIVITY	COST	MONTH											
		1	2	3	4	5	6	7	8	9	10	11	12
Earthwork	20	20											
Foundation	60		30	30									
Structure	150				50	50	50						
Installations	60						20	20	20				
Finishes	180							45	45	45	45		
Facade	20											20	
Final cleaning	10												10
TOTAL	500	20	30	30	50	50	70	65	65	45	45	20	10
CUMULATIVE		20	50	80	130	180	250	315	380	425	470	490	500

Figure 22. Example project schedule (with Cost) (Mattos 2013)

As such, the engineer, while not obliged to give an explicit consent to the submitted schedules, is however required to notify the contractor of the degree to which any such schedule does not comply with the contract requirements. Specifically, the engineer may express no opposition to the schedule but without holding liability for it (Bunni 2013). To be noted is that there is no specification stipulating how the engineer shall perform the review process, although such a required review is expected to be performed within a realistic timetable.

In order to deduce the contractor's and engineer's schedule-related responsibilities, the standard conditions for the construction contract issued by the International Federation of Consulting Engineers (known as the FIDIC), which are broadly adopted on international projects and recommended by the World Bank, were carefully inspected (FIDIC 1999). According to Sub-clause 8.3 (Programme) of these conditions, the contractor must submit to the engineer a detailed programme (i.e., time schedule) within 28 days of receiving the notice for commencement of the works (issued pursuant to Sub-clause 8.1 (Commencement of Works). Furthermore, the contractor is required to:

a. include in his schedule the sequence in which he intends to execute the construction works, (b) to determine the timing of activities executed by nominated subcontractors,
b. identify the order and timing of inspections and tests stated in the contract, and
c. submit a supporting report describing the methodology and resources (i.e., personnel and equipment) required for the planned progress of work.

The contractor, under these conditions, is entitled to proceed with the works in accordance with the submitted schedule unless the engineer, within 21 days from its receipt, gives notice to the contractor stating the extent to which the schedule does not comply with the contract. Aside from other specific checks the engineer may – by the virtue of observing due diligence – be required to perform in respect of the submitted schedule, assessing the reasonableness of the deduced cash flow associated with the inherent planned time-phased progress is a core task, viewed in practice as a prerequisite to the engineer ultimately consenting, or otherwise not objecting to, the schedule. To this end, if the engineer informs the contractor that the current schedule is not consistent with actual progress and the contractor's specified intents, the contractor shall submit a revised schedule to the engineer (FIDIC 1999). Even though not explicitly prescribed in the contract, for it to be appropriately used to monitor project progress and evaluate claims for extensions of time, the revised schedule shall obviously display the revised network analysis and amendments accruing to the critical path, if any (Fawzy and El-adaway 2012).

To be noted is that there is no sanction provided in the FIDIC conditions with regard to the failure by the contractor to submit a schedule within any stipulated time bar (e.g., 28 days, under the FIDIC conditions). Such failure, however, impedes any future claim for an extension of time that the contractor may submit (Fawzy and El-adaway 2012). Actually, the contractor would be in a dilemma as to demonstrating his eligibility for such an extension of time in the absence of an appropriate baseline schedule, and the engineer is expected to question the accuracy of any schedule that the contractor generates on a retrospective basis (Bunni 2013). Other FIDIC conditions are rendered difficult to abide by due to such failure, including those:

a. under Sub-clause 8.3, calling on the contractor to inform the employer of "specific probable future events or circumstances which may adversely affect the work, increase the contract price or delay the execution of the Works",

b. under Sub-clause 8.6, obliging the contractor, in the case of delays that do not entitle him to an extension of time, to submit, upon the engineer's request, a revised schedule and an accompanying report describing the measures the contractor intends to put in place in order to accelerate progress and complete the works within the planned duration (FIDIC 1999).

It can be finally concluded that the consented (or not-objected-to) schedule is the primary tool through which the engineer is afforded the chance of comprehending the plan envisioned by the contractor for the execution of the works. Condition precedent to adopting any such schedule, for both owners' financial planning and progress monitoring and control purposes, is in the reasonableness of its implied time-phased expenditures being fairly assessed against industry-accepted metrics. That said, the following section tackles the review of several empirical forecasting formulations that have been proposed in the literature as capable of predicting construction work S-curves, which can be relied upon by the engineer for judging the reasonableness of contractors' submitted baseline schedules.

7.5 Encountered Empirical S-Curves

One of the most vital features of running a construction business is cash flow management. If not attended to by the involved project participants in accordance with project requirements and contract provisions, this critical function could end up being a primary cause for financial difficulties to arise for owners and/or contractors. Accordingly, many researchers have established various S-curve formulas and models for developing project progress estimates that may be used to support those provided from the traditional schedule-based approach. To this effect, this section presents the research findings concerned with the prediction of the contractor's progress curve before the start of construction.

7.5.1 ***Description of Models***

Based on the thorough and scrutinized review of the work related to cash flow estimates in the preconstruction stages published in the last two decades, five models were found to be dealing with the generation of the project's empirical S-curve. To this effect, these proposed methods, along with their corresponding formulations, are chronologically presented in Table 15. The proposed formulae in each of the encountered models include an array of numerous parameters, which are solved mathematically to develop a preliminary cash-flow estimate in the preconstruction stages. As such, Mavrotas et al. (2005) proposed a sigmoid function based on three parameters (k,α,p) in order to estimate the owner cash flow during the preconstruction stages. Parameter k regulates the S-curve slope and ranges from 0.001 to 10. To this effect, lower k values indicate smoother curves, i.e., k=0.001 signifying a straight line pattern. Additionally, parameter α adjusts the position of maximum slope (i.e., corresponding to half budget) in the interval [0,1], ranging from [0.001,3]. Greater values of α, implying early payments, moves the maximum slope towards of the x-axis (i.e., time axis) origin; for instance, for α=1.5, the maximum slope is located at the 66% of project's duration. However, the third parameter p is added to express the percentage of total amount paid in advance to the contractor for mobilization.

Likewise, Cioffi (2005) proposed a modified logistics equation that a project manager can use by selecting the strength of the rise of the curve (i.e., $r_{0.67}$) and the point at which half the total costs has been spent (i.e., $\beta_{1/2}$), in order to influence schedule planning by providing various alternative cash outflows during the project's preconstruction stages. To this effect, when $r_{0.67}$ takes the value of one, two thirds of the rise happen to occur in the middle curve interval; however, higher values of $r_{0.67}$ (i.e., greater than 1) produce steeper curves. If the project funds are spent earlier rather than later (i.e., front-loaded distribution), $\beta_{1/2}$ will fall in the interval [0,0.5[. Other projects will have this point in time near the middle ($\beta_{1/2}\approx0.5$), or possibly closer to the end of the planned duration (i.e., $\beta_{1/2} > 0.7$).

On the other hand, the traditional approach for generating an S-curve in the preconstruction stages is previously based on grouping projects into several categories and generating a standard curve for each category, merely by fitting one curve into the historical data (Blyth and Kaka 2006). As a way to overcome this obsolete approach, Blyth and Kaka (2006) developed a model that generates an individual S-curve for a specific-type project using a multiple linear-regression analysis. A sample consisting of 50 projects was collected and 20 criteria were identified to categorize these projects. Based on the most influential criteria, a multiple linear-regression model that uses the characteristics of each project was generated to predict the program of works and henceforth the S-curves. Additionally, six additional projects were used to validate and assess the proposed model.

Moreover, Chao and Chien (2009) proposed a cubic polynomial function for producing an empirical S-curve. Neural networks were then adopted to acquire the ability to predict the 3rd-degree formula coefficients (i.e., “a” and “b”) based on actual progress data from historical projects, with the purpose of generating a better early S-curve estimate for a given project conditions. Typically, the value of “a” is negative, whereas the value of “b” is positive. As such, an increase in the value of either “a” or “b” move the inflection point to the end of project planned duration. Moreover, decreasing the value of “a”, but increasing that of “b”, produces a steeper curve in the middle, demonstrating superior work concentration in that region. Conversely, increasing the value of “a” accompanied by decreasing the value of “b” leads to a smoother curve, implying more consistently dispersed work over the project timespan.

Furthermore, Chao and Chen (2015) developed an improved model compared to that proposed by Chao and Chien (2009). This was done by means of (1) altering the outputs to an S-curve's key geometric features values, i.e., the position (p) of, and the slope (s) at, its inflection point, and (2) adding more inputs to the neural network involving project conditions, with the purpose of improving the prediction accuracy. Parameter p falls in the interval [0, 1], whereas the value of "s" shall be greater than one. To this effect, when "s" takes the value of one, the proposed polynomial equation becomes a straight line (i.e., a=b=0), whereas for s<1, a curve reverse to the S shape, whose slope at the inflection point is the minimum, is obtained. Accordingly, the values of p and s are obviously linked to project schedule performance. Since the inflection point is the location where the project work rate is maximum, and its corresponding slope represents the degree of work concentration, the implications of altering their values can be analyzed based on how they relate to project progress, i.e., being either accelerated or delayed, compared to the normal progress conditions (i.e., y=0.5 at time x=0.5).

Similarly, San Cristóbal (2017) proposes a sigmoid function with two main parameters, T_0 and α. As such, T_0 is the time at which half of the total project funds has been used, and α specifies the steepness of the curve. In other words, parameter α elongates or shortens the time dimension and thus regulates the curve slope, whereas T_0 adjusts the location of the maximum slope. Higher values of T_0 shift the maximum slope in the direction of the origin of the x-axis and thus imply early payments, while smaller values of T_0 indicate late payments.

7.5.2 *S-Curve Update*

The actual progress during project execution may diverge from the baseline planned progress due to the influence of many factors, which calls for the need to update the S-curve during the construction stage. Even though the S-curve updates can be best achieved through the critical path method (CPM)-based method, an empirical approach is convenient to assist in giving forecasts for the purposes of checking and control. To this effect, an S-curve update shall be compared with a progress estimate obtained from re-scheduled activity durations and sequences to check if the adjusted schedule-based estimate is reasonable or needs to be adjusted. For instance, contractors may opt to crash the project schedule in order to meet a tight completion deadline; in this case, the original S-curve is not reliable anymore.

As such, Chao and Chien (2010) proposed an empirical S-curve update model used during the construction stage, as an extension to the model proposed by Chao and Chien (2009). This novel approach produces the project updated S-curve by progressively changing the relative weights of the preliminary estimate obtained from the neural network model and the consequent estimate generated from the progress-matching method in consecutive S-curve updates, depending on the elapsed project time (i.e., status date). Although the S-curve can be best achieved from the updated version of the CPM-based schedule, the proposed empirical method is beneficial in giving reliable estimates with the purpose of checking the schedule-based S-curve. Thus, the proposed model is not intended to substitute the traditional estimating method, and contractors still have to forecast the times of unfinished activities for the purpose of project performance control and analysis, although they both contribute in determining the most likely project progress.

7.5.3 *Models Inputs*

This section presents the research findings concerned with the identification of the main inputs needed to predict the construction work progress S-curve in the preconstruction stages. An in-depth review of all encountered factors allowed their classification into general headings, as included in Table 16. The listed headings are presented in a decreasing order of occurrence frequency, with the adopted headings of contract amount and duration, receiving the highest citation frequency of seven, thereby confirming the exceptional implication of having those data for estimating project-level cash flow in the preconstruction stages. As such, it is found that the encountered models rely on a vast array of input variables, including the type of work and location, degree of project simplicity, team competence, curve slope, inflection point, and specific time-money milestones, among others. To be emphasized is that the great majority of these highlighted inputs can be easily determined by the engineer, from the contract documents and schedule submissions made by the contractor.

To this end, the encountered input factors are classified into two main categories, including quantifiable and categorical variables. Seven factors namely contract amount, duration, curve slope, time designating half of the total spent costs, percentage of advance payment, two values of costs and their corresponding occurrences, and position of inflection point are considered to be quantifiable factors. Accordingly, the two top-cited quantifiable factors, contract amount and duration, are found to be significant input variables due to their ability to jointly assess a project's complexity, and thus potentially affecting activities logical relationships (i.e., serial or parallel networks). Other quantifiable factors are easily determined by the construction contract engineer because they are in connection with the payment mechanism, and they are usually stipulated in the payment clauses of the contract conditions. To be noted is that only one of the proposed models is found to be relying on the percentage of the total contract amount that is paid in advance to the contractor (i.e., one-off payment). This is demonstrated by the model proposed by Mavrotas et al. (2005), depicting the functional form of the S-curve used for representing the running cumulative expenses of each project from the owner's perspective.

On the other hand, the factors related to project conditions, which are classified as categorical variables, also have a major influence on the project progress. The “type of work” factor determines the number of trades, lead time, and site logistics; similarly, project location is closely related to weather conditions, which may affect the progress of construction works. Moreover, project simplicity is defined by difficulty in planning and construction, amount of changes, effect of disruptions and payment delays, whereas team competence is determined by each project participant's personnel, skill, competence, in addition to the availability of contractor's resources (Chao and Chen 2015). Furthermore, the effects of degree of project simplicity and team competence on the project progress can be verified by the productivity of team members and crew’s acquaintance with the construction works. Additionally, as it can be inferred from Table 16, four encountered models were found to use historical data as a way to increase the prediction accuracy of the constructed empirical models.

Table 15. Proposed Models for Empirical S-Curves Generation

Research Studies	Methods of Computation/ Analysis	Underlying Parameters	Symbols	Proposed Formulae
Cioffi (2005)	Modified logistics differential equation & Analytic parametrization	Maximum project cost Slope of the rise in the middle part of the curve Time at which half the funds have been expended Standardized time Maximum project cost Total cost of the project Standardized progress	Y_∞ $r_{0.67}$ $\beta_{1/2}$ β Y_∞ Y_1 y	$\ln(\gamma + 2) = 8r_{0.67}\beta_{1/2}$ $y_\infty = \frac{1 + \gamma \exp(-8r_{0.67})}{1 - \exp(-8r_{0.67})}$ $y_\infty = \frac{Y_\infty}{Y_1}$ $y(\beta) = y_\infty \frac{1 - \exp(-8r_{0.67}\beta)}{1 + \gamma \exp(-8r_{0.67}\beta)}$
Mavrotas et al. (2005)	Sigmoid function	Slope of the curve Position of the maximum slope Percentage of total amount which is paid in advance to the contractor Standardized time Standardized progress	k a p x y	$y = p + (1 - p)\frac{\frac{1}{1 + e^{k(a.x-1)}} - \frac{1}{1 + e^{-k}}}{\frac{1}{1 + e^{k(a-1)}} - \frac{1}{1 + e^{-k}}}$
Chao and Chien (2009)	Cubic polynomial function &Neural networks	Standardized time Standardized progress	x y	$y = ax^3 + bx^2 + (1 - a - b)x$ $a = (AB - DE)/(BC - E^2)$ $b = (CD - AE)/(BC - E^2)$ $A = \sum x^3y - \sum xy - \sum x^4 + \sum x^2$ $B = \sum x^4 - 2\sum x^3 + \sum x^2$ $C = \sum x^6 - 2\sum x^4 + \sum x^2$ $D = \sum x^2y - \sum xy - \sum x^3 + \sum x^2$ $E = \sum x^5 - \sum x^4 - \sum x^3 + \sum x^2$
Chao and Chen (2015)	Cubic polynomial function &Neural networks	Standardized time Standardized progress Largest slope of the curve	x y p	$y = ax^3 + bx^2 + (1 - a - b)x$

		Position of the inflection point	s	$a = \left[\frac{(s-1)}{\left(p + \frac{1}{3p} - 1\right)}\right] \div 3p$ $b = \frac{(s-1)}{\left(p + \frac{1}{3p} - 1\right)}$
San Cristóbal (2017)	Sigmoid function	Time at which the project has used half of its total funds Steepness of the curve Two amounts of costs Dates at which those amounts are consumed	T_0 α $f_1 \& f_2$ $t_1 \& t_2$	$f(t) = \frac{1}{1 + e^{-\alpha(t-T_0)}}$ $\alpha = \frac{\ln\left(\frac{1}{f_1} - 1\right) - \ln\left(\frac{1}{f_2} - 1\right)}{t_2 - t_1}$ $T_0 = \frac{\ln\left(\frac{1}{f_1} - 1\right)}{\alpha} + t_1$

Table 16. Input Data for the Proposed Models

Input data	Research Studies							Total
	Cioffi (2005)	Mavrotas et al. (2005)	Blyth and Kaka (2006)	Chao and Chien (2009)	Chao and Chien (2010)	Chao and Chen (2015)	San Cristóbal (2017)	
Contract amount	x	x	x	x	x	x	x	7
Contract duration	x	x	x	x	x	x	x	7
Type of work			x	x	x	x		4
Historical projects			x	x	x	x		4
Location of work				x	x	x		3
Slope of curve	x	x				x		3
Degree of project simplicity					x	x		2
Degree of team competence					x	x		2
Time at which half of total costs will be spent	x	x						2
Advance payment percentage		x						1
Two values of costs and their respective occurrences (times)							x	1
Position of inflection point						x		1

•

7.5.4 *Methods of Computation and/or Analysis*

A more detailed track of analysis tackled the prominence of the above-mentioned findings from the perspective of the various computation methods investigated as part of the reviewed published work. As shown in Figure 23, the adopted research studies have been found to tackle the forecasting of the project-level cash flow in the preconstruction stages using various prediction techniques. These included neural network, regression analyses, analytic parametrization, case-based reasoning, modified logistics differential equation, as well as third-degree polynomial and sigmoid functions, or a combination of such methods, as per the frequencies reported in Figure 23. To illustrate, Mavrotas et al. (2005) and San Cristóbal (2017) proposed the use of sigmoid function to estimate the project progress. As for Chao and Chien (2009) and Chao and Chen (2015), they combined the succinct cubic polynomial function and neural networks in order to generate a reliable S-curve progress estimate in the preconstruction stages.

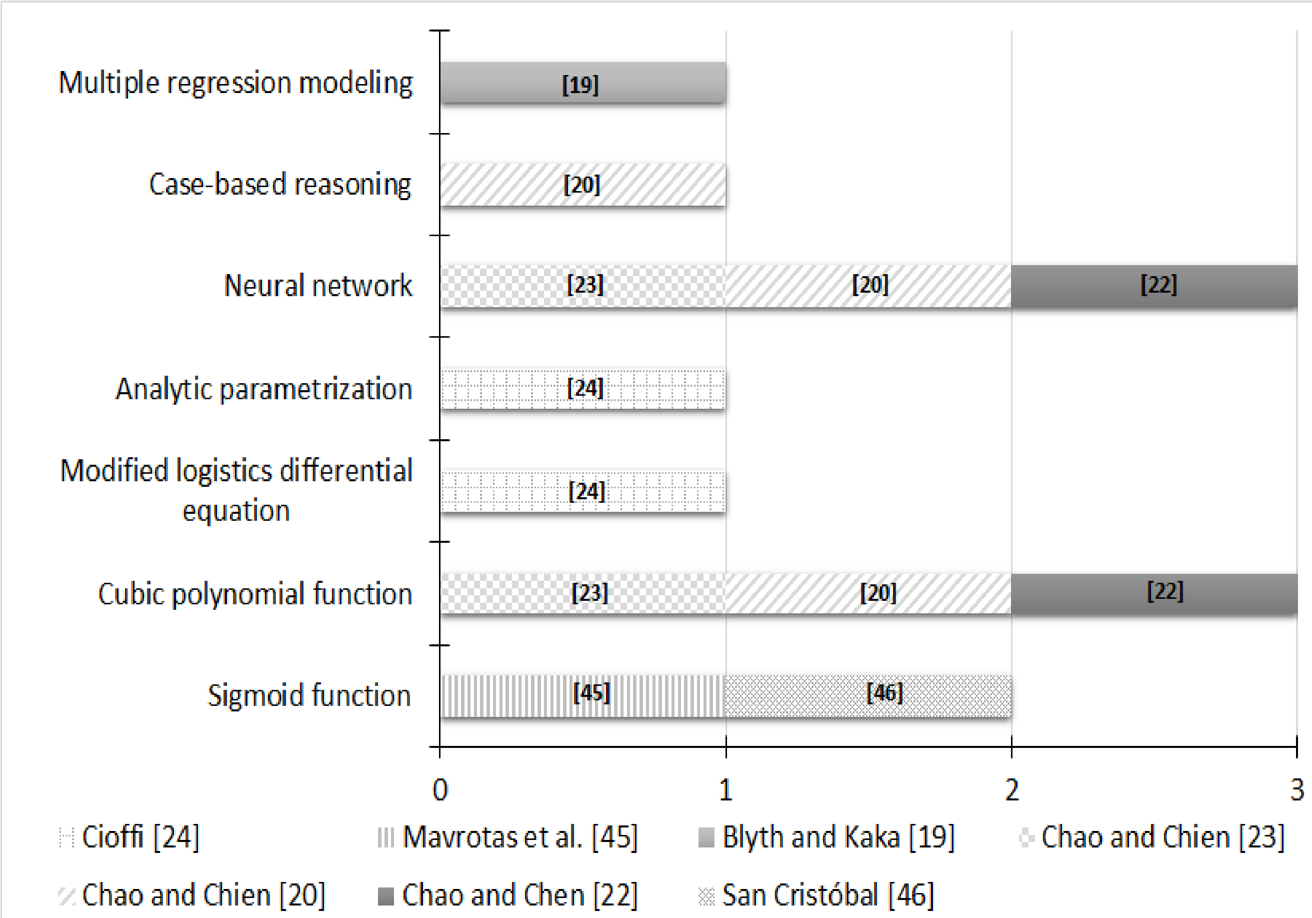

Figure 23. Prediction techniques for S-Curve generation

It can be inferred that the proposed formulae are quite uncomplicated and can be easily relied upon by contract engineers, project managers, and other contract administration practitioners. As such, the remaining part of this chapter presents, through the use of a real construction project case, a proposed methodology that can assist contract engineers in assessing the reasonableness of the schedule's generated S-curve.

7.6 Models Prediction Capabilities

In this section, a real construction project has been used in order to demonstrate the practicable application of the encountered cash flow prediction models and check their reliability. The aim of this section is to specifically compare and interpret the results obtained from the employment of the proposed models against the actual data extracted from the completed construction project adopted for the analysis. Accordingly, the contractor's cumulative expenses, approved earned value (i.e., actual value achieved from the owner's perspective, as certified by the engineer), and actual income flow (payment received from the owner) records, for a high-end residential building project constructed in the Middle East region, were examined for that purpose. In summary, the considered project has a total contract price equal to $6,296,605, spreading over a period of 22 months. As per the widespread practice, progress measurements for the project took place on a monthly basis. To this effect, the attributes of the basic parameters feeding into the computation of the income flow are as follows: (a) 60 days for the payment time lag, (b) ten percent for the retainage, (c) ten percent for the advance payment, (d) 14 percent for the nominal annual borrowing rate, and (e) 80 percent for the partial payment of the invoice value of delivered materials. The profit actually materialized on this job was in the order of 8.95 percent, equaling the amount of $563,405. The actual figures for the various costs incurred by the contractor (i.e., materials, labor, and indirect/overhead expenses) and value of progressed work approved by the engineer were obtained and used for constructing the contractor's cumulative expenditures and owner's earned value curved, respectively.

The data for all three classes of records are included under Table 17 and plotted in Figure 24. In relevance to the analyses carried out subsequently, it is the value of achieved work that is taken into consideration, with such work being that approved by the engineer for incorporation in the contractor's payment statement. As such, it is assumed that the contractor's (actual) earned value curve was exactly equal to the planned value one. That is, the proclamation is that the work on this job had actually progressed in full accordance with the contractor's original PV curve that must have been deduced from the consented baseline construction schedule. In other words, the contractor's cumulative PV figures, which can alternatively be referred to as the expected EV amounts, are assumed to have been successively achieved in their corresponding due times and to have as such been endorsed for payment as exactly incorporated in the interim payment certification applications by the contractor.

Table 17. Contractor's Cumulative Expenditures, Planned Value, and Income Flow

Period	Cumulative contractor's actual expenditures	Cumulative contractor's planned value	Cumulative contractor's income flow
0	$0.0	$0.0	$629,660.5
1	$180,446.0	$0.0	$629,660.5
2	$201,642.0	$0.0	$629,660.5
3	$222,838.0	$0.0	$629,660.5
4	$595,640.5	$0.0	$629,660.5
5	$1,174,099.5	$48,300.0	$629,660.5
6	$1,498,588.0	$162,365.0	$854,688.7
7	$1,933,004.5	$418,337.5	$1,226,009.0
8	$2,438,796.5	$732,987.5	$1,461,147.4
9	$2,892,421.0	$1,099,955.5	$1,814,961.5
10	$3,200,169.0	$1,525,560.8	$2,233,149.4
11	$3,329,266.5	$1,951,166.0	$2,637,476.1
12	$3,435,995.5	$2,376,771.3	$2,968,303.7
13	$3,977,277.5	$2,802,376.5	$3,184,794.9
14	$4,095,766.5	$3,359,020.0	$3,386,970.3
15	$4,554,126.5	$3,979,986.5	$3,867,259.6
16	$5,112,789.5	$4,585,255.5	$4,120,102.4
17	$5,228,758.5	$5,157,922.0	$4,585,473.1
18	$5,323,360.0	$5,622,078.0	$5,107,181.4
19	$5,387,095.0	$5,883,885.0	$5,331,761.0
20	$5,436,641.0	$6,079,248.0	$5,499,174.1
21	$5,483,639.0	$6,246,219.0	$5,580,373.0
22	$5,516,056.0	$6,296,605.0	$5,629,681.0
23	$5,542,803.0	---	$5,668,010.7
24	$5,568,479.0	---	$6,296,605.0

In order to generate the project's S-curves derived from the proposed models, the time (x-axis) and planned value (y-axis) dimensions are first standardized, between the values of zero and one. Consequently, the values of the parameters of each model are extrapolated from the contractor's cumulative PV curve, and solved mathematically using the proposed formulae to develop five predicted project S-curves, as illustrated in Figures 24 to 29. To be noted is that the model proposed by Blyth and Kaka (2006) is not used in this study for predicting the progress of the construction project on hand, since the generated regression equations are not provided in the corresponding research study.

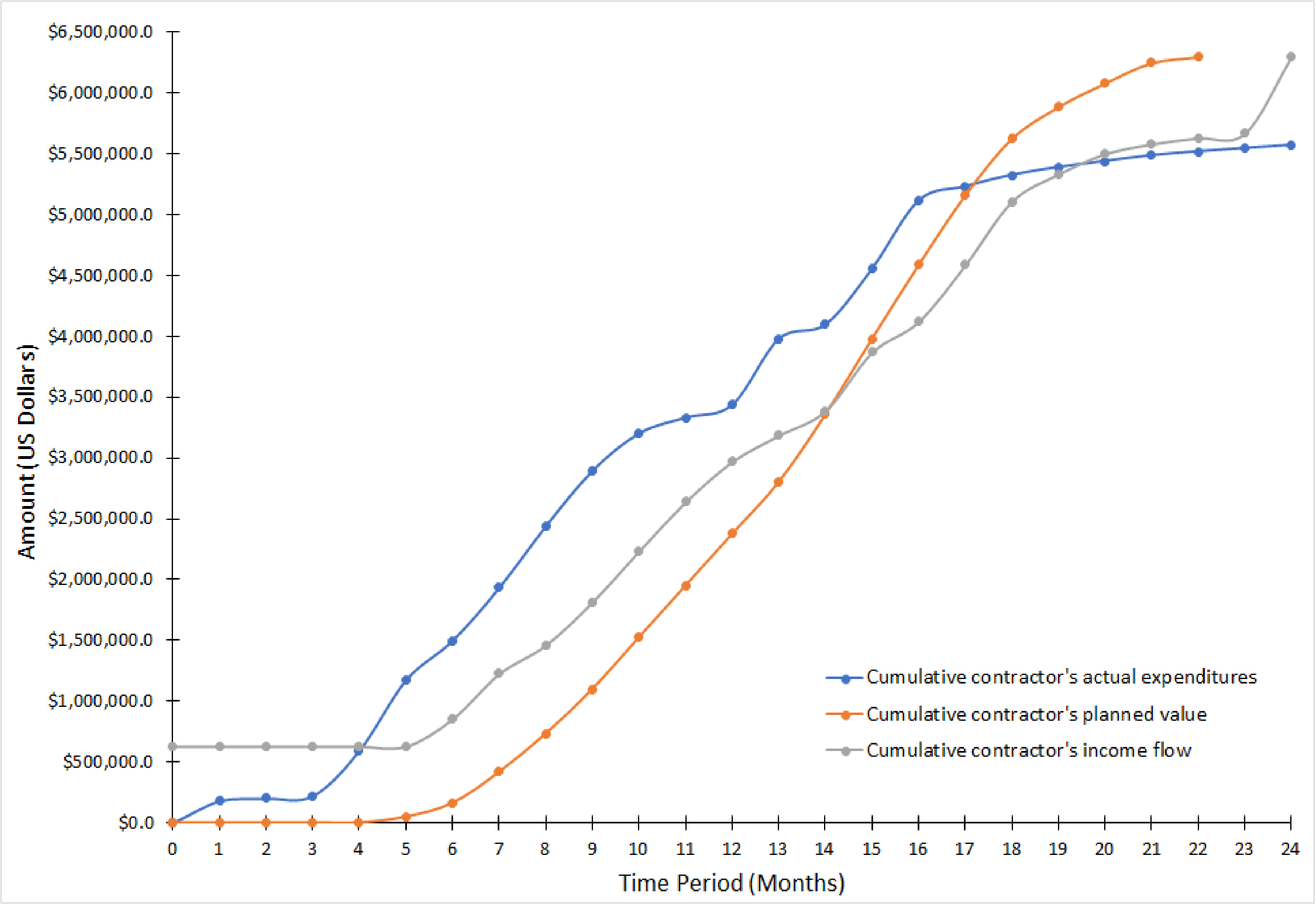

Figure 24. Expenses, planned (actually earned) value, and payment inflow curves

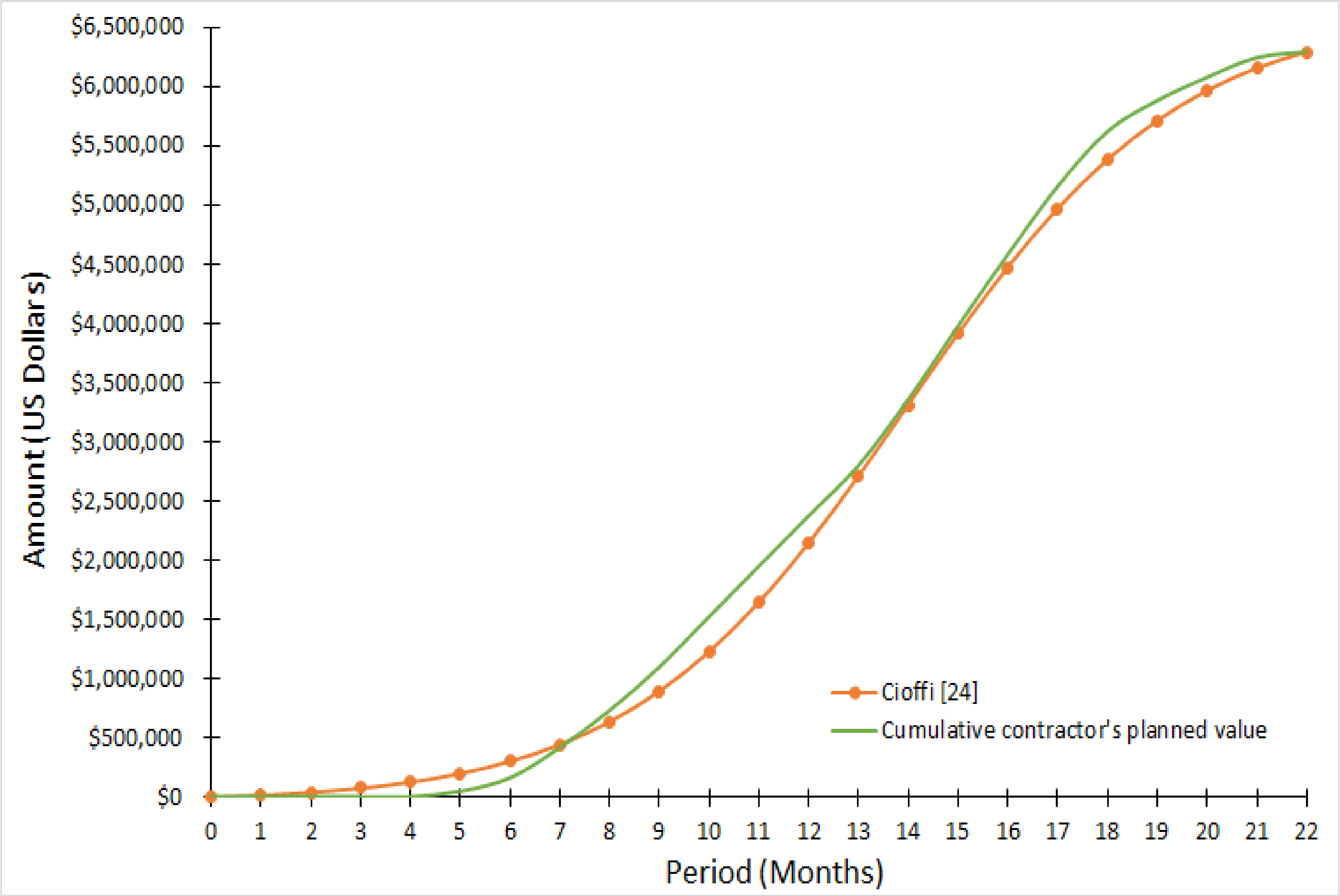

Figure 25. S-curve generated by Cioffi's model

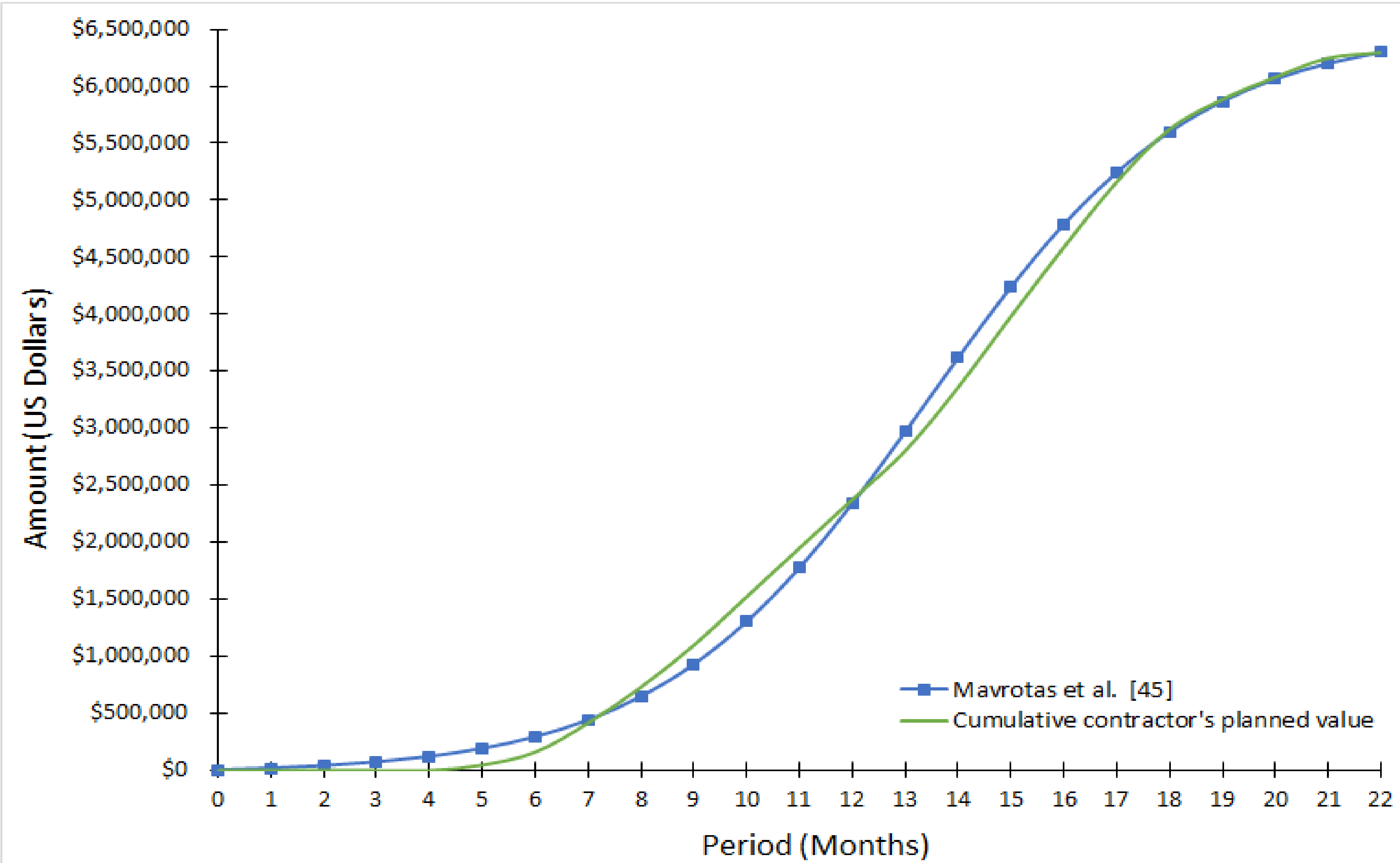

Figure 26. S-curve generated by Mavrotas et al.'s model

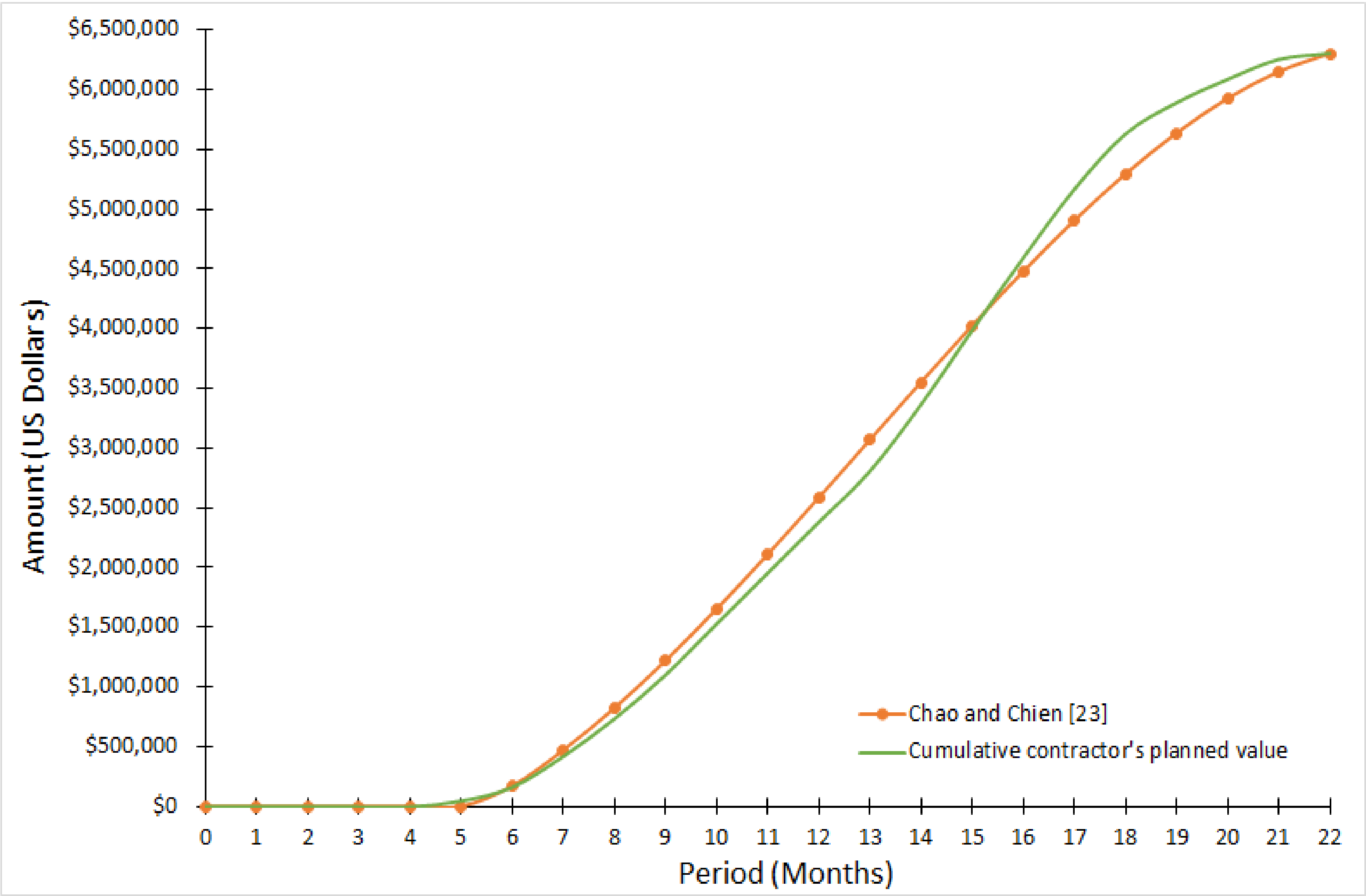

Figure 27. S-curve generated by Chao and Chien's model

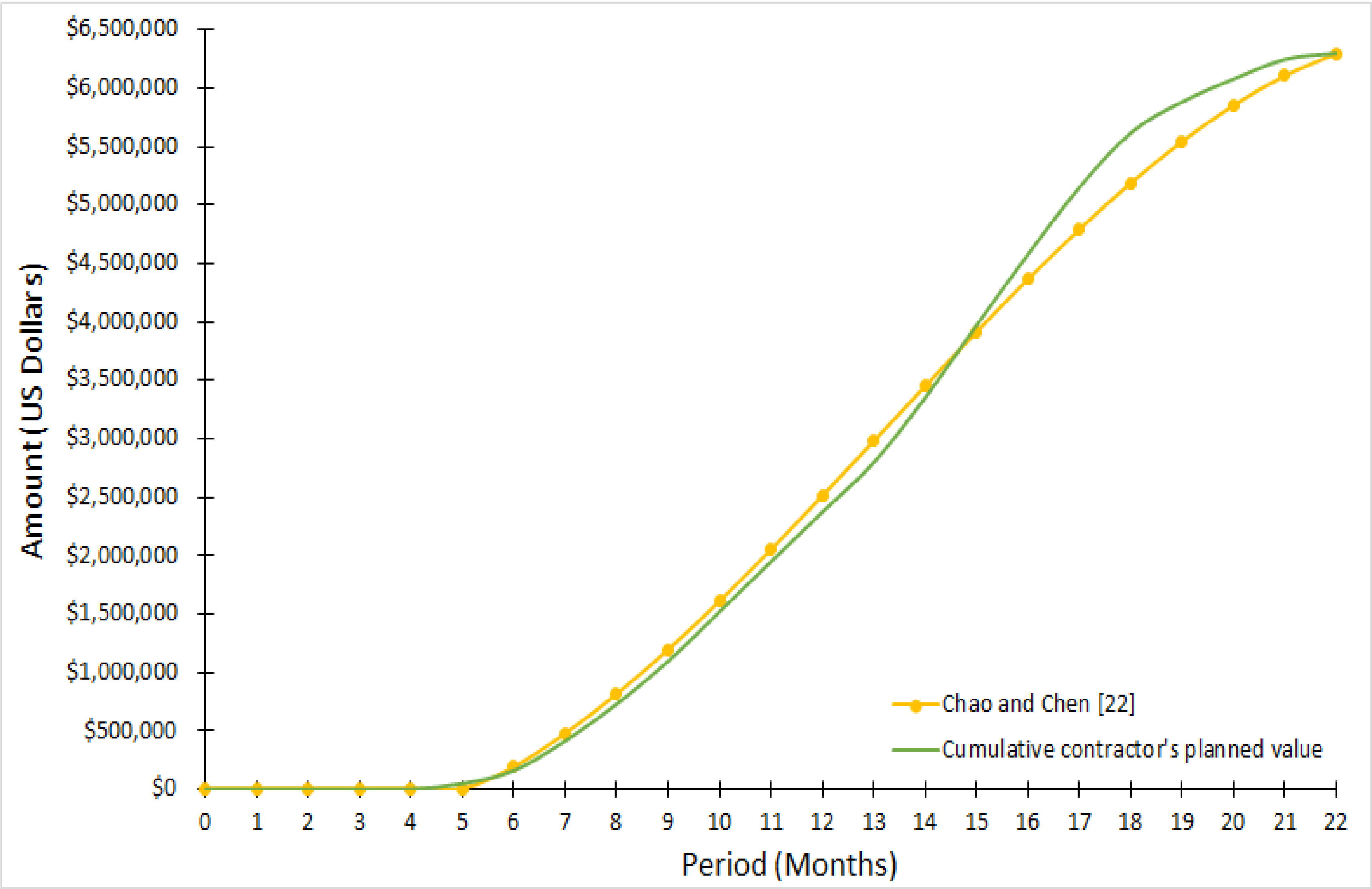

Figure 28. S-curve generated by Chao and Chen's model

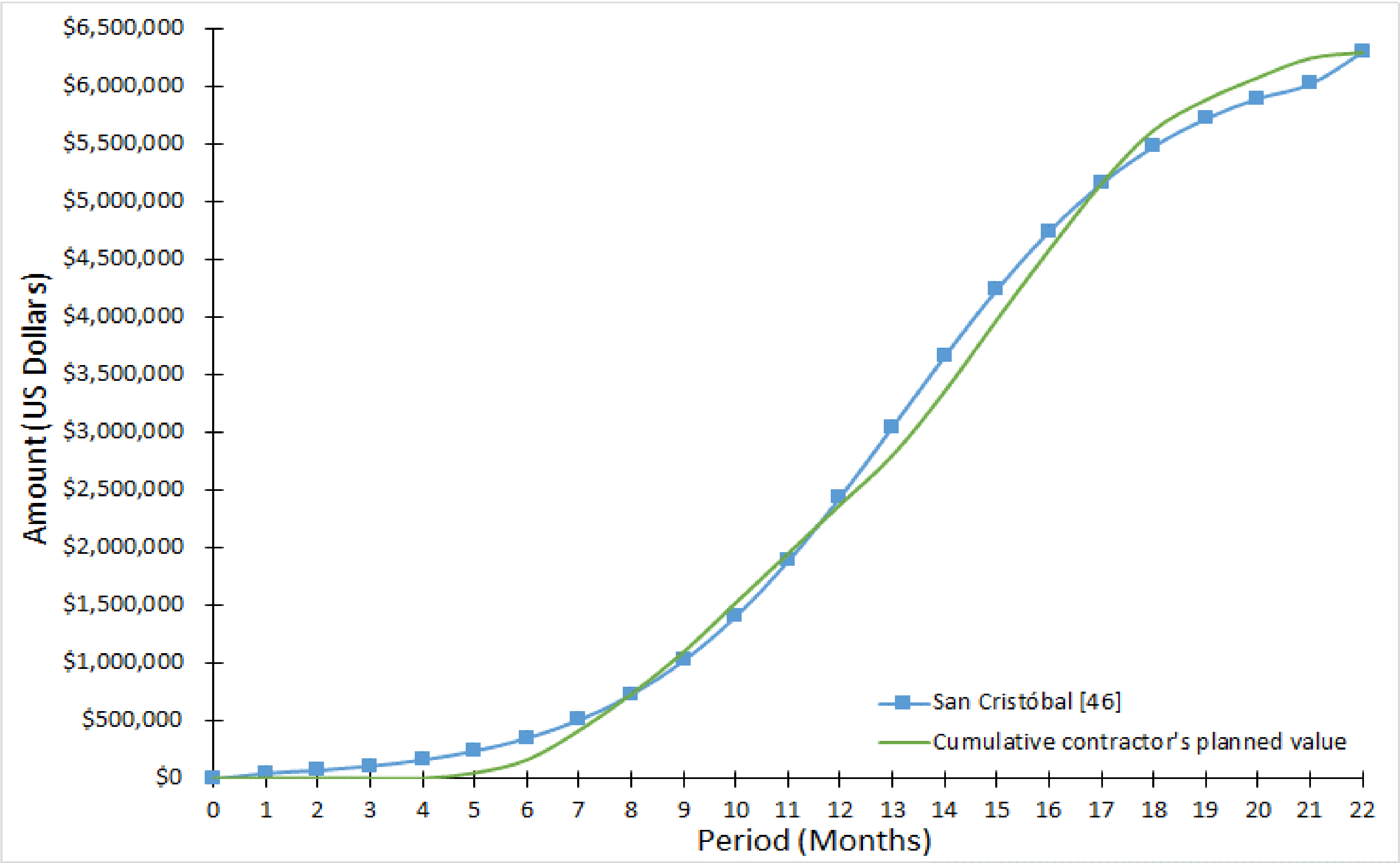

Figure 29. S-curve generated by San Cristobal's model

7.6.1 ***Measurement of Reliability***

Kenley and Wilson (1986) and Kaka and Price (1991) recommended that the error margin of forecasting for construction projects shall be around 3% of the contract amount (i.e., total earned value at project completion time) in order to validate the reliability of the proposed models. To this effect, the mean absolute deviation (MAD) is used for assessing the error for the monthly estimated cash flow for each of the proposed models. MAD is calculated using the following formula:

$$MAD = \frac{1}{n} \; |\hat{y}_t - y_t \,|$$

Equation 1. Mean Absolute Deviation (MAD)

where ŷt = calculated (i.e., forecasted) percent progress at time point "t" produced by any of the proposed models; yt = actual percent progress at time point "t" derived from the case study; and n = number of project time units. The values of MAD obtained from the proposed methods are shown in Table 18. As it can be inferred, the error range of the proposed models is [1.58%–2.01%], which lies within the above-mentioned acceptable limit. Based on the results of MAD calculations, all the proposed models are found as reliable in depicting the project progress for the construction project on hand, with that proposed by Mavrotas et al. (2005) being the most reliable model.

Table 18. Comparison of Reliability of the Proposed Forecasting Models

Research studies	Mean absolute deviation (MAD)	MAD/Contract amount* (%)
Cioffi (2005)	$121,183.4	1.92%
Mavrotas et al. (2005)	$99,769.1	1.58%
Chao and Chien (2009)	$108,164.7	1.72%
Chao and Chen (2015)	$116,116.7	1.84%
San Cristóbal (2017)	$126,253.2	2.01%

* Based on the contract amount of $6,296,605.0

7.6.2 *Measurement of Accuracy*

As it is normal in all S-curve formulae, the fitting error usually exists; a smooth curve generated from the literature-proposed models cannot completely account for all the variations in actual progress caused by reasons related to each project, managerial or else (Chao and Chien 2009). The root-mean-square error (RMSE) is a common metric used for measuring performance accuracy of continuous variables and provides a direct measure of the percentage average error, as defined next:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(\hat{y}_t - y_t)^2}{n}}$$

Equation 2. Root Mean Square Error (RMSE)

where $\hat{y}t$ = calculated (i.e., forecasted) percent progress at time point "t", produced by any of the proposed models; yt = actual percent progress at time point "t" derived from the case study; and n = number of project time units.

As such, the performance of each of the proposed models is assessed in terms of the RMSE, measuring the closeness of fit of the generated S-curve to the actual progress data. Nevertheless, since the 3rd degree polynomial formula fails to meet the boundary conditions of 0% progress (i.e., y=0) at 0% time (i.e., x=0) and 100% progress (i.e., y=1) at 100% time (i.e., x=1), a manual adjustment of the forecasted progress value, either at x=0 or x=1, is performed in order to meet the boundary conditions. This clearly decreases the errors of the forecasts of the concerned method and achieves an improvement of about 20 percent in RMSE reduction, as in the case of Chao and Chien (2009).

As shown in Table 19, all the methods are generally at par with one another, considering the low errors for each proposed formula (i.e., below 3%). To this effect, the contractor's S-curve that was generated from the model proposed by Mavrotas et al. (2005) produced the lowest RMSE value, and, hence, it clearly outperforms the other models in generating the project cash flow estimate for the construction project on hand. According to the results shown in Table 5, the application of the proposed S-curves models for cash flow forecasts achieves a fitting accuracy in the range of [97.3%-98.2%].

The proposed cash-flow forecasting methods are further ranked by increasing RMSE. To this effect, the method with the lowest RMSE is given ranked first, while the method with the second lowest RMSE is allocated ranked second, and so on. As clearly evident from Table 19, the method presented by Mavrotas et al. (2005) is the most accurate method for progress forecasting over the other literature-proposed methods, based on both RMSE results and the ranking approach.

Table 19. Comparison of Fitting Accuracy of the Proposed Forecasting Models

Error measures		Root mean square error (RMSE)		Rank
		Base case	Rectification of boundary conditions	
Research studies	Cioffi (2005)	2.35%	2.35%	2
	Mavrotas et al. (2005)	2.06%	2.06%	1
	Chao and Chien (2009)	2.98%	2.34%	3
	Chao and Chen (2015)	3.13%	2.67%	5
	San Cristóbal (2017)	2.52%	2.44%	4

7.7 Application of Models and Relevance to Practitioners

As previously shown, all the proposed models are found reliable in predicting the project cash flow estimates. That said, an envelope was developed, which includes the five S-curves generated from the encountered models, with the aim of determining the allowable possible variations in the project cash flow, as shown in Figure 30. Although the proposed deduction of this cash flow envelope may in practice require additional computations on the part of the engineer, but, at the same time, it may greatly reinforce the engineer's understanding of the boundaries of possible – yet allowable – cash flow variability, as determined by the predictions provided through the multiple available forecasting models.

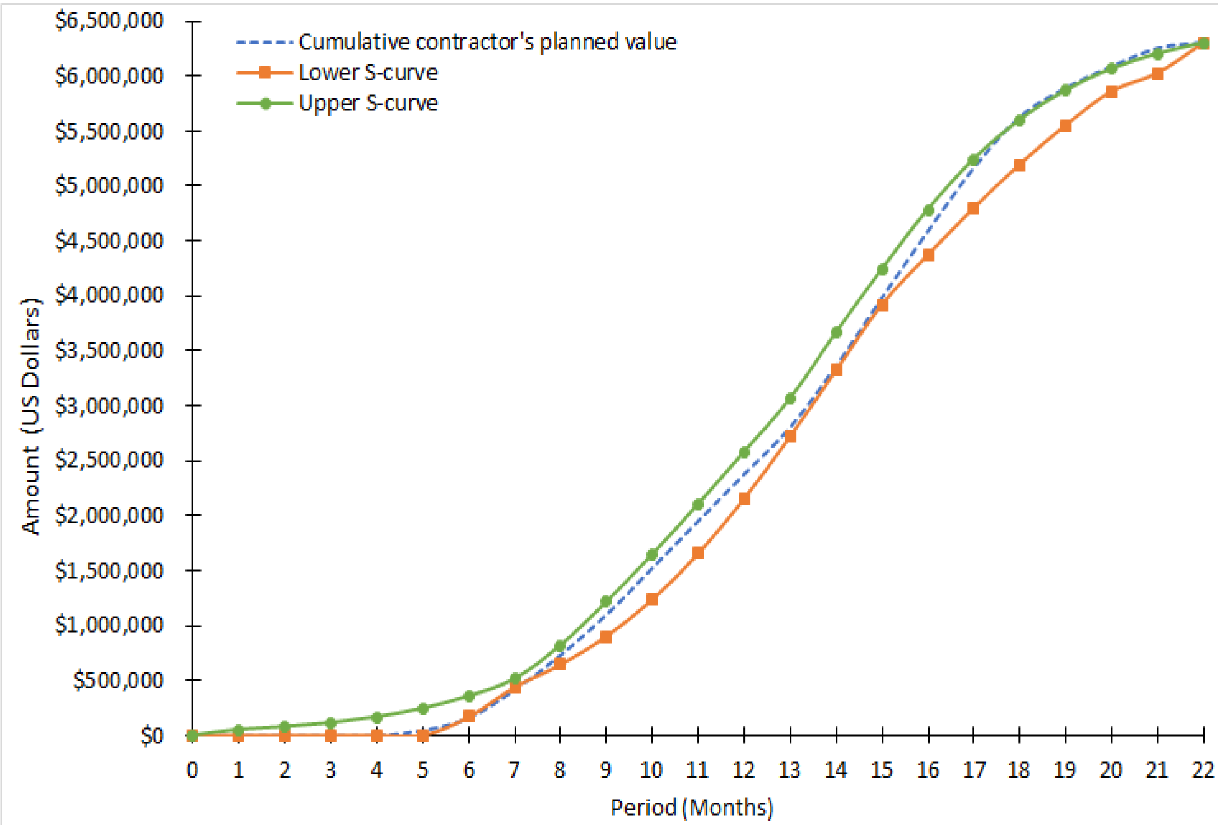

Figure 30. Lower and upper bounds S-curves using all five forecasting models

7.7.1 ***Sensitivity Analysis***

To visualize and investigate the effects of changes in project conditions on the project cash flow estimates, further validation of the proposed models was conducted using a sensitivity analysis. The purpose was that of determining the subranges of the input factors that satisfy an acceptable degree of prediction accuracy, with the condition that the resulting RMSE values do not exceed three percent (Kenley and Wilson 1986; Kaka and Price 1991). The outcome of this analysis is as summarized in Table 20, and the robustness of the proposed methods is indicated to prevail within the allowable percent change shown for each of the parameters of the concerned prediction model. As a result, a group of S-curves for each model has been obtained; however, only the lower and upper boundaries offered by the combined set of the generated S-curve groups have been inferred, as plotted in Figure 31.

Table 20. Acceptable Subranges for Forecasting models' Input Factors

Research studies	Parameters	Symbols	Allowable range	Target value	Sub-ranges	Percentage of change
Cioffi (2005)	Slope of the curve	$r_{0.67}$	$0.001 \leq r_{0.67} \leq 3$	1.0	[0.81 — 1.10]	[-19.0% , +10.0%]
	Project time at which half of the total costs will be spent	$\beta_{0.5}$	$0 \leq \beta_{0.5} \leq 1$	0.64	[0.61— 0.65]	[-4.7%, +1.6%]
Mavrotas et al. (2005)	Slope of the curve	k	$0.001 \leq k \leq 10$	5.35	[4.20 — 6.02]	[-21.5% , +12.5%]
	Position of the maximum slope	α	$0.001 \leq \alpha \leq 3$	1.64	[1.56 — 1.68]	[-4.9% ,+2.4%]
	Advance payment percentage	p	$0 \leq p \leq 1$	0.00	---	---
Chao and Chien (2009)	Coefficients of the 3rd-degree polynomial function	a	---	-2.54	[-2.55 — -2.53	[-0.4% , +0.4%]
		b		4.47	[4.46 — 4.50]	[-0.2% , +0.7%]
Chao and Chen (2015)	Position of inflection point	p	$0 \leq p \leq 1$	0.60	[0.58 — 0.61]	[-3.3% , +1.7%]
	Largest slope of the curve at p	s	$s > 1$	1.65	[1.61 — 1.79]	[-2.4% , +8.5%]
San Cristóbal (2017)	Time at which the project has used half of its total funds	T_o	$0 \leq T_o \leq 1$	0.60	[0.59 — 0.62]	[-1.7% , +3.3%]
	Steepness of the curve	α	$0.001 \leq \alpha \leq 10$	8.65	[8.08 — 8.97]	[-6.6% , +3.7%]

7.7.2 *Applicability of the Proposed Envelope*

The envelope, shown in Figure 31, consists of two cumulative boundaries of cost, defining the tolerable limits in the project cash flow variability that may take place during work execution. In other words, the cash flow pattern is to remain within those established boundaries, if it is to remain in harmony with acceptable predictions, as previously determined. As such, the minimum and maximum cumulative plots represent the limits of expected cash flow at various project progress stages. In other words, the project's envelope represents the minimum and maximum values for the expected cumulative commitments to be honored by the owner at different points in time. In practice, the envelope determines the lowest and highest allowable capital absorption throughout the project execution stage, with capital absorption being defined as the upper and lower cash flow admissible limits at each point in time (Mavrotas et al. 2005).

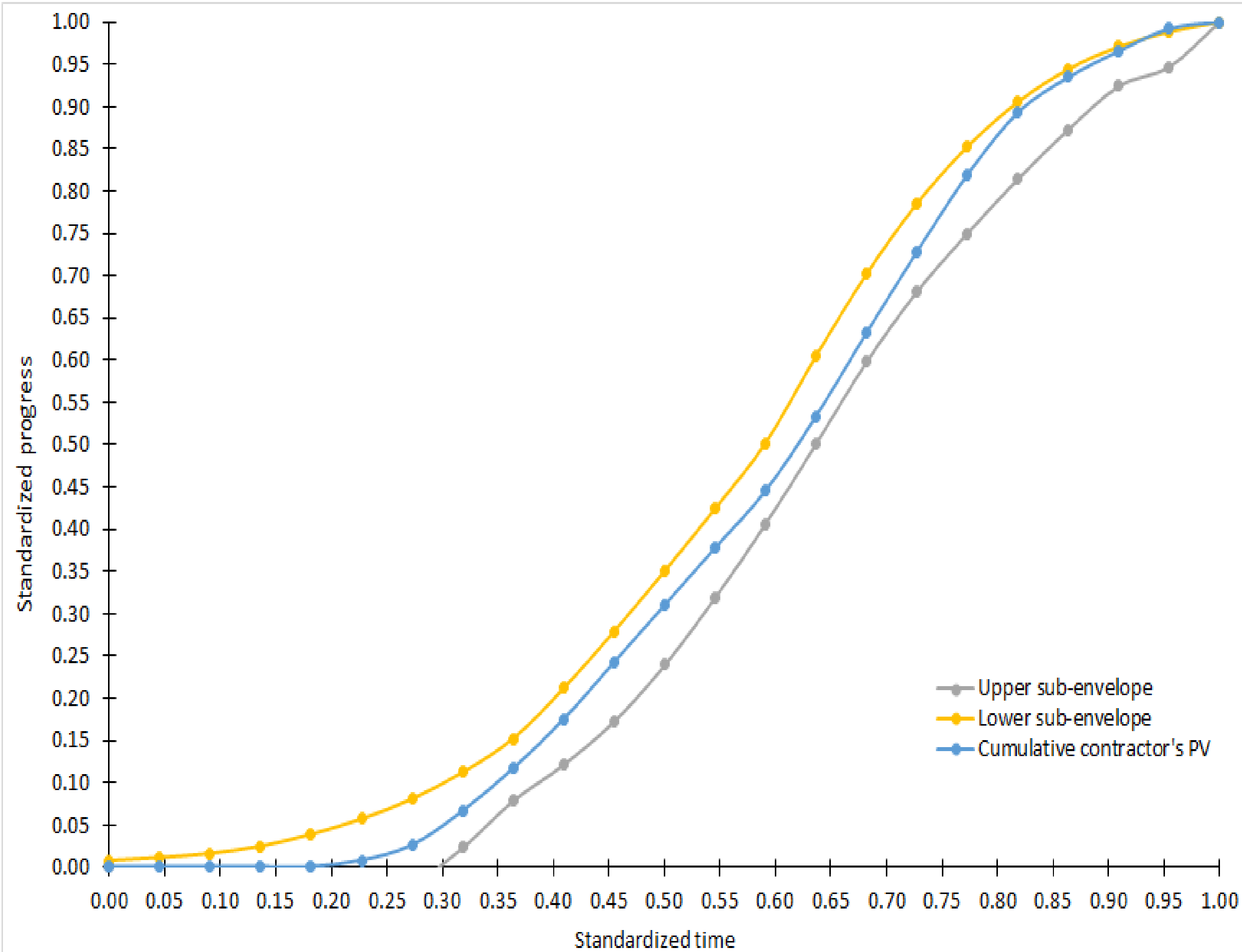

Figure 31. Upper and lower prediction envelopes reflecting models' inputs sensitivity

The proposed reliance by the engineer on the project's envelope, through the use of the upper and lower bounds rather than of a predefined S-curve, is in response to the foreseeable inaccuracy in the estimation of the project cash flow profile. Additionally, a financial analysis conducted on behalf of the project owner may involve comparing the two S-curves forming the envelope in order to determine the variations in capital requirements that need to be addressed. To this effect, the project owner can identify the time intervals during project execution that depict increased fluctuations in capital requirements potentially necessitating a high amount of cash reserves (Maravas and Pantouvakis 2012).

In addition, this envelope, formed by the upper and lower acceptable bounds, serves as tool that can used by the engineer for exercising progress monitoring and control during the course of work execution. At any time during construction, with actual progress data being available, the project status, at any point in time, can be assessed by investigating whether the position of the actual progress curve (i.e., EV curve) is well contained within these proposed upper and lower bounds. As such, the case where the cumulative value earned through actual progress falls below the lower boundary or above the upper one is indicative of an out-of-norms performance. For instance, for the project that is running noticeably under the lower curve, the engineer could safely infer that the project is likely to suffer a delay in completion. In addition, it may have to be consequently accepted that the baseline duration cannot remain as being the basis for an achievable time for completion. On the other hand, if the project is running above the upper permissible boundary, it may be a reflection of the fact that, due to site or other constraints and barriers, the contractor has indeed performed certain work activities out of their originally planned execution sequence. This is normally done at the risk of these activities not possessing all the needed inputs, therefore leading them to be vulnerable to rework that is in turn likely to propagate to subsequent activities. On the other hand, running above the upper bound may be caused by reasons related to schedule compression and acceleration methods, adopted by the contractor in an attempt to put the project back on track (e.g., to catch-up with the planned baseline duration).

7.7.3 *Owner's Cash Outflows Uncertainty*

As construction projects involve large investments, project owners usually procure adequate financing plans that can help them meet their projects' financial requirements. To this effect, developing the project allowable upper and lower boundaries, shown in Figure 32, is critical for (a) managing the variability inherent in the baseline schedule during the execution stage, and (b) determining the spectrum of fluctuations in the owner's cash outflows that may have to be tolerated and consequently planned for. As such, the cash flow uncertainty (CFU) is calculated at each time period, which is basically a measure of the spread between the upper and lower prediction curves. The CFU is calculated using the following formula:

$$CFU = \text{maximum}\, CF_t - \text{minimum}\, CF_t \tag{3}$$

where CF_t is the forecasted cash flow value at time point "t", produced from the sensitivity analysis. To be noted is that the cost figures shown in the second and third columns of Table 21 are obtained by filtering out the minimum and maximum cash flow values at various project percentage progress points. As such, these are generated from the lower and upper boundaries offered by the combined set of the S-curve groups generated using all five models, as shown in Table 21. It can be noted the CFU for the construction project on hand reaches the highest value (i.e., $700,360) at the 11th month from the start of the project. This analysis can be useful in allowing the assessment and visualization of cash flow variability by project owners in a proactive way.

Table 21. Upper and Lower Prediction Envelopes Cost Values Reflecting Cash Flow Uncertainty at Different Points in Time

Period	Lower sub-envelope (min CF_t)	Upper sub-envelope (max CF_t)	Cash flow uncertainty (CFU)
0	$0.0	$0.0	$0.0
1	$0.0	$71,630.1	$71,630.1
2	$0.0	$102,899.4	$102,899.4
3	$0.0	$157,128.0	$157,128.0
4	$0.0	$245,583.9	$245,583.9
5	$0.0	$360,743.0	$360,743.0
6	$0.0	$509,634.1	$509,634.1
7	$146,504.9	$707,549.6	$561,044.7
8	$495,780.8	$958,692.7	$462,912.0
9	$764,700.1	$1,333,408.5	$568,708.4
10	$1,087,206.1	$1,758,170.5	$670,964.4
11	$1,506,650.8	$2,207,011.6	$700,360.8
12	$2,008,380.5	$2,671,411.2	$663,030.7
13	$2,558,670.6	$3,160,677.1	$602,006.5
14	$3,155,760.5	$3,809,517.6	$653,757.1
15	$3,763,458.3	$4,419,389.4	$655,931.1
16	$4,288,069.5	$4,944,518.7	$656,449.2
17	$4,721,771.3	$5,367,919.2	$646,147.9
18	$5,126,635.2	$5,700,380.2	$573,745.0
19	$5,494,605.8	$5,944,490.2	$449,884.4
20	$5,817,627.8	$6,111,544.3	$293,916.5
21	$5,962,137.5	$6,223,181.4	$261,043.9
22	$6,296,605.0	$6,296,605.0	$0.0

7.7.4 ***Project Cash Outflows Mathematical Models***

The aim of this section is to develop the mathematical formulae that can best depict the prediction envelope reflecting the sensitivity analysis performed in relation to the models' inputs variability. The followed approach first involved standardizing the cost and time data of the envelope's curves, followed by performing a regression analysis. To this effect, in a regression-type analysis, the attempt is to fit an expression (e.g., logarithmic, linear, polynomial, exponential, etc.) to a set of garnered data (Blyth and Kaka 2006). In our case, the independent variable is the standardized elapsed time, whereas the dependent variable is the standardized progress. One way to perform regression of the obtained upper and lower prediction curves of the envelope is to fit the appropriate trendline to the available data using Microsoft Excel. In fact, using the polynomial-type function, the resulting regression equations and their corresponding R-squared values are as indicated in Table 22. The R-squared measure is a statistical indication of the variability power of the fitted regression line, also known as reflecting the goodness of fit. It can be readily concluded that a perfect fit (an R-squared value of about 99.9%) was obtained for the fourth-degree polynomial equations expressing the predictions of the lower and upper curves of the constructed envelope, as shown in Figure 32.

Table 22. Trendline Equations Depicting the Upper and Lower Prediction Envelopes

Prediction Envelope	Trendline type	Proposed trendline equation	R^2
Lower	Linear	$y = 0.8497x$	0.8303
	2nd degree	$y = 1.2019x^2 - 0.0718x$	0.9739
	3rd degree	$y = -1.9374x^3 + 3.8403x^2 - 0.8801x$	0.9936
	4th degree	$y = -4.1135x^4 + 5.9314x^3 - 0.7463x^2 - 0.1004x$	0.9987
Upper	Linear	$y = 0.9604x$	0.8984
	2nd degree	$y = 0.8472x^2 + 0.311x$	0.9672
	3rd degree	$y = -2.7131x^3 + 4.7029x^2 - 1.0185x + 0.0505$	0.9955
	4th degree	$y = -4.2312x^4 + 5.7919x^3 - 0.7358x^2 + 0.1525x$	0.9992

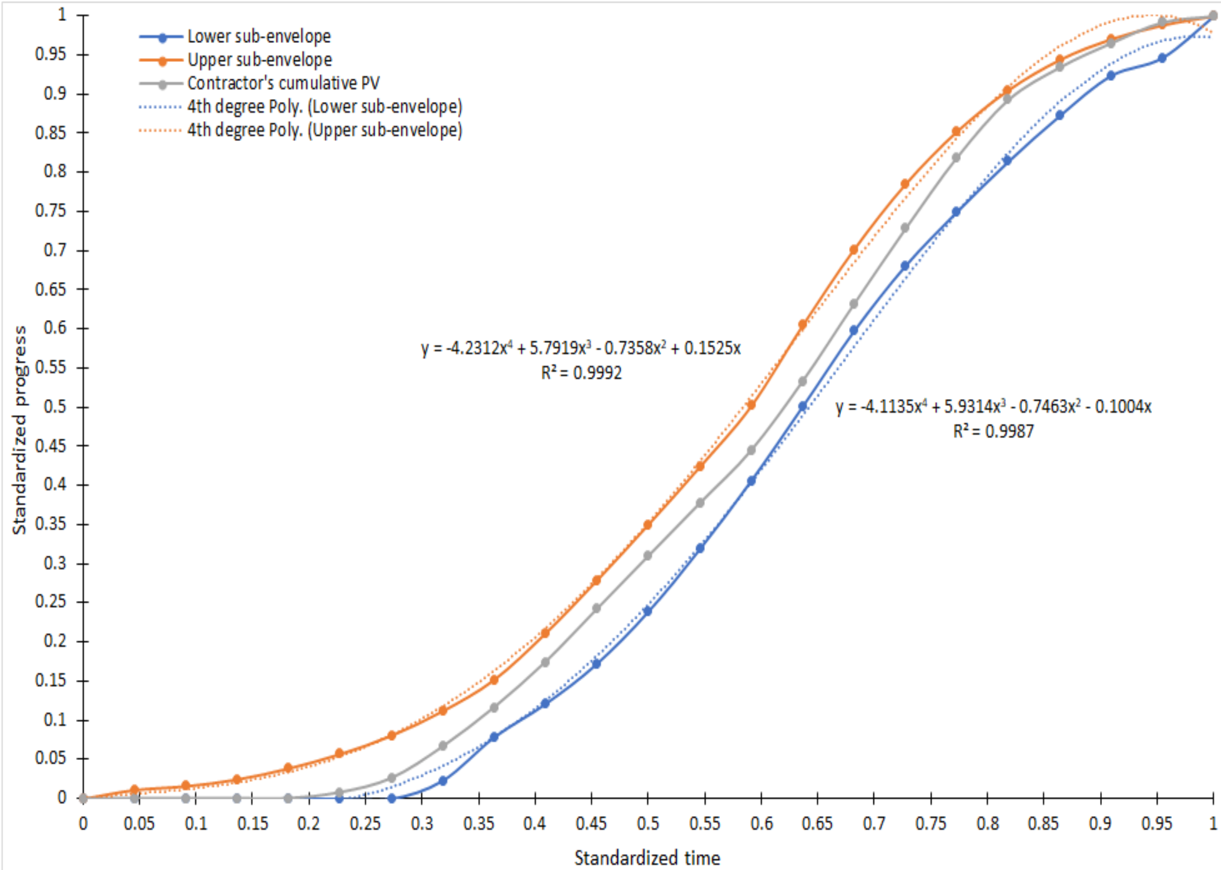

Figure 32. Trendline functions expressing the upper and lower curves of the constructed envelope

In the case of an adjustment in the contract price and/or project baseline duration during the course of work execution, the engineer may have the discretion to rely on the standardized envelope, generated from the sensitivity analysis and expressed in terms of the best-fit polynomial functions, for exercising progress monitoring and control, without worrying about the actual figures of adjusted contract price and/or extended contract duration. At any point in time (being standardized over the project original or extended duration) during construction, and with actual percent progress achieved (also being standardized by the adjusted or original contract amount), the engineer can check the project status by investigating whether the position of the actual progress curve (i.e., EV value) is well delimited within these proposed standardized upper and lower bounds of the envelope.

7.8 Practical Implications

In order to highlight the practical implications of how the various models may be relied upon by the construction contract engineer, the flowchart, shown in Figure 33, has been developed. It forms a roadmap consisting of three proposed steps that may appropriately be followed by the engineer for evaluating the reasonableness of the contractor's submitted baseline schedule and any updated or revised schedules. These involve: (1) predicting construction work S-curves using the several techniques that were identified in the reviewed literature; (2) generating the acceptable S-curve bounds in order to aid the engineer in giving or withholding consent on the submitted time-phased planned value (progress) curve, as judged against such informed metrics (S-curve bounds); and (3) developing the project allowable upper and lower S-curves for managing the variability inherent in the baseline schedule during the course of work execution and for determining the spectrum of fluctuations in the required owner's cash outflows that may have to be tolerated and therefore planned for.

Starting with the top of the roadmap illustrated in Figure 33, it is shown that, following the contract award and receipt of the notice of commencement with the works, the contractor is usually required to submit to the construction contract engineer a baseline schedule for review and possible consent. Deduced from such a schedule is the contractor's PV (planned progress) curve, which is produced in a form that serves the owner's cash flow requirements throughout the construction phase. In view of the absence of explicit guidelines specifying how the engineer shall conduct the review process (of the schedule and its underlying cash flow estimates), leading to issuing or withholding his consent, this chapter proposed a rationalized basis against which the reasonableness of, the contractor's produced S-curve can be checked. To this effect, the engineer can rely on several S-curve forecasting models to predict the cumulative project progress as a function of time. In using each of the proposed models, the values of the inputs should be estimated or extrapolated from the contractor's PV curve, in addition to other input data being determined based on the project brief and the expected project conditions. It follows that some proposed mathematical formulae do not meet the boundary conditions of: (a) 0% progress (y=0) at 0% time (x=0), and (b) 100% progress (y=1) at 100% time (x=1). In this case, the starting and final parts of the project progress S-curve shall be rectified; this is done in order to improve the fitting accuracy of the generated S-curves, prior to the measurement of the reliability and accuracy of the proposed models, performed in the steps. To this effect, the mean absolute deviation (MAD) metric is used for assessing the reliability of the generated S-curves, and the proposed models are consequently considered reliable if the ratio of MAD to the contract amount is equal or less than three percent (3%). Next, the forecasting accuracy of those models deemed as reliable is examined. This is proposed to be done using the root mean square error (RMSE) method, with the passing threshold being three percent (3%), as well. The generated S-curves are then ranked, accordingly. Subsequently, an envelope, encompassing those generated S-curves that meet the reliability and accuracy requirements, can be developed, with the aim of determining that the Schedule-generated S-curve is well contained within its the upper and lower bounds. As such, this envelope can serve as a tool for evaluating whether the project S-curve submitted by the contractor is to be deemed realistic and reflecting good planning and work phasing over the contract duration. It, therefore, supports the expression by the engineer of a consent, approval, or – at least – no-objection.

Subsequently, a sensitivity analysis on the generated S-curves can be performed, in order to determine the subranges of the input factors that satisfy an acceptable degree of prediction accuracy. As a result, an envelope, comprising a lower bound and an upper bound that are deduced from the collective set of the developed S-curve groups, can finally be constructed. The use of this modeled envelop can be instrumental in serving the two prime purposes of (1) progress monitoring and control by the engineer, and (2) planning for project cash outflows by the owner.

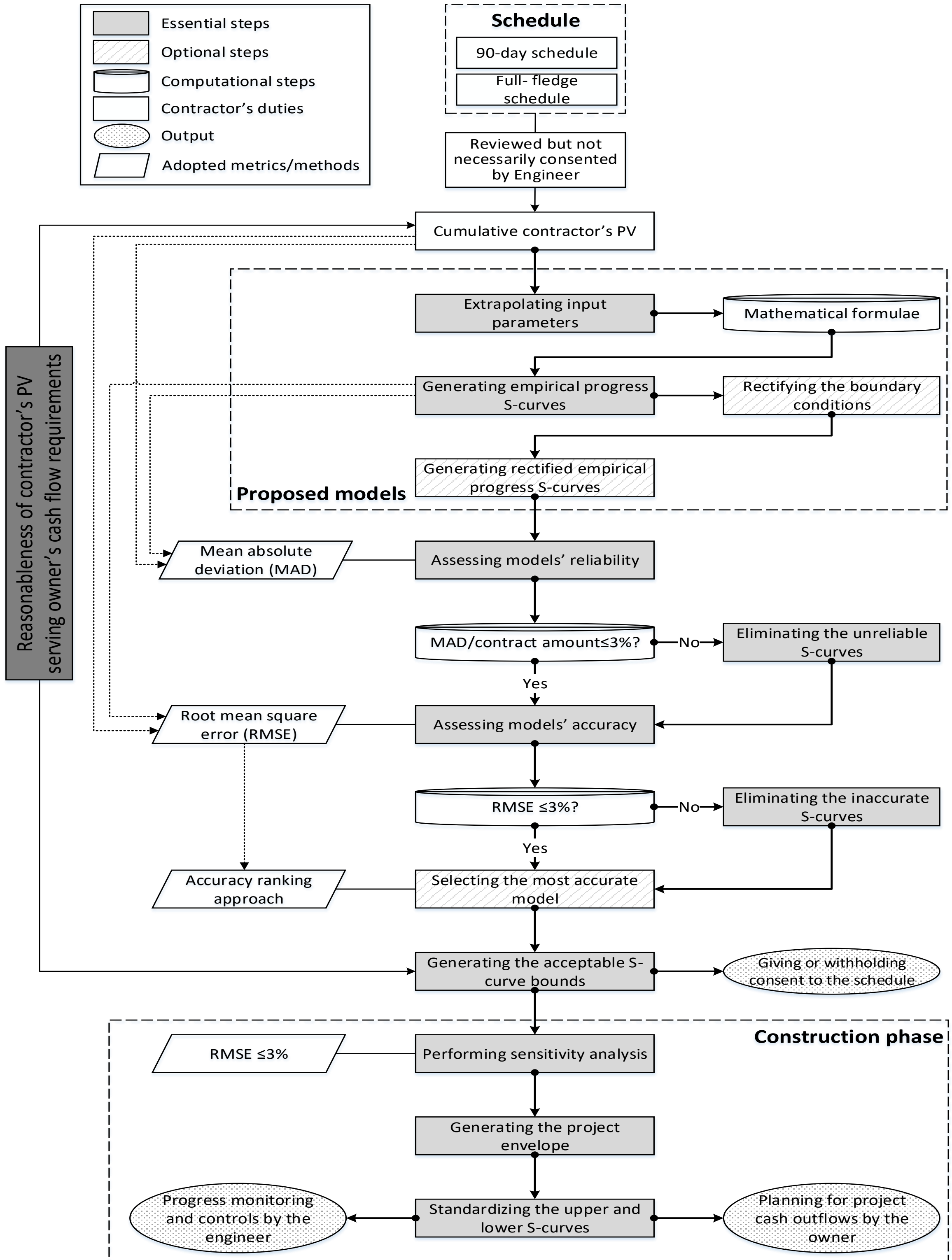

Figure 33. Roadmap for consenting the contractor's schedules

CHAPTER 8

ADMINISTRATION OF CONSTRUCTION CONTRACT INTERIM PAYMENTS BASED ON EARNED-VALUE REDUCTION TECHNIQUES

8.1 Preamble

Progress payment valuations and certifications represent a core construction contract administration function. If not attended to by the concerned contract administrators in accordance with prescribed provisions and in good faith, this vital function could end up being the seed for disputes to arise between contractors and owners. There are many reasons as to why work considered to have been accomplished by contractors end up being denied certification by the contract engineer, thereby leading to the deferral of receipt, if not partial or full denial, of payment to the contractor. This chapter addresses the conditions that could trigger the potential withholding or setting-off by the engineer of amounts that are otherwise viewed as due by the contractor.

8.2 Introduction

The construction industry is viewed as a main driver of economic development (Xu and Cheung 2015). Nevertheless, it has been well established that it is susceptible to disputes and lawsuits (Olatunji 2015; Lee et al. 2017). As such, disputes are almost unavoidable on any construction project, and managing them is consequently considered critical for better outcomes for both disputing parties (Olatunji 2015; Abotaleb and El-adaway 2017). To this end, the delivery of construction projects, while respecting the agreed completion time and contract price and in accordance with the set quality standards, serves the interests of both parties to the construction contract (Bubshait and Almohawis 1994; Gorse and Emmitt 2003). Conditional to such looked-for success is having efficient communication between the owner and the contractor (Gorse and Emmitt 2003). Accordingly, this calls for the need of well-drafted contracts that (1) accurately and expansively define the various technical, financial, and legal characteristics of a project (Bubshait and Almohawis 1994), and (2) take into consideration all probable contingencies likely to be experienced during project execution (Cheung and Pang 2012). To this end, it has been established that a wide-spread agreement does exist among industry practitioners as to the criticality of project monitoring and control to achieving project success (Demachkieh and Abdul-Malak 2018). For close to two decades, the earned value management (EVM) method has been viewed as the underlying platform for exercising project control, and doing so in accordance with a structured and systematic approach. According to PMI (2018), EVM is a method that "integrates the scope baseline with the cost baseline, along with the schedule baseline, to form the performance measurement baseline, which helps the project management team assess and measure project performance and progress." As such, EVM has three main parameters, namely the planned value (PV), actual cost (AC), and earned value (EV). To this effect, the PV, known as the budgeted cost of Work scheduled (BCWS), is defined as the share of the budget that is planned to be spent at a given instant of time. Zhong and Wang (2011) defined PV as "permissible budgeted cost for accomplish project plan workload at some stage during project implementation". Moreover, the AC, also known as the actual cost of work performed (ACWP), represents the money spent for a completed work package at some stage of the project. On the other hand, the EV, previously called the budgeted cost of work performed (BCWP), represents the amount budgeted for executing the work that was performed by a given point in time. The Association for the Advancement of Cost Engineering International defines earned value as “the periodic, consistent measurement of work performed in terms of the budget planned for that work” (Amos 2004). To compute the EV for a work item, its total budget is multiplied by the corresponding percent complete. Alternatively, it can also be computed using quantities, where it will be equal to the quantity installed for an activity multiplied by its agreed unit rate or price. With the EV, AC, and PV being expressed in monetary terms, the project manager can adopt the EVM to evaluate the project’s schedule and cost (Borges Jr and Mário 2017). For each reporting period, the project manager is required to calculate two types of performance measures, namely variances and indices, based on the three main EVM parameters. As these variances and indices are interrelated, they both contribute in estimating the expected at-completion forecasts for the project duration and cost. From a project owner’s perspective, such a computed EV amount, which is earned in respect of the work accomplished by the contractor up to a certain point in time, is significant for the purpose of comparison with the value that was planned (i.e., PV) to be achieved by that time. Also, it is this EV amount, claimed by the contractor to be representing the portion of the contract price that has become due, that will be the subject of payment certification consideration by the construction contract’s engineer (or project manager) appointed by the owner.

As such, the payment process is one of the critical areas that needs to be attended to by the various parties involved in the construction of the intended facility (Hinze 2001;

Abotaleb and El-adaway 2017), where work progress and quality are significantly impacted by delays in certifying and making payments, settling cost claims, and discharging retention amounts (Odeyinka et al. 2008). Unlike normal discernment, it is not an “inherent or implied right” of a contractor to obtain interim payments from the project owner; this is a right that is granted in the contract (Hinze 2001). To this effect, releasing regular interim payments to contractors is necessary in order to provide funding for construction work progress, and contractors should be fully acquainted with the provisions for interim payment applications administration in order to appropriately support their construction cash flow analyses (El-adaway et al. 2013). To this end, management of cash flow in construction projects is critical because projects are complex and take longer time to be completed, relative to other industries, and progress payments also tend to be bulky (Makarfi Ibrahim 2010). In fact, one of the leading sources of disputes in the construction industry is payment-related (Kartam and Kartam 2001; Chan and Suen 2005; Cheung and Yiu 2006; Kennedy 2006; Abdul-Rahman et al. 2013; Ramachandra and Rotimi 2014). Although contractual provisions dealing with the owner’s payment obligations are often explicitly stated in contracts, they are frequently misinterpreted and/or misemployed, leading to claims and disputes between the parties to the contract (Ramachandra and Rotimi 2014). As also indicated by Ramachandra and Rotimi (2014), failure of payment provisions fulfillment, disagreement on quantification of executed work for interim and final payment certificates, and issues related to the valuation of variations are the main causes of disputes between owners and contractors . Similarly, Abotaleb and El-adaway (2017) stated the common payment-related problems in construction projects to include: (a) delay in payment or nonpayment of certified amounts, (b) valuation of final account, (c) late release of retention money, (d) valuation of variation orders, (e) flawed payment procedures, and (f) withholding/setting-off amounts from interim payments without a contractual basis. As for this cited payment-reduction problem, it is argued that although contracts incorporate detailed provisions concerning the mechanisms concerned with interim payments, which provide the engineer with the authority to withhold or set-off amounts from these payment applications submitted by contractors, they do not offer explicit language or basis for effectuating such reductions and for their possible reimbursement at a later stage (Abotaleb and El-adaway 2017). The work presented in this chapter has thus been motivated by the need to have clear and rationalized bases that can be relied upon by the contract engineer when deciding to exercise withholding or setting-off certain sums from amounts presented by the contractor to be representing the value of executed work allegedly earned by the owner at the time of submitting an interim payment certificate application (IPCA).

8.3 Contract Language Governing Interim-Payment Certification

Standard conditions of contract are normally regarded as preserving an equitable approach in allocating the responsibilities, obligations, rights, liabilities, and duties of each party to the construction contract, and those provisions dealing with payment-related matters are no exception. To this end, such terms invariably specify the authorities and roles assigned to the contract engineer for periodically certifying the amounts due to the contractor.

To deduce a standard set of the engineer's payment-related responsibilities, the standard conditions for the construction contract issued by the International Federation of

Consulting Engineers (FIDIC), which are used extensively on international projects and endorsed by the World Bank, were closely examined (FIDIC 1999). Table 23 summarizes the attributes of the prescribed roles for both the contractor and engineer, as directly adopted from the concerned general conditions' sub-clauses. In addition, guiding clarifications, offered by the FIDIC under its corresponding "guide" version of the examined conditions, are also presented across the listed sub-clauses' requirements. A number of observations can be withdrawn as follows:

- The engineer is required to inspect executed work without unreasonable delay, and the quantities of completed work should preferably be agreed between the engineer and contractor as part of a continuous process;
- The engineer is authorized to withhold an amount from an interim payment certificate if the work executed by the contractor is deemed not to be in accordance with the contract, or due to a disagreement as to the assessment of executed quantities resulting from differing methods of measurement respectively employed by the contractor and engineer;
- The engineer is authorized to make any proper modification to the previously issued payment certificates;
- The contractor is entitled to be informed of the payment which he is to receive, without being requested to modify his statement (i.e., payment certificate application);
- The contractor is under the obligation to rectify any defective products, materials, or works to ensure compliance with the contract;

- The employer (referred to as “owner” under other standard conditions) has the right to employ and pay other persons to perform the work, due to the contractor’s failure to comply with the engineer’s instructions calling for the remedy of such defective work;
- The contractor is entitled to receive financing charges compounded monthly on amounts unpaid by the owner and for which an interim payment certificate has been issued; and
- The employer has the right to ultimately terminate the contract due to the contractor’s performance noncompliance.

The deductions made above are believed to be representative of what other standard contract conditions typically stipulate in respect of administrating IPCAs submitted on a periodical basis by construction contractors. Whether or not these – or other similar – stipulations are properly adhered to and/or exercised in practice remains to be answered on a case-by-case basis, depending on the varying industry cultures and concerned participants’ behaviors when acting under such terms.

Table 23. Standard Contract Language Pertaining to Payment Certification (Based on FIDIC 1999)

Sub-Clause Number	Sub-Clause Description	Described Role	FIDIC Guide's Clarifications
7.3	Inspection	The Contractor shall give notice to the Engineer whenever any work is ready and before it is covered up, put out of sight, or packaged for storage or transport The Engineer shall then either carry out the examination, inspection, measurement or testing without unreasonable delay, or promptly give notice to the Contractor that the Engineer does not require to do so.	If the Contractor does notify, the Engineer must be reasonably prompt in responding, by carrying out the examination, inspection, measurement or testing without unreasonable delay, or by giving written notice to the Contractor that it is considered unnecessary. Unreasonable delay may entitle the Contractor to an extension of time under Sub-Clause 8.4(e).
7.5	Rejection	The Engineer may reject the Plant, Materials or workmanship by giving notice to the Contractor, with reasons.	The Contractor may request clarification of the reasons why it is considered to be defective, but there is no need for the Engineer or other Employer's Personnel to identify the cause of the defect.
7.6	Remedial Work	The Engineer may instruct the Contractor to: ... (b) remove and re-execute any other work which is not in accordance with the Contract. If the Contractor fails to comply with the instruction, the Employer shall be entitled to employ and pay other persons to carry out the work.	--- ---
12.1	Works to be Measured	Whenever the Engineer requires any part of the Works to be measured, reasonable notice shall be given to the Contractor's Representative, who shall: (a) promptly either attend or send another qualified representative to assist the Engineer in making the measurement, and (b) supply any particulars requested by the Engineer. The Contractor shall, as and when requested, attend to examine and agree the records with the Engineer, and shall sign the same when agreed. If the Contractor does not attend, the records shall be accepted as accurate.	Quantities should preferably be agreed between the representatives of the Engineer and the Contractor, as a continuing process, and as the execution of the Works proceeds. Although the second paragraph empowers the Engineer to take the initiative in requiring a measurement to be made, this activity should be regarded as a joint activity.
14.6	Issue of Interim Payment Certificate	The Engineer shall, within 28 days after receiving a Statement and supporting documents, issue to the Employer an Interim Payment Certificate which shall state the amount which the Engineer fairly determines to be due, with supporting particulars. An Interim Payment Certificate shall not be withheld for any other reason, although:(a) if any thing supplied or work done by the Contractor is not in accordance with the Contract, the cost of rectification or replacement may be withheld until rectification or replacement has been completed;... The Engineer may in any Payment Certificate make any correction or modification that should properly be made to any previous Payment Certificate.	The Contractor is to be notified of the payment which he is to receive, without being requested to amend his Statement. Such a request would typically be inconsistent with the procedures for payment specified in Clause 14. If an item of work is so non-compliant that its contract value is zero, there would typically be no payment due and therefore nothing from which a deduction for withholding may be effected. The final paragraph allows an Interim Payment Certificate to be corrected or modified in any subsequent Payment Certificate.
14.7	Payment	The Employer shall pay to the Contractor: …..(b) the amount certified in each Interim Payment Certificate within 56 days after the Engineer receives the Statement and supporting documents,…	If the Employer considers himself entitled to claim against the Contractor, notice and particulars must first be submitted under Sub-Clause 2.5. The Employer's entitlement is then to be agreed or determined, and incorporated as a deduction in a Payment Certificate.
14.8	Delayed Payment	If the Contractor does not receive payment in accordance with Sub-Clause 14.7, the Contractor shall be entitled to receive financing charges compounded monthly on the amount unpaid during the period of delay.	Financing charges are calculated for a period which is "deemed to commence on the date for payment specified in Sub-Clause 14.7", even if the Engineer had not issued an Interim Payment Certificate by such "date for payment".
15.2	Termination by Employer	The Employer shall be entitled to terminate the Contract if the Contractor:...(c) without reasonable excuse fails:...(ii) to comply with a notice issued under Sub-Clause 7.5 or Sub- Clause 7.6, within 28 days after receiving it,...	---
15.4	Payment after Termination	After a notice of termination under Sub-Clause 15.2 has taken effect, the Employer may: ...(b) withhold further payments to the Contractor until the costs of execution, completion and remedying of any defects, damages for delay in completion (if any), and all other costs incurred by the Employer, have been established.	---

8.4 Examined Building Construction Project Cases

In this section, the payment application, certification, and reimbursement records of three building construction projects completed in the last five years in the Middle East and North Africa (MENA) region were examined. Two of them were high-end residential complexes, whereas the third was a 400-room luxury hotel development. All projects adopted sequential payment certification and honoring periods, with two specifying 28 days for each of these stages and the third opting for the figures of 30 days and 14 days, respectively. The main common observation was that the contractors were asked to correct and resubmit their originally submitted statements prior to the engineer issuing the corresponding payment certifications. The other shared observation was that the differing opinions as to the executed work to be included in payment certification applications were invariably in relation to quantity measurement differences and quality-related issues. Other specific main findings, pertaining to the studied projects on a case-by-case basis, were as follows:

- In the first project case, a claim for financing charges was pursued by the contractor in connection with payments having allegedly been made late by the owner. In this claim, the contractor measured both the delay in issuing certifications followed by the delay in effectuating certified payment by the owner. The former was primarily the result of having been requested to correct originally submitted statements to reflect the differing assessments held by the contractor, on one hand, and the engineer, on the other, concerning the eligibility of executed work for inclusion in payment certification applications. The latter accounted for the actual dates on which the value of payments made by the owner became effective.

- In the second project case, two significant issues are worth reporting on. Firstly, the project owner, and on more than one occasion during the project's construction lifespan, had been held in default in relation to several consecutive interim payments. This resulted in a major dispute following the contractor's pursuing of a claim in connection with both the project completion time to be targeted and the corresponding additional compensation. The second issue had to do with the contractor having been persuaded by the owner to agree that, for the woodwork shipments to be allowed into the site and their installation work to be permitted to proceed with, a reduction was to be effectuated to the total value of this multi-million dollar woodwork package. The woodwork in question was fabricated in a country different from that of the project locality and shipped by trucks across the boundaries of multiple neighboring countries. The then-intended reduction was agreed to by the contractor, and in writing, but only on the principle of instituting it with no percent reduction figure explicitly expressed. The reduction was primarily in connection with the quality of the veneer that ended up being used, assessed by the engineer as having been inferior in comparison with that of the samples that had been approved. The reduction ultimately applied by the engineer was in the order of about 50 percent of the package's total value, which was viewed by the contractor to have been enormously excessive. In fact, the contractor later purported that the reduction had been set to such an unrealistic ceiling in order to give the owner more leverage in negotiating the then-pending contractor's claims and owner's counter-claims.

- In the third project case, three payment-related issues were distinctively identified. These were: (1) the deferred or delayed attendance by the engineer to inspection requests issued by the contractor, (2) the effect of overstated quantities in the bill of quantities (BOQ), with the contract price having been of the lump-sum type, and (3) the lack of a schedule of value (SOV) for integrative items of work. The delayed inspection practiced on the part of the engineer was strongly thought of by the contractor to have been deliberate and aimed at precluding work that could have otherwise been considered for inclusion in a payment certificate in question. As for the overstatement of quantities for some BOQ's work items, the contractor was being denied the payment of work item's price subtotals in an interim payment certificate in question despite the fact that no more work was still required concerning the concerned items, with the total executed quantity having turned out to be less than the total quantity originally estimated and listed in the BOQ. An example of the lack of SOV issue was with the main work item of "carpet," which entailed executing multiple layers of work starting with a concrete screed and ending with the carpet layer with a couple of other layers in between. A dispute as to the value corresponding to the screed layer emanated when the engineer opted to apply for the purpose of certifying interim payments a BOQ's existing rate, listed in relation to concrete screed work specified for stairways' landings. The resolution of this matter was achieved after lengthy discussions of the contractor's submitted analysis of the costs that were being actually incurred. All three issued, as explained above, were viewed by the contractor to have resulted in interim underpayment and EV misrepresentation throughout the construction duration.

8.5 Effectuating Payment Reductions in Practice

Based on the deductions made from the work presented in the two previous sections, a synthesis was done of the types of differing assessments of the value of work earned, followed by highlighting the reasons that can lead to payment withholdings and/or setting-offs by the engineer. Furthermore, the incompatibility between the quantities forming the basis for payment certifications and those that are reflected in the construction schedule updates, generated by the contractor and submitted in congruence with payment certificate applications and their accompanying progress reports, has been underlined.

8.5.1 *Differing EV Assessments*

Accurate progress measurement helps ensure that payment applications presented by contractors are exact and timely. Before payments are certified by the engineer, the typical practice is for the value of the work to be ascertained by determining the correct amount of work executed to date. To this effect, calculating accurate quantities in a transparent manner and based on sound methods may contribute to reducing or preventing payment-related conflicts between owners and contractors.

The BOQ document comprises a list of the items of works to be carried out under the contract. These items are briefly described, with their estimated quantities entered against each along with the corresponding unit rates offered by the contractor. The work descriptions and quantities are usually prepared based on a specific standard method of measurement. While the chief function of the BOQ document is to present a breakdown of the total contract price according to the work items involved, one of its main uses is to form a basis for computing the value of work completed for the purpose of successive interim payment applications and certifications. To this end, it can be said that the BOQ document provides an effective and agreed-upon basis for periodically quantifying the value of progressed work, firstly, by the contractor for preparing an interim payment certificate application and, secondly, by the engineer for issuing the payment certificate, thereby causing payment to have become due to the contractor.

Table 24 summarizes several types of work items having differing progress assessments, respectively made by the contractor and engineer. For directly measured quantities, where the principle for quantifying work progress is based on the quantities being directly measured on site, the actual quantities executed up to date multiplied by the unit rates offered in the BOQ contribute to the calculation of the subtotals included in the IPCA submitted by the contractor to the engineer. As stated earlier, the involved quantity measurement process must be as transparent as possible and should be based on sound standards of measurement. To this effect, work item No. 1 in Table 24 corresponds to the case where the contractor and the engineer disagree on the assessment of quantities actually executed to date by an amount "q_m", due to the lack of reference to a specific standard method of measurement. As such, this discrepancy in quantity measurement is considered to be the first reason justifying the reduction applied by the engineer when certifying an IPCA. In addition, the inability to meet the specified technical performance or quality requirements for the executed work can be regarded as another main reason leading to a discrepancy between the assessed and certified amounts in the interim payment cycle. The engineer may temporarily reduce the amount to be certified to the contractor by adjusting the actual quantity executed to date by the defective quantity “q_d”, as shown for work item No. 2 in Table 24, in order

to cause the contractor to rectify the defective units in question. Alternatively, the engineer may have reasons to accept the defective works or systems, at a quality level inferior to that originally desired, but in this case by applying a percent reduction to the unit rate of the concerned work item (as in work item No. 5 in Table 24). Moreover, work item No. 3 (Table 24) also corresponds to executed works, but for which a delay in inspection by the engineer has taken place for a partial (executed) quantity “q_i”. In this case, the contractor may request in the submitted IPCA the amount corresponding to the full quantity executed to date, whereas the engineer responds in deducting the amount associated with the quantities that are yet to be inspected, despite the inspection requests having been already made by the contractor. To this end, and provided that these partial quantities end up being accepted later upon performing the necessary inspection by the engineer, this practice puts into effect a total effective retention that may far exceed the threshold set forth in the contract.

Furthermore, the total actual quantity of a work item may end up being different from the total estimated quantity shown in BOQ. For instance, work item No. 4, in Table 24, corresponds to the scenario with a BOQ quantity "x" being overstated by a quantity “q_0”; that is, the contractor will, upon completing the whole actual quantity, be paid in the interim less than the full amount corresponding to the price subtotal of the concerned work item, unless the completion of the work item in question coincides with the completion of the whole of the works. As such, overstated BOQ quantities, in a lump sum contract, may lead to underpayment of the contractor during construction, if the BOQ is relied upon as the basis for making periodic payments. The resulting underpayment would be the difference between the amount assessed by the contractor and that certified by the engineer during the interim payment cycle on hand, which is equivalent to the quantity q_0 multiplied by the corresponding unit rate of the work item in question. Finally, an SOV incorporates a list of progress milestones for a given item of work, indicating the percent unit rate corresponding to each described milestone. If specified, it can aid in providing more transparency as to the value used for describing achieved progress, by allowing both the contractor and the engineer to rely on the same basis for payment application and certification purposes. Therefore, with such a tool being provided as in the case of work item No. 6 of Table 24, the contractor and engineer may end up in disagreement as to the description of achieved progress corresponding to the work actually executed, thus leading to a difference between the contractor's assessed and engineer's certified amounts, as shown in Table 24. An extension of this analysis can be done by considering work item No. 7, representing the case where an SOV is not specified in the contract, and the disagreement here will be twofold, involving: (1) differing subjective progress assessments and, subsequently, (2) conflicting work valuation judgements. As indicated in Table 24, the result will transpire in two different unit rate percent values being applied, one by the contractor upon submitting the IPCA and a lower one by the engineer for computing the certified sums.

Table 24. Types of Differing Assessments of Value of Work Earned

Item	Description	Total quantity (x)	Unit Rate (UR)	Full billable subtotal at	Actual quantity (y) of units executed	Conditions	Interim payment cycle: Contractor's assessed amount	Interim payment cycle: Engineer's certified amount
1	Direct measurement, with measurement disagreement by an amount "q_m"	x_1	UR_1	$x_1 \times UR_1$	y_1	$y_1 \leq x_1$ $q_m \leq y_1$	$y_1 \times UR_1$	$(y_1 - q_m) \times UR_1$
2	Direct measurement, with a quantity "q_d" being inspected by the engineer and considered to be defective	x_2	UR_2	$x_2 \times UR_2$	y_2	$y_2 \leq x_2$ $q_d \leq y_2$	$y_2 \times UR_2$	$(y_2 - q_d) \times UR_2$
3	Direct measurement, with a delay in inspection by the engineer for an executed quantity "q_i"	x_3	UR_3	$x_3 \times UR_3$	y_3	$y_3 \leq x_3$ $q_i \leq y_3$	$y_3 \times UR_3$	$(y_3 - q_i) \times UR_3$
4	Direct measurement, with a BOQ quantity "x" being overstated by a quantity "q_0"	x_4	UR_4	$x_4 \times UR_4$	$y_4 = x_4 - q_0$	$0 < q_0 < x_4$	$x_4 \times UR_4$*	$y_4 \times UR_4$
5	Direct measurement, with a quantity "q_a" being accepted by the engineer at lower than desired quality	x_5	UR_5	$x_5 \times UR_5$	y_5	$y_5 \leq x_5$ $q_a \leq y_5$	$y_5 \times UR_5$	$(y_5 - q_a) \times UR_5$ $+ q_a \times (1 - \alpha) UR_5$
6	Schedule of value, with stipulated payment milestones	x_6	UR_6	$x_6 \times UR_6$	y_6	$0 \leq y_6 \leq x_6$ $y_6 = k + l + m + n$	$k \times UR_6 + l \times \theta_3 UR_6$ $+ (m + n) \times \theta_2 UR_6$	$(k + l) \times \theta_3 UR_6$ $+ (m + n) \times \theta_1 UR_6$
7	No schedule of value, with differing subjective progress assessments	x_7	UR_7	$x_7 \times UR_7$	y_7	$0 \leq y_7 \leq x_7$	$y_7 \times (\beta_c UR_7)$	$y_7 \times (\beta_e UR_7)$

*: Total actual quantity is completed before project completion time
α: Percent reduction in the unit rate of the work item
k, l, m, n: Individual units of the same item of work
θ: Percent unit rate corresponding to a milestone in the work item's SOV
β_c : Percent unit rate applied by the contractor
β_e : Percent unit rate applied by the engineer

8.5.2 *Payment Withholdings and Setting-Offs*

It can be concluded at this stage that two general classes for possible reductions can be effectuated by the engineer to the sums purported by the contractor in the submitted IPCAs. Namely, these are: withholding and setting-off, as shown in Figure 34. The two highlighted classes happen to originate from also two reasons that can be regarded as justifying the effectuation of reductions by the engineer: (1) discrepancy in quantity measurement and (2) quality-related reductions. As for the differing assessments, firstly by the contractor and subsequently by the engineer, regarding the executed quantities for work items under progress or completed, these are found to lead to effecting withholdings pertaining to: (1) difference in the method of measurement used for quantities take-off, (2) delay in carrying out inspection by the engineer, and (3) overstated BOQ quantities for certain work items under a lump sum contract. On the other hand, in the case of failure by the contractor to deliver the executed works according to the set quality requirements during the relevant payment period, the engineer may resort to a temporarily withholding of a part of the requested interim payment until the contractor remedies the defective work. This reduction is put into effect through either reducing the quantities executed to date or the item's subtotal, as the case may be, until the contractor attends to the remedy of such defective work and ensures that the corrected work is compliant with the contract requirements. However, if the contractor fails to comply with the instruction to rectify the defective quantities, the engineer shall be entitled to set-off the withheld amount, and the owner may then pay other persons to carry out the work. In case the engineer accepts the executed works or systems while not being in full conformity with the contract requirements, a permanent set-off is exercised, either by reducing the work item's unit rate or subtotal, as the case may be. The outcome here is one where the work or system in question will be taken over by the owner at lower than the desired performance levels or quality requirements.

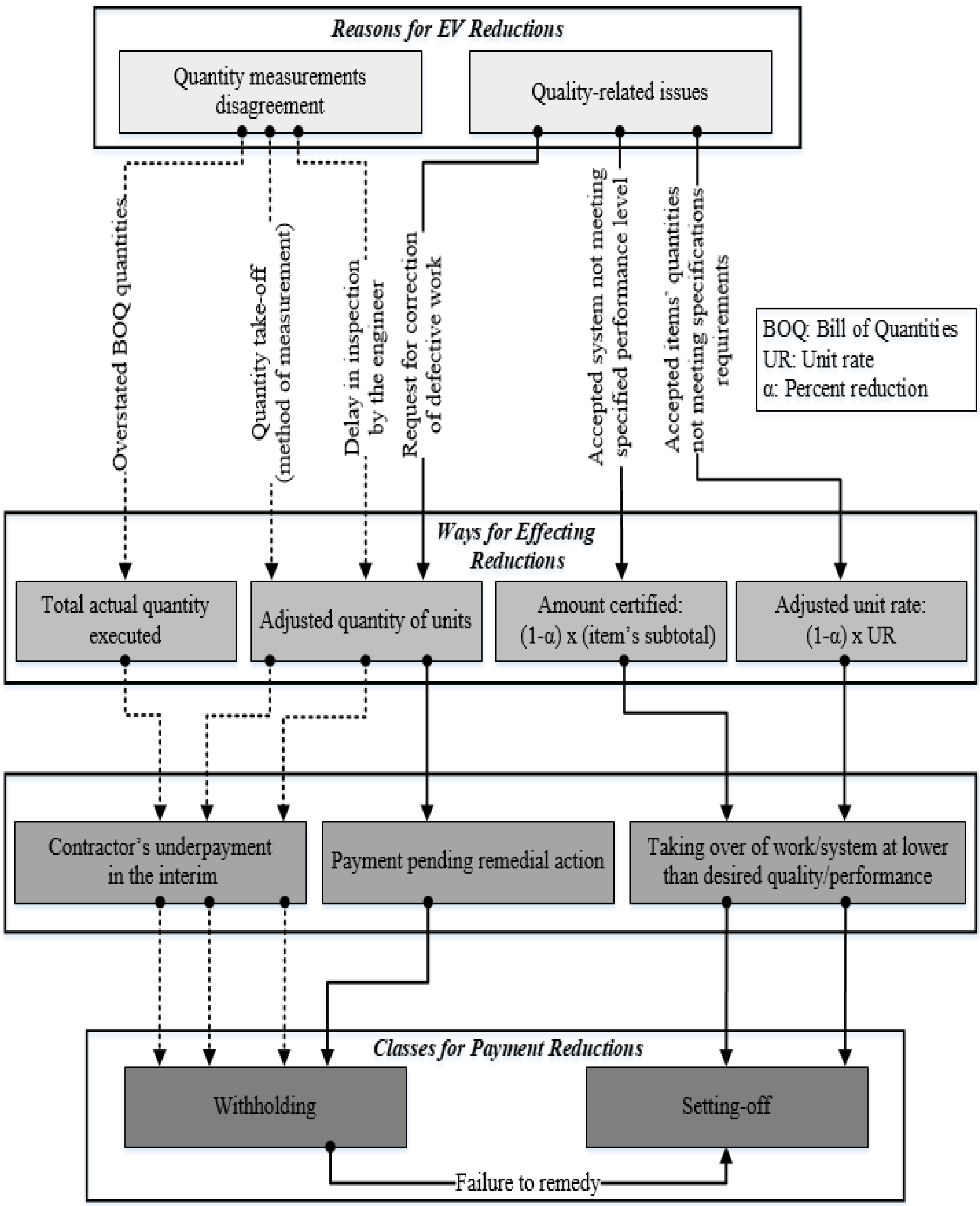

Figure 34. Reasons leading to payment withholdings and/or setting-offs

8.5.3 *Incompatibility with Construction Schedule Updates*

Regardless of whether the means for introducing reductions (withholdings and/or setting-offs) to contractors' assessed payment amounts are used rightfully in all instances by the contract engineer, an issue seems to inevitably surface. This is stemming from the fact that the quantities based on which a payment certification is issued may be different from – or, more exactly, lower than –those used by the contractor to produce the construction schedule update accompanying the submitted IPAC. In turn, this incompatibility is likely to manifest itself in the form of a discrepancy between (1) on one side, progress metrics generated through the updated version of the schedule, and (2) on the other, the total value earned to date, as computed in the latest issued payment certificate, relative to the value of the contract price.

8.6 Disagreement Avoidance and Preventive Reduction Techniques

This section presents several techniques related to EV assessment, which were identified from the related literature and summarized in Table 31. They aim at (1) introducing objectivity to the measurement of executed work and (2) justifying the effectuation of reductions in connection with noncompliant work as well as work performed out of the planned sequence or not in satisfaction of a dependency with the work of other activities. Indicative examples on selected building construction work items are offered, to the extent possible, by way of demonstrating the applicability of the identified techniques to the formulation of EV assessments or reductions. A brief discussion of each of the proposed methods indicated in the second column of Table 31 is therefore offered as follows.

8.6.1 *Measurement Assessment*

Two proposed formulations can be used for more objectively assessing or measuring the level of achieved progress: the fuzzy EV and internal earned value (IEV) techniques. These proposed methods allow the contractor and engineer to use an identical basis for interim payment application and certification purposes, thereby potentially diminishing the disagreement as to the assessment of executed works and preventing excessive contractor's underpayment during the interim payment cycle on hand. As for the fuzzy EV technique (Moslemi-Naeni and Salehipour 2011; Moslemi-Naeni et al. 2011), it is used in the case where an SOV, based on which the progress estimates should be made, is not specified in the contract. It aims at the prevention of having differing achieved progress assessments, and consequently biased and conflicting work valuations judgements. As such, activity progress is stated using linguistic terms, such as "very low," "high," "more than half," etc., which are transformed into fuzzy numbers by assigning a membership function to each term. Evidently, those linguistic terms cannot be applied while performing EV analyses, unless they are converted to real numbers by using fuzzy-set principles; EV formulae and rules are then adjusted to reflect fuzzy numbers, as shown in Table 31. For instance, the construction of an earth dam requires the excavation of the soil layers, until the hard layer of rock is reached. To this effect, and before reaching this layer, the exact amount of the operations cannot be known, and consequently, the percent complete of the activity cannot be exactly measured. Therefore, it would be better to assess the percent completion of the activity by using linguistic terms, instead of evaluating it exactly and deterministically. In reality, a linguistic term contributes in the estimation of the activity progress simply by answering the question: "What fraction/ percent of the activity is complete?." (Moslemi-Naeni et al. 2011).

A swimming pool example has been developed, consisting of a unique activity (i.e., activity A) in the baseline project schedule, with the purpose of testing the potential applicability of the fuzzy approach in the construction industry. The budget of this activity is $20,000, spread over a duration of 10 weeks. Suppose that the swimming pool work package includes four tasks, spread over a total duration of 10 weeks. The data regarding activity progress and activity budget at completion (BAC) are shown in Table 26. The various linguistic terms describing the progress of tasks are transformed into fuzzy numbers, as shown in Table 25, and the result of the transformation is shown in Table 26. According to the BAC of each task, the fuzzy $\widetilde{EV}$ of each task is calculated, and the total EV of the work package, i.e. the total EV for all of the four tasks, as shown in Table 26. As deduced from Table 26, the total fuzzy $\widetilde{EV}$ for activity A is [$5120, $6320, $6640, $7840].

Table 25. Assigned Fuzzy Numbers to Each Linguistic Term

Linguistic Term	Fuzzy number
Very low	[0,0,0.1,0.2]
Low	[0.1,0.2,0.2,0.3]
Less than half	[0.2,0.3,0.4,0.5]
Half	[0.4,0.5,0.5,0.6]
More than half	[0.5,0.6,0.7,0.8]
High	[0.7,0.8,0.8,0.9]
Very high	[0.8,0.9,1,1]

Table 26. Percent Complete and the EV of Tasks

Task i	BAC ($)	Progress	$\tilde{F}_i$	$\widetilde{EV}_i$
1	4000	High	[0.7,0.8,0.8,0.9]	[2800,3200,3200,3600]
2	3200	Less than half	[0.2,0.3,0.4,0.5]	[640,960,1280,1600]
3	4800	Low	[0.1,0.2,0.2,0.3]	[480,960,960,1440]
4	8000	15%	---	1200

As shown in Figure 35, the EV figure that describes the achieved progress of activity A is $6880, the value corresponding to the right-hand side of α-cut (0.8 in this case) of fuzzy EV. The value of α is preferred to be small in projects with high degree of risk associated. In other words, it might be useful to consider members with small membership degrees (i.e., small possibility of occurrence) in case of risky projects, thus α is chosen to be small (Moslemi-Naeni and Salehipour 2011; Moslemi-Naeni et al. 2011).

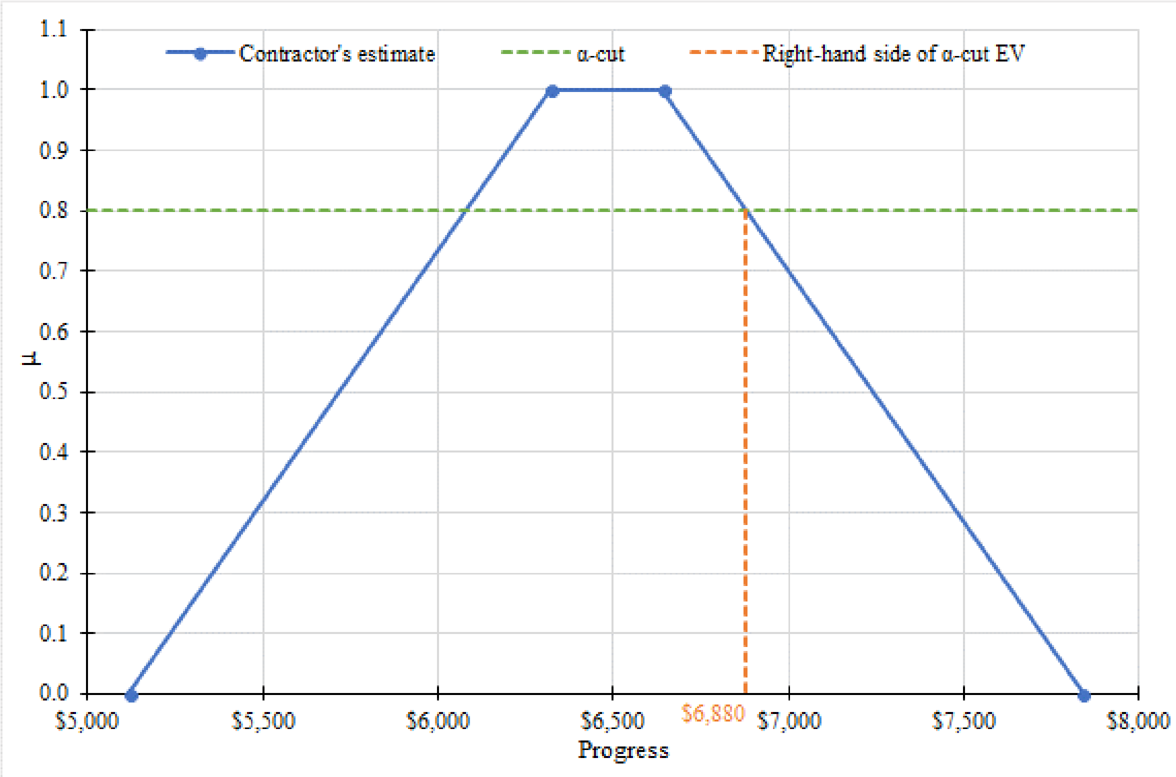

Figure 35. Trapezoidal fuzzy EV and its α-cut value

On the other hand, the IEV technique, proposed by Forouzanpour et al. (2016), adopts the evidential reasoning approach to calculate the EV of those executed works with subjectivities being inherent in the assessments of their progress metrics. This method relies on the concept of belief degrees in estimating the completion percent of each activity, with two or more attributes as decision makers having normalized weights evaluated for them (Forouzanpour et al. 2016). As shown in Table 31, the assigned decision makers are asked in each reporting period to determine the achieved progress stage described in the work item's SOV with a certain probability. Consequently, the basic probability masses assigned to the grade interval are computed, and the percent complete of the activity and – subsequently – the interval EV are calculated based on the interval-valued evidential reasoning algorithm.

To illustrate the applicability of the IEV method, the same example of activity A related to the construction of the swimming pool is used. In each reporting period, two decision makers (i.e., DM1 and DM2) are asked to determine the progress (i.e., percent complete) of the activity, with normalized weights for DM1 (w1) of and for DM2 (w2). Accordingly, the decision makers are asked to determine the achieved progress stage described in the work item's SOV with a certain probability. Consequently, the basic probability masses assigned to the grade interval are computed, and the percent complete of the activity and – subsequently –the interval EV are calculated based on the interval-valued evidential reasoning algorithm. The results of the IEV calculations are shown in Table 27.

Table 27. Calculation of the EV for activity A

Status/Reporting Date (months)	Weight	Decision makers	Belief degrees				Basic probability masses		Percent complete	Earned value
			H_{ij}	β_{ij}	H_{ij}	β_{ij}	DM_{ij}	DM_{ij}		
0.5	0.6	Senior Civil Engineer	3	0.75	4	0.25	0.45	0.15	0.16	3140
	0.4	Construction Manager	2	0.2	3	0.8	0.08	0.32		
1	0.6	Senior Civil Engineer	5	0.6	6	0.4	0.36	0.24	0.34	6880
	0.4	Construction Manager	4	0.75	5	0.25	0.3	0.1		
1.5	0.6	Senior Mechanical Engineer	9	0.4	10	0.6	0.24	0.36	0.77	15480
	0.4	Construction Manager	8	0.3	9	0.7	0.12	0.28		
2	0.6	Senior Electrical Engineer	9	0.7	10	0.3	0.42	0.18	0.81	16160
	0.4	Construction Manager	10	1	---	---	0.4	---		
2.5	0.6	Senior Architectural Engineer	12	1	---	---	0.6	---	0.98	19640
	0.4	Construction Manager	11	0.9	12	0.1	0.36	0.04		

The client's representative, engaged as an adjudicator to solve any disagreement between the contractor and engineer as to the value used to describe the achieved progress, may refer to the IEV method with the purpose of agreeing as to the reduction to be effected. Taking the example of the swimming pool, in case the engineer disagrees with the contractor's measured progress after one month (i.e., second measurement point) has elapsed since the execution of the activity A, the client's representative is given the discretion to interfere in order to decide on the amount due to the contractor. The two decision makers, namely the contractor (DM1) and the engineer (DM2), with 0.3 and 0.7 as normalized weights, respectively, are asked to assess the progress at a certain probability, as shown in Table 28.

Table 28. Progress Assessment Performed by the Client's Representative

Status/Reporting Date (months)	Weight	Decision makers	Belief degrees				Basic probability		Percent complete	Earned value
			H_{ij}	β_{ij}	H_{ij}	β_{ij}	DM_{ij}	DM_{ij}		
1	0.3	Contractor	5	0.6	6	0.4	0.18	0.12	0.31	6190
	0.7	Engineer	4	0.75	5	0.25	0.525	0.175		

Additionally, referring back to the example of activity A, whose achieved progress is assessed using the fuzzy approach by the contractor, the engineer may determine the activity progress based on the same method (i.e., fuzzy method), as shown in Table 29. To this effect, Figure 36 shows the α-cut fuzzy numbers for the engineer's and contractor's estimate for activity A. As deduced, the certified amount by the engineer is $4,400, compared to the assessed amount that the contractor included in the IPCA ($6,880).

Table 29. Engineer's Estimate for Activity A

Engineer's Estimtate				
Activity i	BAC ($)	Progress	$\tilde{F}_i$	$\widetilde{EV}_i$
A	$20,000	Low	[0.1,0.2,0.2,0.3]	[2000,4000,4000,6000]

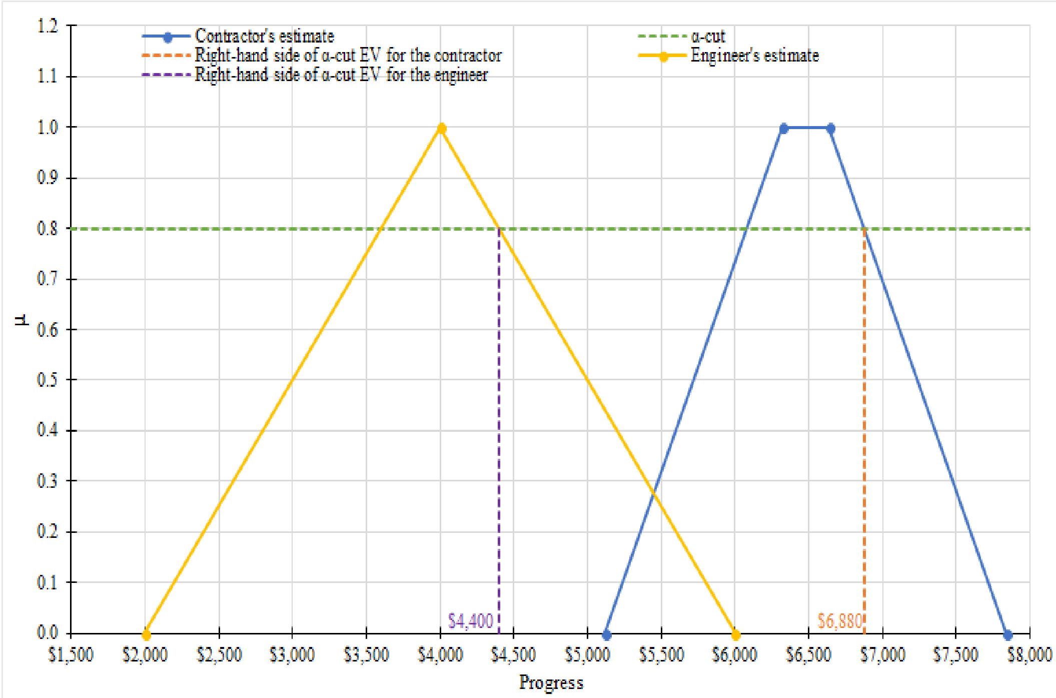

Figure 36. Contractor's vs. engineer's EV estimates

In order to elaborate on the practical implications of the use of the modern information management technologies reported in the existing literature as contributing to the automated collection, retrieval, and transfer of onsite data for accurate computation of the earned value of executed works, a framework was developed, as shown in Figure 37. Ultimately such information can be used for faster release of interim payments on the basis of completed work-packages, contributing to integrated cost and schedule control. As such, the framework shown in Figure 37 shows the process steps for EV quantification to be followed by the contractor in order to prepare the IPCA. By way of closing, a framework has been developed, summarizing the main steps that shall be followed by the contractor in order to prepare the IPCA. The literature encountered techniques, for instance, the fuzzy and interval EV, are found to be instrumental in preventing the discrepancy between the contractor’s assessed amounts and the engineer’s certified ones.

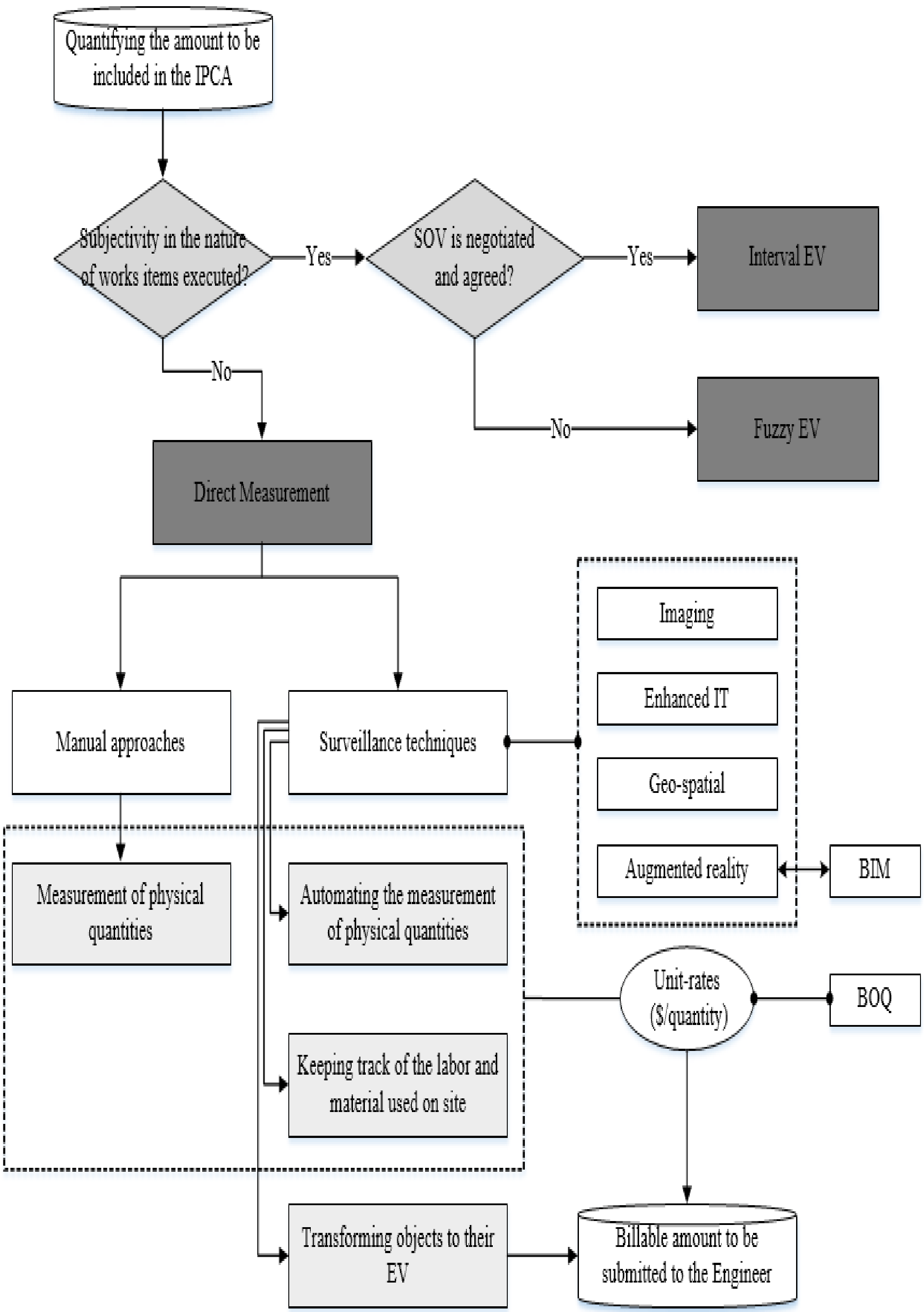

Figure 37. Process steps for EV quantification

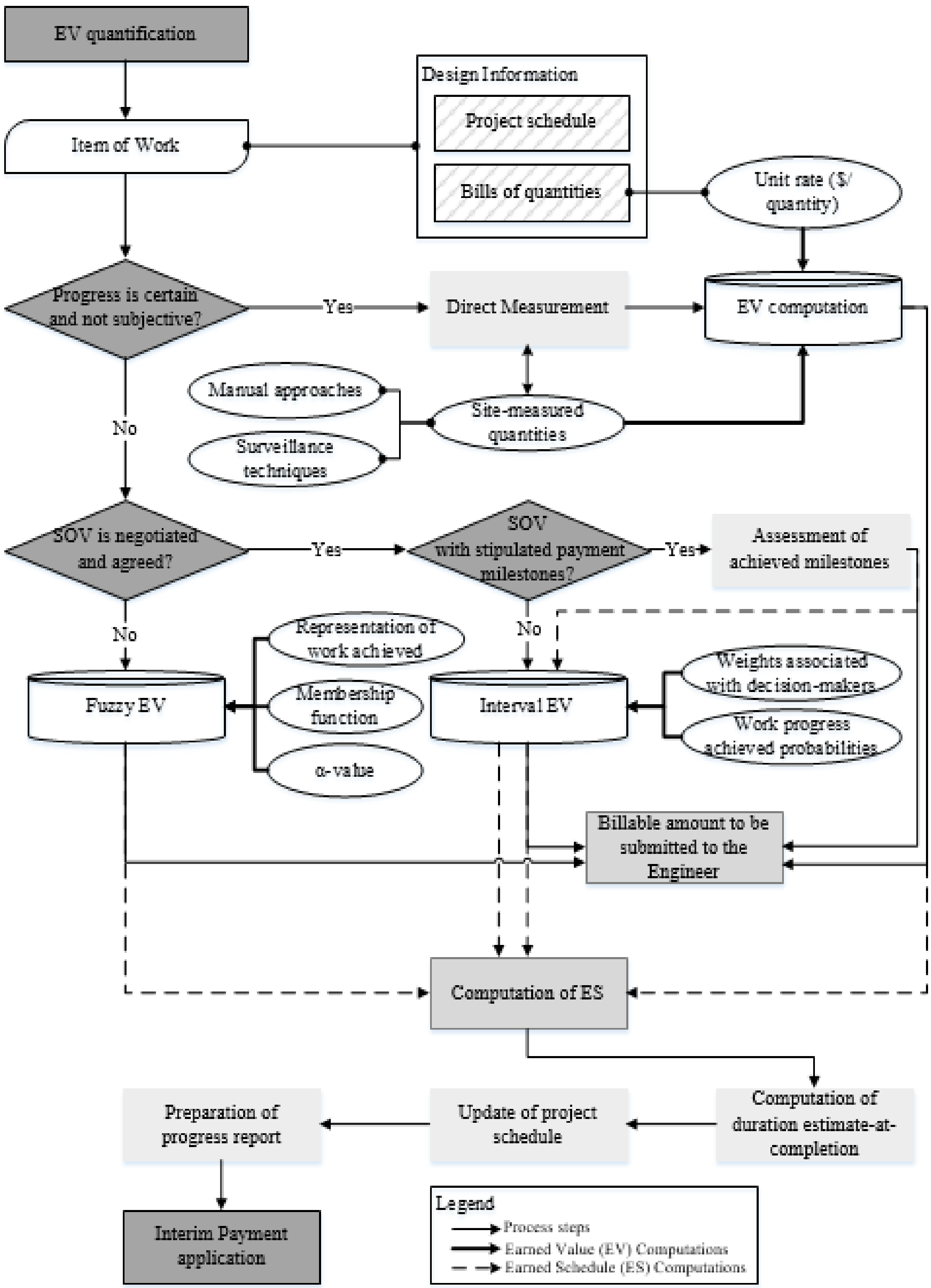

Figure 38. Framework for EV measurement by the contractor

8.6.2 *Quality-Related Reductions*

It has been established earlier through this work that, in reaction to the contractor's failure to implement a remedy, suitable contractual mechanisms are in place, allowing the owner to effectuate a setting-off and pay others to make good the executed work. It has also been found that work executed to a quality (or performance) level deemed inferior to the minimum prescribed by the specification requirements may still be taken over (i.e., accepted) by the owner, for the owner's defensible reasons. Payment-reduction formulae may be incorporated in the contract in order to facilitate agreeing as to the reduction to be effected. Alternatively, such deductions may be implemented at the discretion, and based on the judgement, of the engineer, which may in this case lead to the matter being disputed by the contractor. When addressed properly in the conditions of the construction contract, in terms of the authority entrusted in the engineer and the basis or technique to be used for quantifying such deductions, the engineer would then be acting within such prescribed authority, albeit the possibility that this eventually may lead to a dispute based on the disagreement of the contractor with the engineer's judgement.

As stated above, the inability to meet the specified technical performance for the executed work can be regarded as one of the main reasons justifying the exercising by the engineer of his authority to effectuate reductions to the sums proposed by the contractor in an IPCA. To this end, the literature revealed a number of methods that can be used to measure the achieved quality of performed work, including: (1) performance-based EV, (2) quality EV, and (3) earned quality. Hernández et al. (2013) proposed an extension to the EV method, termed "performance-based earned value" (PBEV), where a decrease of the EV amount is applied in case the technical objectives are not satisfied, as shown in

Figure 39. This application of this technique is well supported by the excessive reduction applied in relation to the multi-million dollar woodwork package, as in the third project case discussed above.

As such, the pay-adjustment factors are widely adopted in asphalt pavement construction to evaluate the effects of variations in quality of the executed works from the specification limits (i.e. noncompliance with compaction requirements), determined by comparing the in-situ quality criterion (i.e., density) to the specified target criterion (i.e., lab density), and reducing the corresponding unit rate (UR) by the engineer accordingly in case of inferior or lesser quality, by way of a setting-off. The percent of the target density achieved at the end of the construction is then associated with the percent pay to the contractor, displayed as a reduction from the unit rate of the work item, as shown in Table 30. To this effect, the achievement of at least 95% of target density qualifies the contractor for full payment for the executed pavement. However, if the target density is in the range of [92.8% – 94.8%], the pavement lot will be accepted at a reduced pay and hence, the pay factor will be adjusted accordingly, corresponding to [0.5,0.9] of the UR respectively. However, if the target density is below 92.8 percent, the contractor will receive total rejection of the executed works, thus the contractor is required to remove and replace the pavement at his own expenses to achieve the desired density, in compliance with preset specifications.

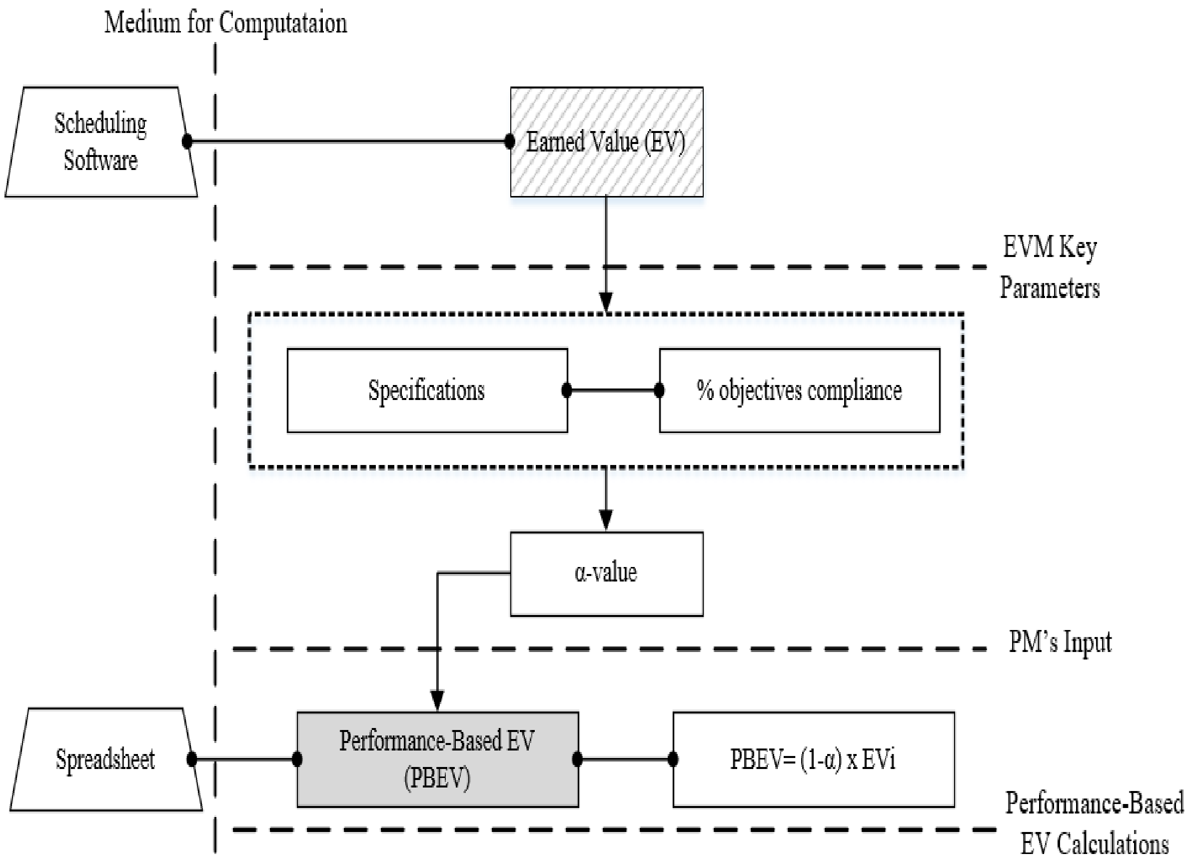

Figure 39. Performance-based EV technique (based on Hernández et al. 2013)

Table 30. Compaction Pay Factors for Percent of Target Density (Moore et al. 1981)

Percent of Target	Percent Pay (Pay Factor)
94.9 – 100	100
94.2 – 94.8	90
93.5 – 94.1	70
92.8 – 93.4	50
< 92.8	0

Table 31. Techniques for EV Measurement Disagreement Avoidance and Preventive Reductions

Track	Proposed method	Applicability	Underlying inputs	Formulation	Limitations
EV Measurement	Fuzzy earned value (Moslemi-Naeni and Salehipour 2011; Moslemi-Naeni et al. 2011)	No schedule of value, with differing subjective progress assessments	Membership function with its corresponding fuzzy numbers ($\tilde{F}_i$)	Fuzzy EV for activity i ($\widetilde{EV}_i$) $\widetilde{EV}_i = \tilde{F}_i \times BAC_i$	Subjectivity in choosing α-cut value and membership function
			Budget at completion of activity i (BAC_i)	Total fuzzy EV ($\widetilde{EV}$) $\widetilde{EV} = \sum_{i=1}^{n} \widetilde{EV}_i$	
			α-cut value: $0 \leq \alpha \leq 1$	Right-hand side of α-cut value of $\widetilde{EV}$ (${}^{\alpha}_{R}\widetilde{EV}$)	
	Interval earned value (Forouzanpour et al. 2016)	Schedule of value, with stipulated payment milestones	Belief degrees (β_{ij})	Upper limit of activity progress ($u_{max}(A)$) $u_{max}(A) = \sum_{i=1}^{N} \sum_{j=i}^{N} \beta_{ij}\mu(H_{jj})$	Subjectivity in assessing the EV between upper and lower limits
			Utility values $\mu(H_{ii})$	Lower limit of activity progress ($u_{min}(A)$) $u_{min}(A) = \sum_{i=1}^{N} \sum_{j=i}^{N} \beta_{ij}\mu(H_{ii})$	
EV reduction (Quality-related issues)	Quality earned value (Dodson et al. 2015)	Multiple quality criteria	Quality Requirements (QR) and limits of specifications	Quality Index Number (QIN) $QIN = \sum QPI / \sum NQR$	Criteria having equal weights
		Criteria with specifications limits	Number of QRs (NQR)		QPI values either 1 or 0
			Quality performance index (QPI)		
	Earned quality of work performed (Paquin et al. 2000)	Multiple quality criteria with different weights	Planned contribution to the expected result x_j^* as measured by criterion c_j attributable to the work scheduled for activity a_i at time t ($r_{ij}{}^*(t)$)	Planned Quality of Work Scheduled (PQWS) $PQWS = \sum_{i=1}^{I} \sum_{j=1}^{J} w_j \emptyset_j (x_j^*) r_{ij}^*(t)$	Subjectivity in assigning weights and value functions for quality criteria
		Connection between project schedule and quality criteria	Estimated relative contribution of activity a_i to criterion c_j (r_{ij})	Planned Quality of Work Performed (PQWP) $PQWP = \sum_{i=1}^{I} \sum_{j=1}^{J} w_j \emptyset_j (x_j^*) r_{ij}(t)$	
			Estimated contribution to the actual result $\hat{x}_j$ as measured by criterion c_j attributable to the work performed on activity a_i at time t ($\hat{r}_{ij}(t)$)	Earned Quality of Work Performed (EQWP) $EQWP = \sum_{i=1}^{I} \sum_{j=1}^{J} w_j \emptyset_j (\hat{x}_j) \hat{r}_{ij}(t)$	
			Relative contribution of criterion c_j to the overall quality objective (w_j)	Quality Variance (QV) $QV = EQWP - PQWP$	
			Result expected by the client with regard to criterion c_j (x_j^*) Actual result achieved with regard to criterion c_j of the work performed at time t ($\hat{x}_j$) Value function ($\emptyset_j$)	Quality Performance Index (QPI) $QPI = \frac{EQWP}{PQWP} \times 100$	
EV reduction (Schedule-related issues)	Rework-adjusted earned value (Lipke 2004; Lipke 2011)	Violation of planned work execution sequence	Planned value for tasks associated with ES (PV_j)	p − factor (p) $P = \frac{\sum EV_j}{\sum PV_j}$	Subjectivity in assigning the percent rework
			Earned value at actual time AT corresponding to and limited by the planned tasks (EV_j) Percentage of rework (R%)	Effective earned value (EV(e)) $EV(e) = \left[\frac{1 + p \times R\%}{1 + R\%}\right] \times EV$	
	Customer earned value (Kim et al. 2015)	Inability to transfer the executed work to internal schedule's customer	Percent reduction (α)	Customer EV (CEV) $CEV = (1 - \alpha) \times EV$	Linear relationships between activities

The subjectivity inherent in the quantification by the engineer of the ceiling for such a reduction, applied by way of a setting-off, presents a serious limitation, potentially leading to payment-related disputes between the contractor and owner. To mitigate this limitation, the engineer may refer to the method proposed by Dodson et al. (2015), shown in Figure 40, which calls for the assessment of the operating performance of construction activities in order to ultimately satisfy the project quality requirements during construction.

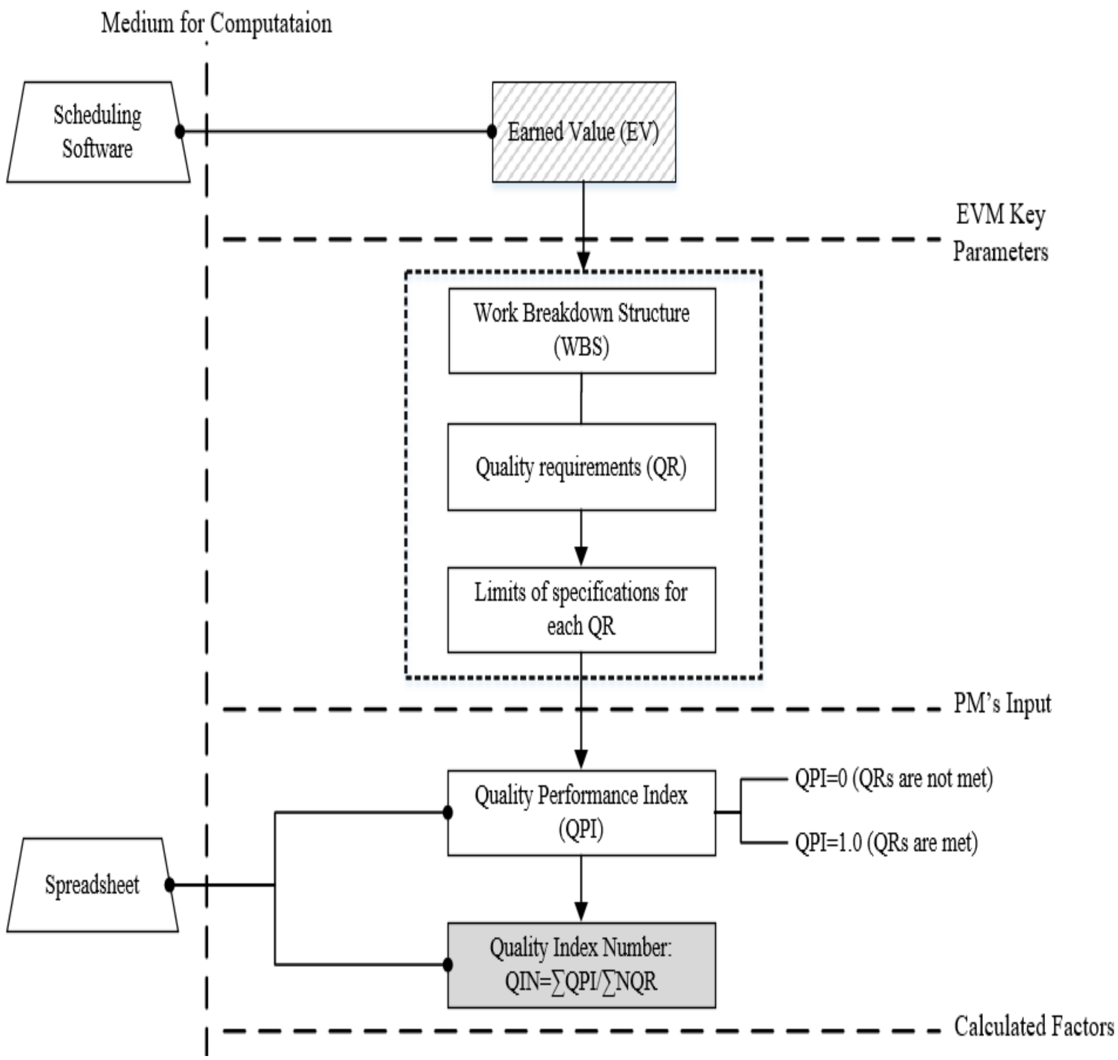

Figure 40. Quality EV based on Dodson et al. (2015)

To illustrate the applicability of this proposed method, a performance-based concrete specification example has been developed, which involves the execution of a work package (e.g., concrete columns) having three quality criteria: compressive strength, density, and air voids. The acceptance tests for hardened concrete along with the related procedural and statistical requirements are usually spelled out in the specifications. Table 32 summarizes the quality criteria considered applicable to concrete performance specifications and lists the set limits to be satisfied. For instance, the strength level of each batch of concrete shall be considered acceptable if the average of all sets of tests performed on in-situ concrete samples for the batch in question at 28 days equals or exceeds the specified strength (e.g., 35 MPa) up to a maximum strength of 45 MPa, with no individual strength test result being more than 3.0 MPa below the specified strength. In addition, testing for air voids shall be in accordance with ASTM C642-13, with satisfactory air void falling between six and eight percent, but not below five percent. Similarly, the acceptable in-place density values for structural lightweight concrete are in the range of 1440 to 1840 kg/m3. As shown in Table 33, the lack of quality pertaining to the air void criterion results in a quality index number (QIN) of 0.67 for the first batch. This indicates that, for each $1.0 submitted by the contractor for this part of the work package, only $0.67 met the limits set by the specifications (i.e., converted into “right” deliverables). As a result, a setting-off can be exercised by the engineer, thereby reducing the work item’s unit rate by 33 percent. This is of course assuming that (1) ordering rework is not practicable to entertain and (2) accepting the executed work in question at less than the desired performance levels remains within the range of reasonable decisions or actions that may be taken by the engineer, on behalf of the owner. In other words, if it were for the compressive strength test results criterion, more analysis would be warranted, possibly leading to instructing partial or full rework of the work's affected parts.

Table 32. Quality Requirements and Limits of Specifications: Hardened Concrete Example

Description	Compressive Strength (Mpa)	Density (kg/m³)	Air voids (%)	Quality Performance Index (QPI)
Lower Specification Limit	32	1440	5	1
Target	35	1650	6	1
Upper Specification Limit	45	1840	8	1
Out of Specification	>45 and <32	>1840 and <1440	>8 and <5	0

Table 33. Quality Index Number Calculations

Executed works	Compressive Strength			Density			Air voids			QIN
	Measured	QR	QPI	Measured	QR	QPI	Measured	QR	QPI	
Batch 1	40		1	1585		1	6		0	0.67
Batch 2	32	35	1	1630	1650	1	7	6	1	1.00
Batch 3	38		1	1910		0	8		0	0.33

QR: Quality requirements; QIN: Quality Index Number; QPI: Quality Performance Index

On the other hand, Paquin et al. (2000) proposed an earned-quality method, shown in Figure 41, that links the construction schedule activities to the project quality attributes. This method evaluates and controls the quality of performed work throughout the execution stage, by detecting quality deviations and tracing them to their associated activities.

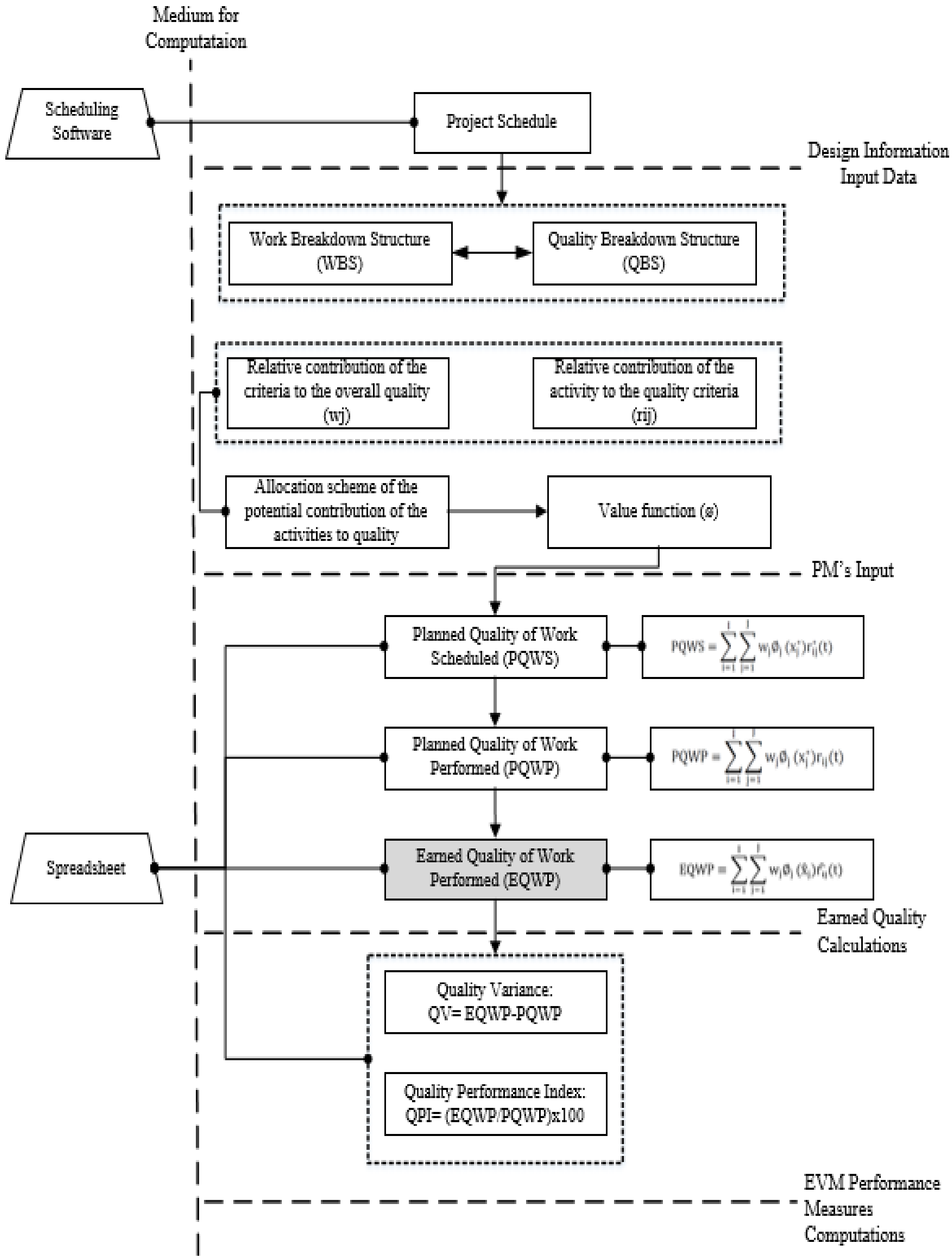

Figure 41. Earned Quality of Work Performed (EQWP) method (Based on Paquin et al. (2000))

A simplified example of a project's curtain wall work package is presented, illustrating the calculations required for the effective implementation of the method. The package is assumed to be constituted of three activities, namely (1) installing vertical and horizontal mullions (a1), (2) sealing the corners (a2), and (3) glazing the walls (a3). As for the quality requirements, it is assumed that three such criteria of concern exist: (1) structural integrity (c1), (2) air tightness (c2), and (3) water tightness (c3). That is, although curtain wall systems are considered as secondary structures in the building-type projects, they have to be evaluated and tested in order to safely withstand wind, seismic, and thermal loads, in addition to meeting performance requirements related to air and water tightness. As such, the structural performance of a curtain-wall system is a function of the frame design, arrangement of mullions and studs, transoms, anchoring details, and glass panels' fixation. On the other hand, although air leaks may not be fairly as noticeable as water penetration, they can show up as current of air or hot and cold spots at panel corners, leading to high heating and cooling cost. Accordingly, performance criteria pertaining to air and water leakage are critical to specify for curtain walls system due to the fact that such leakages lead to unhealthy indoor air quality during building operation, by providing an environment conducive for mold growth. Factors affecting such performances are primarily related to glazing details, frame structure and connection, drainage details, frame gaskets, and perimeter seals. On the air-tightness performance end, for example, ASHRAE (2009) provides three levels of air leakage for typical buildings, namely: (i) 0.5 L/s·m2 (liters per second air leakage per square meter of exterior envelope area) at 75 Pa interior/exterior pressure differential for "tight" buildings, (ii) 1.5 L/s·m2 at 75 Pa for "average" buildings, and (iii) 3.0 L/s·m2 at 75 Pa for "leaky" buildings. As for the test methods that may be employed, the air leakage resistance, water penetration resistance, and structural performance of an installed curtain wall system can be evaluated in accordance with ASTM E 283-04, ASTM E 331-00, and ASTM E 330-02, respectively.

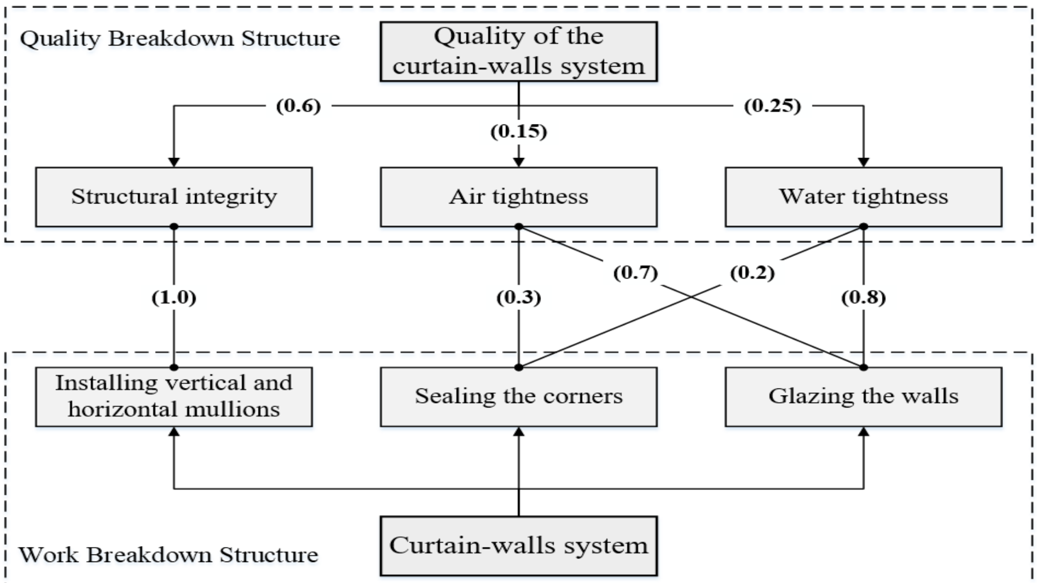

Figure 42. The WBS-QBS integration for the curtain wall work package

The integration of the work breakdown structure (WBS) and the quality breakdown structure (QBS) can be as proposed in Figure 42. The allocation scheme for the assumed potential contribution of the activities to quality, relative contribution of the criteria to the overall quality objective, and relative contribution of the activities to the quality criteria are also shown in Figure 42. In addition, the value functions for all three quality criteria, which – ideally – are to be determined jointly by the engineer and contractor, can be as shown in Figure 43. Furthermore, Figure 44 shows the Gantt chart for the work package with the planned start and finish times of the three activities, along with the timings of control milestones, marked with asterisks. To be noted is that these control points are decided upon based on the number of major elements in each activity.

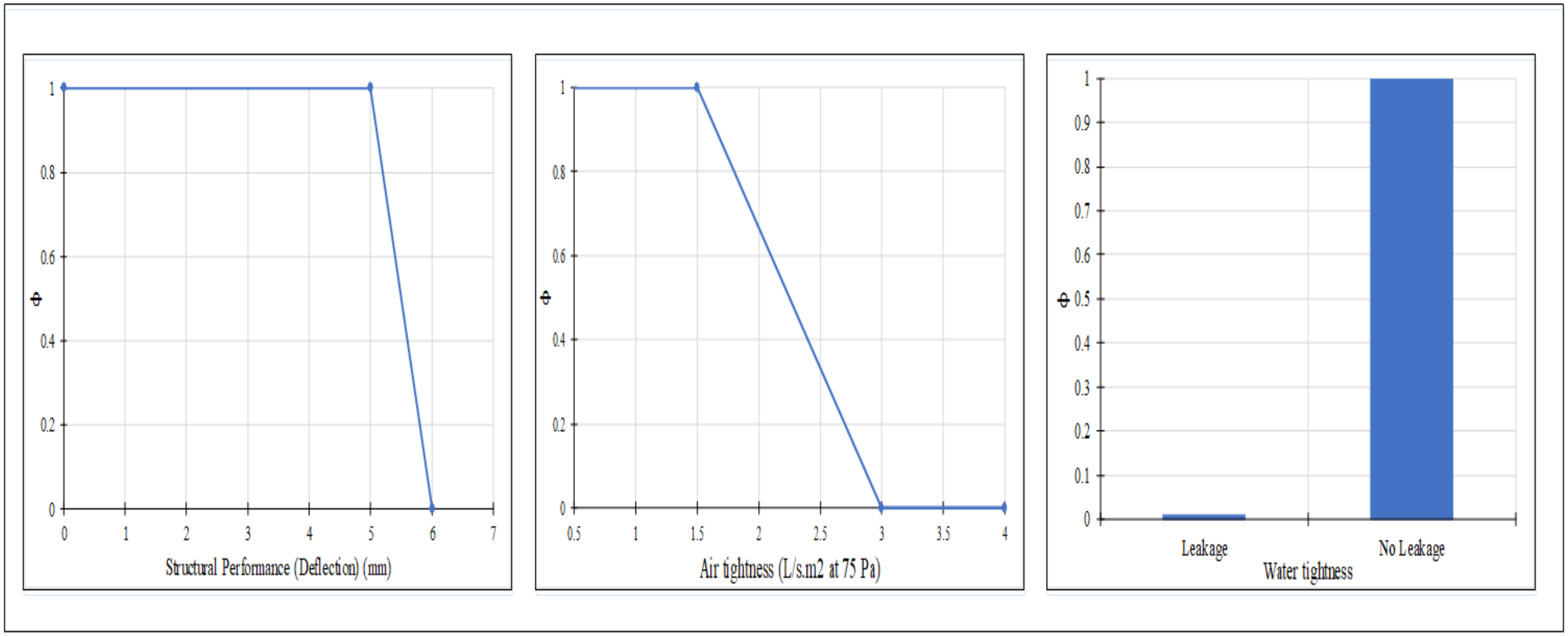

Figure 43. Value functions for the quality criteria

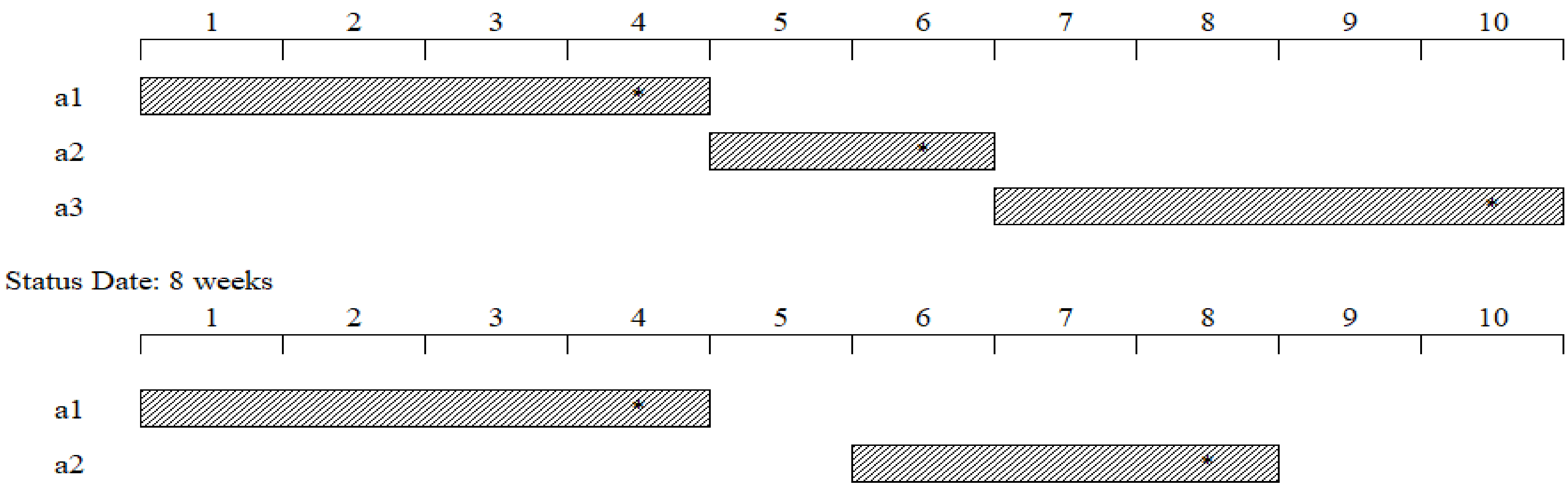

Figure 44. Gantt chart for the work package

Now, assuming that eight weeks have elapsed since the start of execution, activity a2 is shown to have started at period 6 instead of period 5 and requires one more week to be completed; however, activity a3 has not started yet due to unexpected conditions. Consequently, the planned quality of the work scheduled (PQWS), the planned quality of work performed (PQWP), and the earned quality of work performed (EQWP), along with the quality variance (QV) and the quality performance index (QPI) are computed as shown in Table 33, using the formulae summarized in Table 31. The grey-shaded columns in Table 33 represent the planned contribution of work scheduled to the quality criteria. At time period 8, the earned quality is 2.3 percentage points below the client's expectation, and the QPI is equal to 97 percent, below the acceptable threshold. Thus, in case the engineer ends up accepting the curtain wall system while not being in full conformity with the contract quality requirements, a setting-off in the order of three percent of the work item’s unit rate or price subtotal can be exercised.

By way of summarizing, the reduction applied by the engineer to the sums proposed by the contractor due to his inability to meet the specified technical performance for the executed work is often viewed by the contractor to have been enormously excessive, in the absence of an explicit basis for effectuating such reductions. Thus, in deciding on the amount to be permanently deducted, techniques such as the above-discussed “quality EV” and/or “earned quality of work performed” methods can be found instrumental in reducing the subjectivity with which such reduction may otherwise be effected. This can potentially be expected to diminish the likelihood of disagreement between the contractor and engineer as to the assessment of the amount to be reduced, thereby leading to mitigating payment-related disputes.

Table 34. Earned Quality Calculations

t	a1 (0.6)			a2 (0.15)						a3 (0.25)		PQWS (t)	PQWP (t)	EQWP (t)	QV	QPI
	c1 1.0	c1 1.0	φ	c2 0.3	c2 0.3	φ	c3 0.2	c3 0.2	φ	c2 0.7	c3 0.8					
1	0.0	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000	0.000	0.000	0.000	0%
2	0.0	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000	0.000	0.000	0.000	0%
3	0.0	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.000	0.000	0.000	0.000	0%
4	1.0	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.600	0.000	0.000	0.000	0%
5	1.0	1.000	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.600	0.600	0.600	0.000	100%
6	1.0	1.000	1.0	0.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.675	0.600	0.600	0.000	100%
7	1.0	1.000	1.0	0.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.675	0.600	0.600	0.000	100%
8	1.0	1.000	1.0	0.3	0.3	0.5	0.2	0.2	1.0	0.0	0.0	0.675	0.675	0.653	0.023	97%
9	1.0	1.000	1.0	0.3	---	---	0.2	---	---	0.0	0.0	0.675	---	---	---	---
10	1.0	1.000	1.0	0.3	---	---	0.2	---	---	0.7	0.8	1.050	---	---	---	---

1.1.1 Work Dependencies and Actual Execution Sequence

Two schedule-related methods, proposed in the current literature, were identified as justifying the effectuation of reductions by the engineer to the sums proposed by the contractor in a submitted IPCA. The first is based on the inability to transfer the executed work to an internal schedule's customer, whereas the second is founded on the rework possibly caused by the violation of the work's planned execution sequence.

To this effect, the new metric of customer earned value (CEV), shown in Figure 45, has been proposed by Kim et al. (2015). It is defined as the budgeted amount of work completed that is needed by the successors on a network. For instance, taking the case of two trades, such as an earthwork contractor and a structures contractor, the structure trade can initiate its work in the assigned area after the earthwork contractor releases the area. Nevertheless, if the last part of activity A, such as slope trimming and leveling, is slow in progress, this will be unsuccessful in EV terms. Then, activity B, which represents an internal customer of activity A, cannot start its job as a result of the area still being unreleased. The traditional EV method gives complete credits for all the executed works of activity A, yet none of them are transferable to its internal customer (Kim et al. 2015). However, the CEV of activity A is not credited until activity B starts its work in the released area. The contractor, when assessing the amount to be included in an IPCA, does not differentiate between the value-generating activities (i.e., work that generates value for the internal customer) and nonvalue-generating activities. The amount included in an IPCA may thus be questioned by the engineer, who might apply suitable reductions to the contractor's assessed amounts.

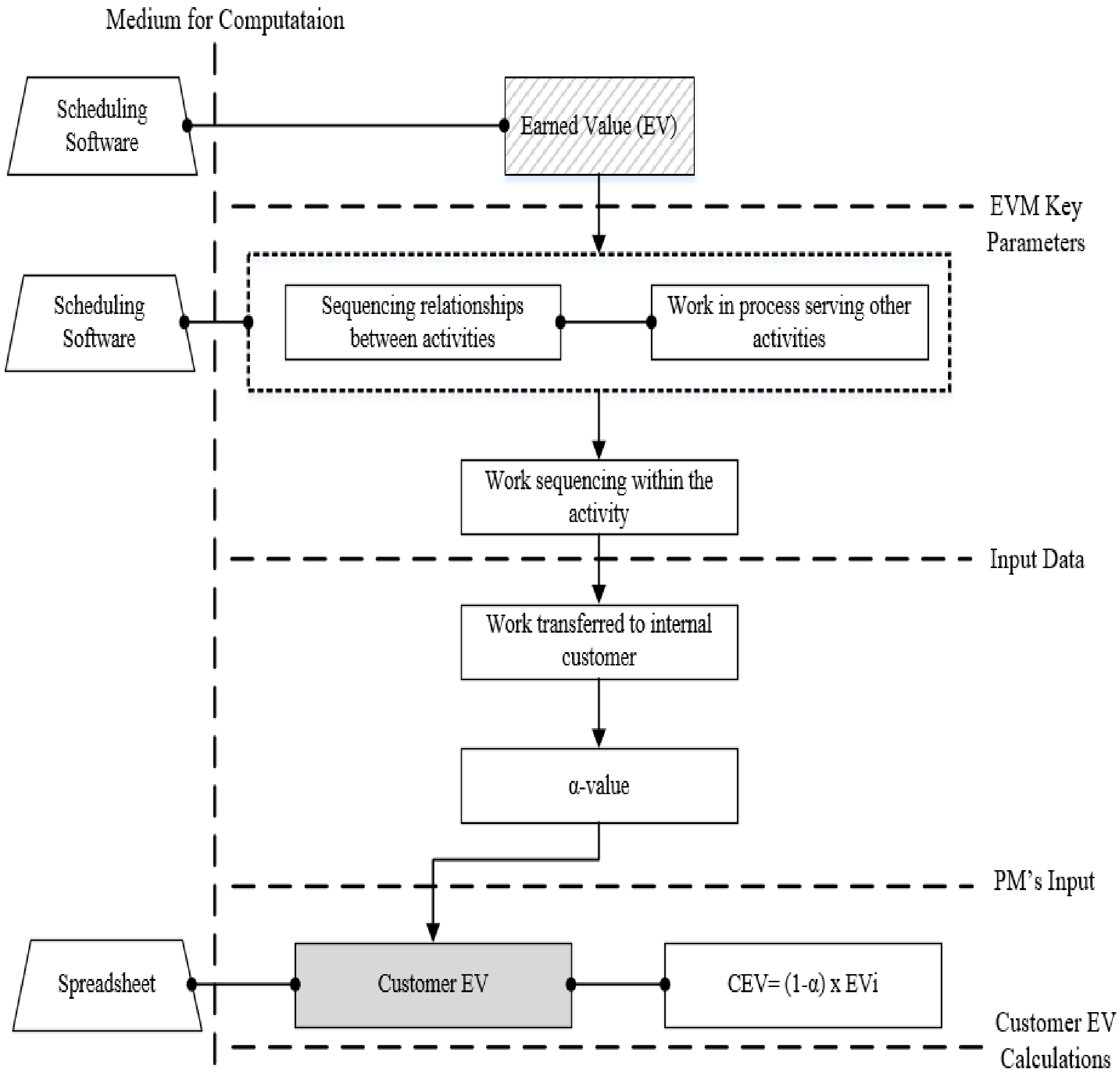

Figure 45. Customer EV (based on Kim et al. 2015)

The application of the CEV method requires the investigation of the relationships between schedule activities. To this effect, the project schedule includes four types of logical relationships between two dependent activities or milestones, namely: (1) finish-to-start, (2) start-to-start, (3) finish-to-finish, and (4) start-to-finish, as shown in Figure 46. The first type of relationship is manifested by the case of two trades, such as an earthwork contractor and a structures contractor, the structure trade can initiate its work in the assigned area after the earthwork contractor releases the area. Nevertheless, if the last part of activity A, such as slope trimming and leveling, is slow in progress, this will be unsuccessful in EV terms. Then, activity B, which represents an internal customer of activity A, cannot start its job as a result of the area still being unreleased. The traditional EV method gives complete credits for all the executed works of activity A, yet none of them are transferable to its internal customer (Kim et al. 2015). However, the CEV of activity A is not credited until activity B starts its work in the released area. The contractor, when assessing the amount to be included in an IPCA, does not differentiate between the value-generating activities (i.e., work that generates value for the internal customer) and nonvalue-generating activities. The amount included in an IPCA may thus be questioned by the engineer, who might apply suitable reductions to the contractor's assessed amounts.

The second type of relationship (i.e. start-to-start with or without lag), in which a successor activity B cannot start until a predecessor activity A has started, can be illustrated by the following example. Once the installation and connection of electrical cables (i.e. activity A) in the facility under construction started, electrical labors do not have to wait till all the cables are installed to initiate the subsequent activity, namely the connection of the cables to the panel (i.e. activity B). However, if the work executed in activity A was not transferred to its internal customer due to out-of-sequence performance the work within activity B, the CEV in this case is zero for activity A. The third type of logical relationship (i.e. finish-to-finish), in which a successor activity B cannot finish until a predecessor activity A has finished, is very common in construction projects. This dependency type is often used when one of the activities is a final inspection by the engineer and no activity can be considered 100% complete until the inspection is performed. Moreover, if a series of electrical wiring is being installed as one activity (activity A), another activity consisting of installing air conditioners (activity B) is being performed at the same time, then, functional air conditioners cannot be obtained until the electrical work is finished. To this effect, if some tasks within activity A are rejected by the engineer due to non-conformance with the set of quality standards for example, activity B is then cannot be finished on the allocated date, thus CEV of activity A shall be computed accordingly. Last but not least, the fourth type of logical relationship (i.e. start-to-finish), represents a sequencing relationship in which a successor activity B cannot finish until a predecessor activity A has started. To this effect, the dewatering activity (activity B) cannot be finished until the construction of the third floor (activity A) starts.

On the other hand, when constraints and impediments are faced during work execution, the contractor is most likely to direct labor to perform activities out of the originally planned sequence. This is done at the risk of these activities not having all the required inputs, consequently making them susceptible to rework that is likely to ripple into succeeding activities. As such, the method calls for adherence to the planned execution sequence to ideally be heeded for the engineer to certify the whole sums assessed by the contractor. The p-factor measure has been proposed by (Lipke 2004; Lipke 2011) to designate adherence to the project plan, calculated as the ratio of the EV corresponding to the plan to the total EV. This factor, in combination with an assessed percentage of rework, is then used to adjust the EV amount to a lesser amount, named "effective EV," as shown in Figure 47. When the value for the p-factor is far less than

1.0, the engineer is then presented with a strong indication that the project is experiencing the burden of an impediment and, consequently, likely to suffer a delay in completion. The main formulae needed to calculate the effective or rework-adjusted EV are shown in Table 31.

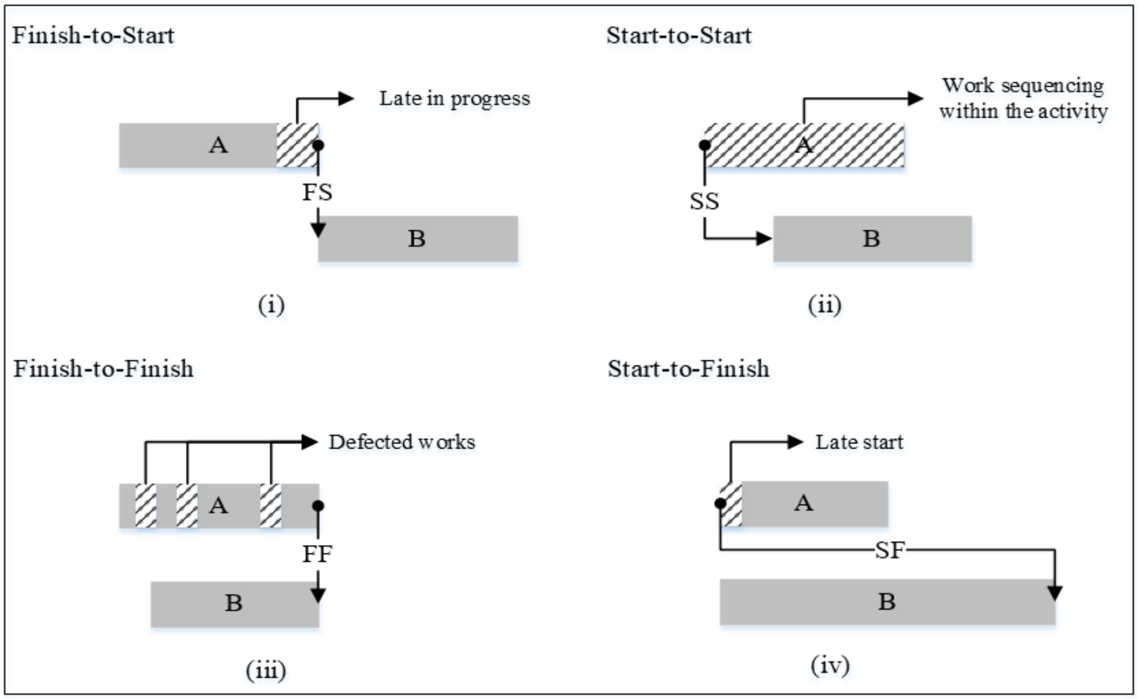

Figure 46. Logical sequencing variations for CEV application

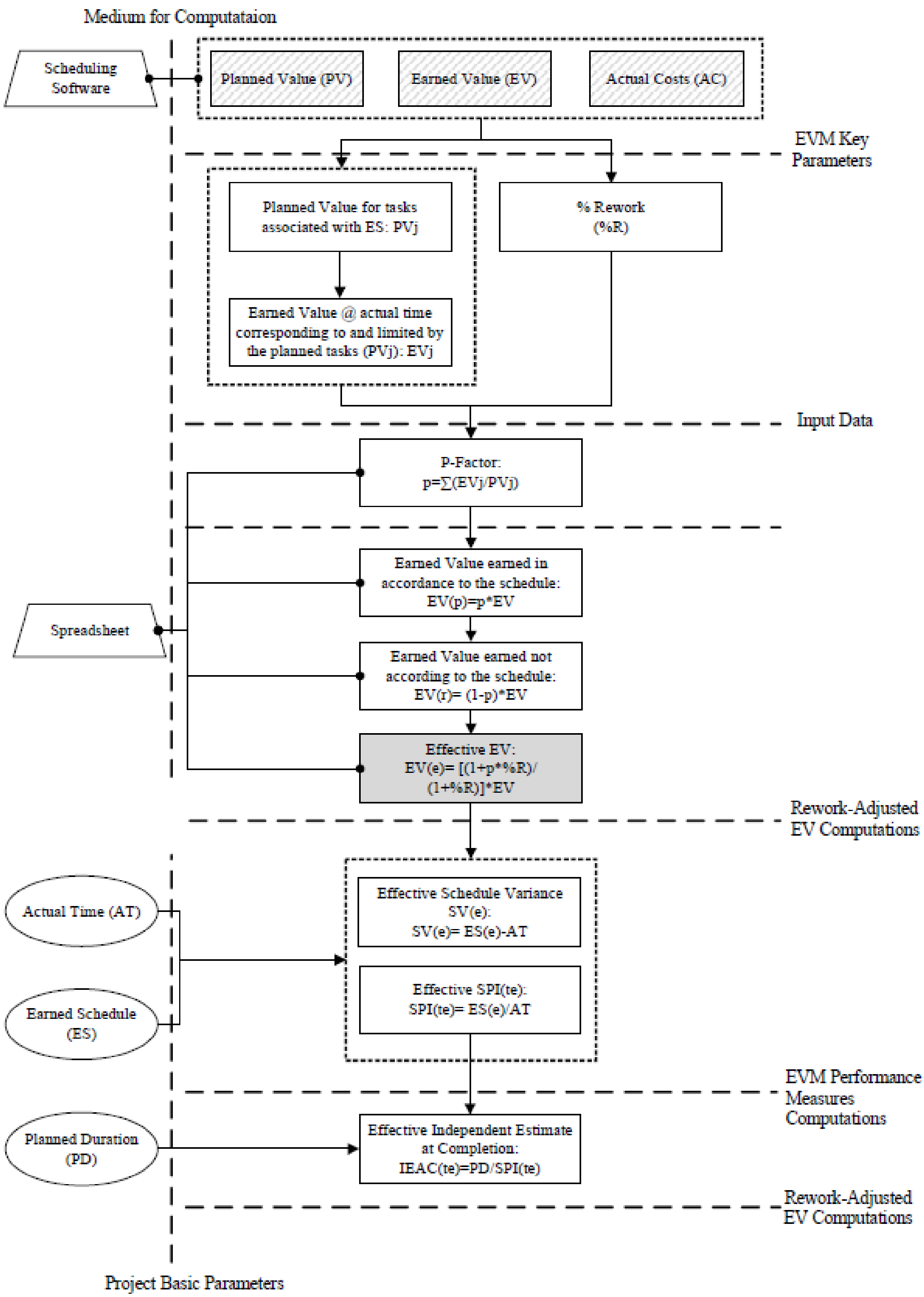

Figure 47. Rework-adjusted EV (Based on Lipke 2004)

1.2 Discussions and Practical Implications

A number of observations can be withdrawn from the work previously presented. They are believed to help better inform contract administrators, working for either party to the construction contract, as to: (1) the approaches that need be observed for mitigating EV disagreements and (2) the techniques that may be adopted for justifying the effectuation of preventive EV reductions. Although data concerned with the extent of practical reliance on and the effectiveness of these identified methods seem to be lacking, a brief discussion reflecting the authors' perspectives as to the relative suitability of the various encountered EV-adjustment methods is nevertheless offered. To this effect, it can be argued that the two proposed methods related to EV assessment (fuzzy and interval EV) shall be taken as mutually exclusive. Yet, regarding the fuzzy EV technique, its use suits the case where an SOV, based on which the progress estimates should be made, is not specified in the contract. As for the IEV technique, it can be a better choice for the situation where multiple decision makers (whether belonging to the same team or to different teams) are expected to collectively contribute in yielding an assessment of the achieved progress in relation to the stages expressed in the work item's SOV. Similarly, the two schedule-related methods (namely, the customer EV and effective EV ones) are to be applied also in different circumstances. The application of the first method, which is based on the inability to transfer the executed work to the internal schedule's customer(s), can be considered in respect of those schedule activities whose sequencing relationships are agreed to be critical to the effective progress of their respective successors. On the other hand, the second method, being founded on the rework that may possibly be caused as a result of violating the planned work execution sequence, can have the effect of promoting a more thoughtful approach on the part of contractors in conceiving the work's method statement and deciding the sequencing of work program activities. Lastly, the three methods related to the measurement of the achieved quality of performed work can be applied for different situations. The application of performance-based EV is mainly represented through the use of pay-adjustment factors, which are usually incorporated as an integral part of the construction contract. However, if the executed work item incorporates several quality requirements (i.e., criteria) that can be regarded to be of equal weights, the engineer can then be given (through the contract) the discretion to refer to the quality earned value method, proposed by Dodson et al. (2015). On the other hand, the method particularly proposed by Paquin et al. (2000) shall be capable of evaluating and aggregating the lower-level quality criteria into higher-level quality objectives, which may be problematic in the case of qualitative criteria requiring subjective assessments. This requires that a formal approach be agreed to between the parties, in order to quantify the (1) criteria's subjective values, (2) relative weight of each criterion with respect to the overall quality objective, (3) estimated contribution of each schedule activity to its related quality criterion, (4) value function for each criterion, and (5) number of schedule-embedded control points. As such, quality is accrued progressively and cumulatively as the work package is being executed, while the project activities are properly linked to the work package's quality attributes.

In order to further elaborate on the practical implications of the outcomes of this research work, a framework has been conceptualized, as illustrated in Figure 48, synthesizing the several critical requirements that need to be properly incorporated and, more importantly, observed under the construction contract. These start with the need for treating the measurement of work under progress or completed as a continuous process; yet, such measurement is to be jointly performed by the contractor and engineer. Inherent to this process is the condition that any work being measured shall have already undergone the proper examination and inspection by the engineer and, as a result, have been cleared for possible incorporation in the payment statement. The contractor may be instructed to remedy or re-execute work that is deemed defective for which a withholding may then be in order. Failure to so remedy on the part of the contractor shall entitle the owner to pay others to rectify such work. Conversely, if the defect is irremediable and executed work ends up – for the owner's defensible benefits – being accepted at lower than the desired quality or performance levels, the effectuation of a setting-off shall then be viewed as justifiable. In deciding on the amount to be permanently deducted, techniques such as the discussed "quality EV" and/or "earned quality of work performed" methods (Table 31) can be found instrumental in reducing the subjectivity with which such reduction may otherwise be effected. To be noted is the strong dependence by the latter technique on the construction schedule, as its underlying principle is founded on establishing a strong link between the project time schedule's activities (i.e., WBS) and the project quality attributes (i.e., QBS).

In addition, being condition precedent to determining whether or not executed work is eligible for incorporation in a payment statement, the carrying out of inspection by the engineer shall be attended to without unreasonable delay. Here, more accurate wording may be introduced in the contract conditions or the specifications' procedural requirements, setting forth the periods within which different types of inspection are to be fulfilled by the engineer.

If at the time of payment statement submission by the contractor the executed work in question has not yet been inspected, despite the expiry of the corresponding inspection period, the engineer may legitimately entertain allowing payment for the quantities of such work. The risk arising from such a practice, as proposed above, is mitigated by the fact that the engineer is authorized to make corrections to any previously certified amounts in future payment certifications. Furthermore, it goes without saying that such a mechanism, when formalized through the construction contract, is likely to help avoid excessive construction financing costs and reduce the likelihood of such extra costs being the subject of future claims raised by the contractor. It can also help resolve the incompatibility between the quantities used in assessing the total value earned to date and those that are used for reflecting achieved work progress in the activities of the construction time schedule updates. Finally, it can act as a control tool, with the likely effect of discouraging the engineer from deliberately deferring the examination of work that is ready for inspection. This is assuming that the requests or notices for inspections have been duly and timely served by the contractor and in accordance with the explicit or implied requirements of the construction schedule kept current by the contractor.

The recommended standard practice, calling for measurements to be conducted jointly as part of a continuous process (FIDIC 1999), can allow both parties to resolve possible differences in assessed progress/quantities that may otherwise prevail when measurements are made individually, first by the contractor in preparation for submitting an IPCA and then by the engineer for the purpose of issuing a payment certification. Under such a joint assessment/measurement of work progressed, the subjectivity traditionally inherent to assessments made in pertinence to integrative work items can be reduced through the reliance on methodologies such as the “fuzzy EV” and “interval EV” methods, as previously discussed. Joint assessments can also help abide by the recommended standard practice of not requiring the contractor to amend an already-submitted statement. At the same time, this can minimize the chances of the periods specified for payment certification and reimbursement being exceeded, which – in turn – can help avoid having financing charges assessed by the contractor in relation to delinquent payments. By the same token, when it is jointly known that the total field quantity (as opposed to the BOQ-listed quantity) of a certain work item has indeed been executed, it will be only fair that the contract lump-sum price’s subtotal corresponding to the work item in question be wholly reflected in the current interim payment certificate. As such, the possibility of a misleading understatement to the owner of the total value earned for work executed to date can be circumvented. In addition, the risk of contractor’s overpayment is diminished by the fact that the engineer may at any later stage correct any amounts previously certified, if it becomes evident that there has been an oversight, and – subsequently – more work is still being required under the work item in question.

By way of closing, the value earned for executed work that has been already approved, cleared, or accepted by the engineer, and whose quantities (or progress milestones) have been finally agreed by the contractor and engineer to have been properly or objectively measured, may ultimately undergo a further reduction based on schedule-related compliance criteria. That is, if any work, for which measurements have been agreed, is found (1) to have been executed out of the sequence prescribed by the current (consented) construction schedule or (2) not to have appropriately served other activities (customers) of this schedule, with which work dependencies do exist and based on which the schedule rationale has been based, the total value earned may be reduced. This can be done by resorting to the “effective EV” and “customer EV” techniques (Table 31), as previously explained . Taken without saying, the authority of the engineer to possibly effectuate such reductions better needs to be prescribed under the particular conditions of the contract in question, in order for the engineer to be acting within the limit of its prescribe authority. In re-iteration to what has been stated earlier, it can be argued that the primary –and rather driving – motivations justifying the employment of such approaches for deriving to a more representative EV figure include: (1) promoting the adoption of more realistic activities’ sequencing constraints and other assumptions in the formulation of the construction schedule, (2) closer observance of the specifications’ execution requirements in the adopted activities’ dependencies, (3) enabling a more effective follow-up on planned work by the engineer, and (4) minimizing the risk of payment being certified for out-of-sequence executed work, which may possibly lead to rework.

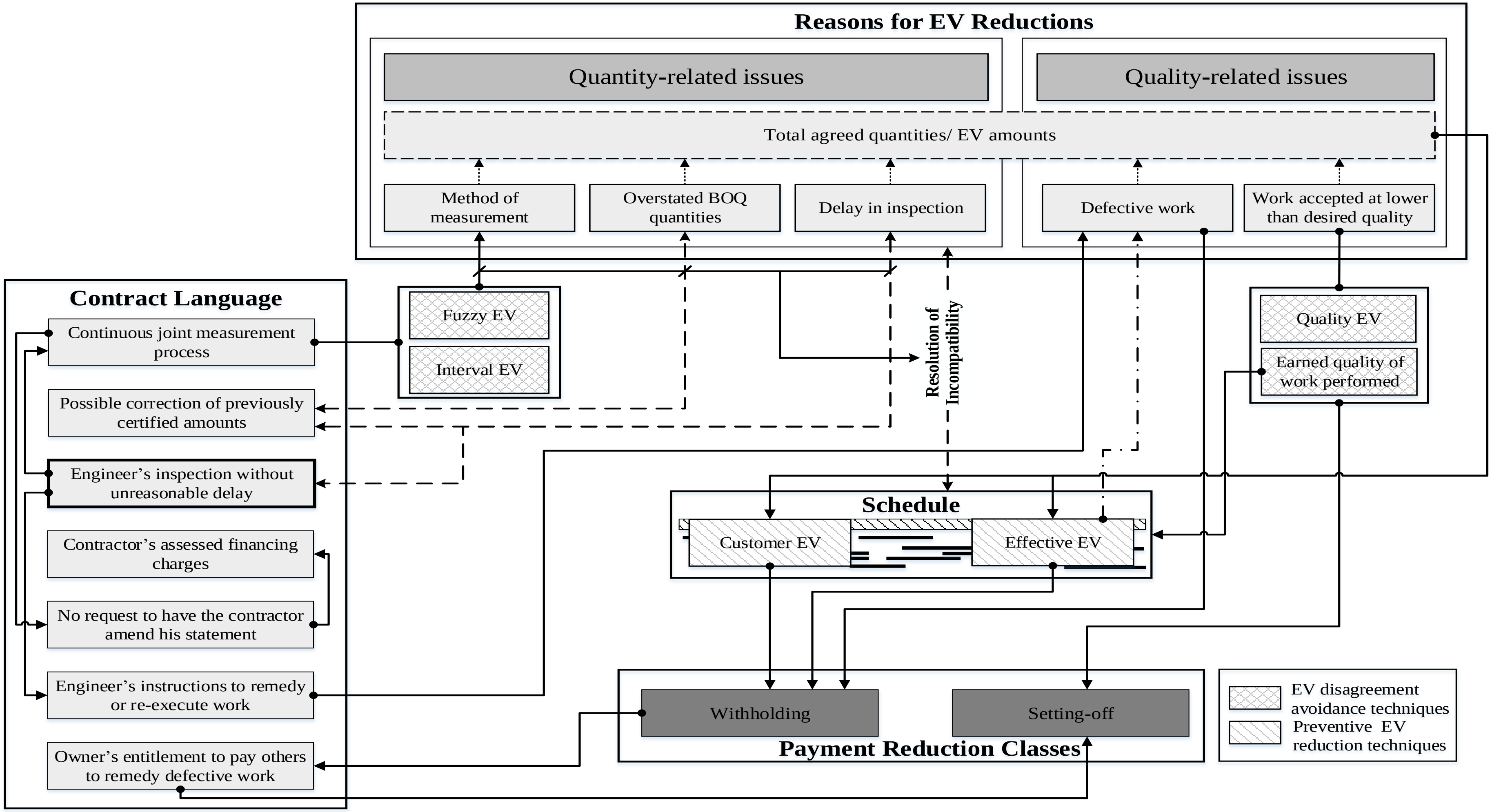

Figure 48. Approaches for mitigating EV disagreements and techniques for justifying preventive EV reductions

CHAPTER 9

EMERGENT EVM TECHNIQUES FOR CONSTRUCTION SCHEDULE PERFORMANCE MEASUREMENT AND CONTROL

9.1 Preamble

The earned value management (EVM) method remains as the most recognized project performance measurement and control tool. An extensive number of techniques dealing with ways and means that improve the forecast of the at-completion project duration have been proposed in the last two decades. That said, the objective of the work presented in this track of analysis is to investigate and propose a framework that can systematically guide the construction contract engineer in measuring and controlling project schedule performance. The proposed framework aims at making this control tool better accustomed and suited for exercising construction schedule control. In that respect, it accounts for the several emergent extensions, involving variant metrics that have been developed in complement to other proposed EVM-compatible methods, in order to offer better means for studying the project schedule performance and measuring the total expected delays. A notional project has been used to demonstrate the practicability of the majority of the steps incorporated under the proposed framework. The main research contribution lies in allowing a systematic and transparent evaluation that supports the schedule-based delay analytical methods employed in determining project owners' right to recover liquidated damages in case of expected schedule delays.

9.2 Introduction

The construction industry has consistently expanded over the past few decades, leading to nowadays having multiuse and more complex projects, with all their correspondingly increasing challenges (Orgut et al. 2018). Irrespective of its scale and duration, each construction project usually has the three core objectives of cost, time, and performance to realize, and managing the tradeoffs among them is the main task of a project manager (Mortaji et al. 2014). A recent study deduced that 98% of megaprojects (i.e., projects having a budget greater than $1 billion) have to survive with 80% cost overruns and an average of 20 months of schedule delays (Changali et al. 2015). Similarly, Nassar et al. (2005) considered that construction projects are rarely "on-schedule" during their execution. As such, the delivery of construction projects under the pressure of respecting the agreed completion time and contract price, and while being in accordance with the set quality standards, has further emphasized the significance of project monitoring and control in recent years (Aliverdi et al. 2013). Similarly, Demachkieh and Abdul-Malak (2018) confirmed the sustained need for improving the efforts, systems, or mechanisms related to putting in place effective project control processes in order to achieve project success, for projects in all industries and more critically for those in the construction industry.

Since project management is mainly related to decisions concerning the future, time and cost forecasts are vital to project success (Vanhoucke 2012; Batselier and Vanhoucke 2015). Accordingly, project managers, and especially in the construction industry, consider the ability of forecasting time and cost to complete as the most significant value of a project control method (Kim et al. 2003). Without accurate estimation, there can be no justification in making a correct decision, and thus one will have to rely on project adaptability to emergent situations (Caron et al. 2016). To this end, project duration forecasting is considered critical for conducting proactive schedule performance measurement and control in order to achieve an on-time project delivery (Kim and Reinschmidt 2010; Vanhoucke 2012; Kim and Kim 2014; Batselier and Vanhoucke 2015). A project manager is then able to track the current status and trends of project performance, forecast possible project outcomes, and steer the project under construction, so that prompt control decisions can be taken in a timely manner (Dvir and Lechler 2004; Kim and Kim 2014). As such, one of the most broadly adopted tools for obtaining such estimates is the earned value management (EVM) method, which is used for:

a. measuring and assessing the project physical progress (Vandevoorde and Vanhoucke 2006; Zhong and Wang 2011; Aliverdi et al. 2013; Kim 2014; Mortaji et al. 2014; Vanhoucke 2018),
b. analyzing trends and statutes (Czemplik 2014; Salehipour et al. 2015), and
c. providing a quantitative measure for estimating a project's actual completion time figure (Nassar et al. 2005; Leu and Lin 2008; Pajares and López-Paredes 2011; Batselier and Vanhoucke 2015).

To this effect, a detailed description of the basic principles and the use in practice of this technique is comprehensively found in several publications (Anbari 2003; Fleming and Koppelman 2006; PMI 2018).

A prevalent project control topic is the investigation for consistent and reliable project forecasting techniques (Wauters and Vanhoucke 2014). In an EVM framework, the forecast of the time estimate-to-complete (ETC(t)), i.e., time needed to complete the project, is highly needed for the initiation of appropriate corrective actions, in order to reach the project objectives (Caron et al. 2016). To this end, the review conducted by Demachkieh and Abdul-Malak (2018) of the archived research literature concerned with project controls and the use of EVM revealed that the EVM limitation corresponding to the quality of outputs (namely, mistaken results of time estimate-at-completion (EAC(t)) forecasts) is the top-cited shortcoming, thus leading to hindering the effective employability of EVM in the construction industry.

Moreover, Demachkieh and Abdul-Malak (2018) presented a synthesis of the main tracks along which the literature-reported EVM enhancements can be classified and showed that the highest frequency of encountered improvements (i.e., 30 percent) is associated with the previously mentioned limitation (also having the highest citation occurrence). As such, those enhancement-related studies tackle the development of a diversity of innovative EVM-based techniques in order to accurately forecast the project duration at completion. These state-of-the-art methods can be categorized into two main classes, namely deterministic and probabilistic (Barraza et al. 2004). The deterministic approaches produce point estimates of the forecasted project duration figures, whereas probabilistic methods produce confidence intervals and/or probability distributions of such figures (Batselier and Vanhoucke 2015). To this effect, the deterministic duration forecasting methods predict the EAC(t) duration based on the most likely duration values for the activities involved in the project (Barraza et al. 2000), and thus do not offer any information regarding the array of probable outcomes for achieving the project objectives (Kim and Reinschmidt 2010). In contrast, the probabilistic methods forecast the expected project duration using the variability of duration integrated in the project activities. For instance, a simulation tool is used for producing the stochastic S-curves, which:

a. allows a more objective evaluation of project performance, thereby overcoming the limitations of the deterministic approaches, and
b. enables more accurate forecasts of EAC(t) duration variations (Barraza et al. 2000; Barraza et al. 2004; Barraza and Bueno 2007).

On the other hand, the estimation of activities' progress come from people's views, involving errors and uncertainty, and consequently biased judgments (Moslemi-Naeni et al. 2011). To this end, the encountered deterministic duration forecasting methods ignore the uncertain nature of activities progress, calling for the need to develop new approaches to extend their applicability under real-life and uncertain situations. For instance, the fuzzy-based earned value (EV) approach is argued to be providing a more practical tool, compared to the traditional EVM method, where measuring or assessing an activity's progress under uncertainty can be efficiently performed (Moslemi-Naeni and Salehipour 2011; Moslemi-Naeni et al. 2011; Aliverdi et al. 2013; Naeni et al. 2014). In addition, as the deterministic EVM forecasting methods are stated to provide unreliable results in the project early stages due to small sample size (Christensen and Heise 1992; Zwikael et al. 2000), the integration of experts' knowledge with the project records allows the improvement of the forecasting process, especially in the project early stages. For instance, the use of the Bayesian approach (Caron et al. 2016) and the Kalman filter (Kim and Reinschmidt 2010) offers an effective probabilistic tool that accounts for previous performance data, experts knowledge, uncertainty during project construction, and measurement errors. Additional encountered examples of probabilistic approaches used for forecasting the project duration included:

a. artificial neural network models that rely on project data reflecting continual and seasonal cycle patterns (Pewdum et al. 2009; Rujirayanyong 2009),
b. support vector machines, stemming from artificial intelligence, that introduce variability in activity durations to compute the EAC(t) figure (Cheng et al. 2010; Wauters and Vanhoucke 2014), and

c. the change point analysis that can be used for producing reliable forecasts for the project final duration and cost, taking into account the latest periods during which the performance level is found to be stable (Mortaji et al. 2014).

Nevertheless, despite the enhanced results resulting the probabilistic approach (Crandall and Woolery 1982), deterministic tools are usually used in the construction industry because they adopt simpler tools and approaches (Barraza et al. 2000).

Even though these probabilistic methods have been confirmed valuable for estimating project duration, a thorough explanation of these techniques is beyond the scope of this research, as the emphasis of this research is on the deterministic EVM-based duration forecasting methods, whose applicability in construction has also been confirmed, as previously stated, to be more practicable. Accordingly, this chapter is organized as follows. In the following section, the main research objectives and the adopted methodology for this chapter are presented. Later, a state-of-the-art review of the duration forecasting methods along with several EVM-based emergent extensions are briefly offered. Subsequently, a framework is proposed with the aim of making EVM method better accustomed and suited for exercising schedule control by the construction contract engineer. Afterward, a notional project, developed using a scheduling application, is used to assess the forecasting accuracy of the proposed methods. The results of this evaluation are thereafter presented and discussed.

9.3 Research Scope and Methodology

Schedule monitoring and control is considered as one of the most crucial functions of project management that continues to receive considerable research attention. To this effect, the EVM method is a well-established project performance technique, originally established as a cost management and control tool and later extended to track schedule performance. While there are many shortcomings to the use of EVM data for the purpose of schedule performance measurement and analysis, the literature has proposed duration forecasting methods to supplement and enhance the effectiveness of schedule analysis for the construction project.

That said, the objective of the work presented in this chapter is to investigate and propose a framework that can systematically guide the construction contract engineer in measuring and controlling project schedule performance. The adopted methodology included the following:

a. a synthesis of the several techniques that were encountered in the reviewed literature as serving the critical task of forecasting and updating the EAC(t) figure for the duration of a construction project on hand,
b. a compilation of a number of additionally emergent extensions, involving variant metrics that are proposed in complement to other proposed EVM-compatible methods, in order to offer better means for studying the project schedule performance and measuring the total expected delays, and
c. an examination of the applicability and prediction accuracy of the proposed techniques and metrics using a hypothetical project demonstrated through scheduling software.

The study's outcomes shall be of value to the contract engineer involved in administrating construction contracts, through stipulating an integrated set of methods and metrics for more reasonably forecasting the remaining project duration. The ultimate implication is intended to be one that supports the traditional schedule delay analysis in a fair initiation of the recovery of liquidated damages (LDs) in case of schedule delays, thereby minimizing the likelihood of conflicts and disputes to arise between owners and contractors on construction projects as a result of such LDs-enforcement actions.

9.4 EVM Fundamentals

The EVM method has long been recognized as a well-established tool offering an integrated approach for the efficient monitoring and controlling of the project's cost and schedule targets during the course of execution (Ballard and Koskela 1998; Cioffi 2005; Valle and Soares 2006; Humphreys and Visitacion 2009; Zhong and Wang 2011; Moreira and Figueiredo 2012; Kim 2015). Accordingly, the Project Management Institute (PMI 2011) defines EVM as "a method for integrating scope, schedule, and resources, and for measuring project performance." Due to its ability to consolidate cost, schedule, and technical performance, EVM has become an important project performance technique used for:

a. monitoring the physical completion of executed works (Warhoe 2004; Cioffi 2006), and
b. perceiving problems early enough for the initiation of suitable corrective actions (Buyse et al. 2006; Vandevoorde and Vanhoucke 2006; Chou et al. 2010; Kerzner 2013).

To this effect, EVM includes three main key parameters, namely: (a) the budgeted cost of work scheduled (BCWS), also known as the planned value (PV), (b) the budgeted cost of work performed (BCWP), previously called the earned value (EV), and (c) the actual cost of work performed (ACWP), also known as the actual cost (AC) (AACE International Recommended Practice No. 10S-90). The PV, as defined by the American Association of Cost Engineers (AACE) (AACE International Recommended Practice No. 10S-90), is "the measure of the amount of money budgeted to complete the scheduled work as of the data date." Moreover, the AC is the realized cost (i.e., money spent) incurred for the work performed as of a data date. On the other hand, the EV is the measure of the value of work performed (i.e., earned) at the date of analysis (Amos 2004). When compared with the PV, it provides "a measure of performance taking into account both time and cost expended" (AACE International Recommended Practice No. 10S-90).

Given that EVM main parameters are expressed in the unit of the project's financial currency (e.g., dollars, euros, pounds, etc.), the project manager can espouse this technique with the purpose of monitoring and controlling the project status in terms of cost, schedule and technical/physical achievement, irrespective of the project type, size, or complexity (Kim and Kim 2014; Borges Jr and Mário 2017). Principally, the EVM entails a static reference point, determined by the project baseline schedule and the budget at completion (BAC), with the purpose of frequently monitoring and controlling the project performance during construction. Monitoring performance related to time and cost is done by:

a. comparing the three pillars of EVM, namely the PV, AC and EV,
b. generating performance cost and schedule variances and indices, and
c. forecasting and updating the expected-at-completion figures for the duration and cost of the project on hand.

Although EVM had been established to monitor cost and – later – time , the majority of previous research focused on issues related to the cost aspect (Vandevoorde and Vanhoucke 2006; Willems and Vanhoucke 2015; Vanhoucke 2018). Traditional EVM provides two recognized performance measures, namely the schedule variance (SV), and the schedule performance index (SPI), typically computed in cumulative manner in order to measure the project progress (Nassar et al. 2005; Leu and Lin 2008; Salehipour et al. 2015). The SV is calculated as the difference between the earned value (EV) and the planned value (PV), and the SPI is calculated as the ratio between the earned value and planned value. They both represent the project’s condition, in that a schedule variance SV<0 (>0) and a schedule performance index SPI<1 (>1) indicate that the project is behind (ahead of) schedule. When the SV is equal to zero (i.e., SPI=1), the project is said to be right on schedule. While a monetary variance can signify a project cost variance (CV), it is not usual, however, that a value originating from a monetary variance is taken to best estimate a project’s schedule variance (SV) or time variance (TV) (Borges Jr and Mário 2017). The behavior of the EVM’s SV and SPI performance measures during project execution has been criticized by many authors for several reasons, of which:

a. SV is measured in monetary units (Lipke 2003; Lipke 2009; Lipke et al. 2009; Rujirayanyong 2009; Khamooshi and Golafshani 2014; Monteiro and Daher 2015; Chang and Yu 2018) ;
b. an SV value of zero (i.e., SPI=1) could imply that a task is 100% completed, but it could also indicate that the task is performing according to plan (Rujirayanyong 2009; Khamooshi and Golafshani 2014; Monteiro and Daher 2015; Chang and Yu 2018); and
c. at the end of the project, SV is always equal to zero (i.e., SPI=1), signifying an effective performance although the project could be late (Lipke 2003; Henderson and Lipke 2006; Lipke et al. 2009; Rujirayanyong 2009; Narbaev and De Marco 2014; Chang and Yu 2018).

As a result, the SV and SPI metrics are flawed and thus lose their predictive capability, especially over the last third of the project (Vandevoorde and Vanhoucke 2006; Rujirayanyong 2009; Narbaev and De Marco 2014).

9.5 Need for Schedule Duration Forecasting

The construction schedule is a necessity for each participant involved in the construction project. To this effect, it is needed by the engineer for progress monitoring purposes and for the owner and contractor to plan the project and construction financing requirements, respectively. At best, any such schedule represents the contractor's best intent or plan for the execution of the works, incorporating the contractual project completion date, activities' logical sequencing constraints, along with resource and cost loading. Accordingly, both the owner and his appointed engineer are entitled to rely on the submitted schedule to plan for the availability of their personnel during work execution, taking into consideration the higher needs for on-site staff during the periods where high progress rates are planned for the works to be performed (Booen 2000).

9.6 Consenting the Contractor's Schedule

Following the contract award and soon upon receiving the notice of commencement with the works, the contractor is normally required to submit to the engineer an overall preliminary schedule. In practice, this high-level schedule should incorporate sufficient details for the activities that are planned to take place in the first 90 days of the construction contract duration. A complete full-fledge schedule is then submitted before the expiry of the first 90-day period, reflecting sufficient details for the vast array of activities envisioned to take place in fulfillment of completing the whole of the works. As such, the engineer, while not being under the obligation to give an explicit consent to these schedule submissions, is nevertheless to inform the contractor of the extent to which he finds any of these schedules to be not compliant with the contract requirements. That is, the engineer may show no objection to the schedule but without undertaking accountability for it (Bunni 2013). To be noted is that there is no specification determining how the engineer shall conduct the review process. However, empirical S-curve formulations have been proposed (Cioffi 2005; Mavrotas et al. 2005; Blyth and Kaka 2006; Chao and Chien 2009; Chao and Chen 2015; San Cristóbal 2017), which may aid in checking the reasonableness of the contractor's PV curve. Here, it is the owner's cash flow projection curve that is of relevance; this is generated by loading the activities of the contractor's schedule with the work items' costs, represented by the agreed unit rate for an item in question multiplied by the quantity of that item that is planned to be accomplished in each of the schedule's concerned activities.

9.7 Measuring and Controlling the Project Schedule

During project execution, the contractor is required to submit a monthly progress report that includes:

a. a comparison between planned (i.e., PV) and actual progress (i.e., EV),
b. a description of any events or situations which may endanger the project planned completion date, and
c. a summary of the mitigation actions taken in order to overcome schedule delays, if any.

However, there are many reasons as to why work considered to have been accomplished by contractors, as presented in the interim payment certificate application (IPCA) and reflected in the updated schedule (both accompanying the monthly progress report), is denied certification by the engineer (Demachkieh and Abdul-Malak 2019). These have been identified to include:

a. disagreement on the quantification of executed work,
b. quality or technical performance of executed work,
c. potential rework caused by the violation of the planned work execution sequence, and
d. the inability to transfer the performed work to internal schedule's customers.

From a project owner's perspective, such a certified or adjusted EV amount, which is earned in respect of the work accomplished by the contractor and approved by the engineer up to a certain point in time, is significant for the purpose of comparison with the value that was planned (i.e., PV) to be achieved by that time (Demachkieh and Abdul-Malak 2019). As such, the incompatibility between the EV amounts certified by the engineer and those that are reflected in the construction schedule update submitted by the contractor in congruence with the monthly progress report is the main reason that triggers the need for the engineer to independently compute an EAC figure for the construction duration (EAC(t)), for the purpose of assessing the project schedule performance. Several duration forecasting methods may be relied upon in this regard, as shown in the framework illustrated in Figure 49. This conceptualized framework synthesizes the several requirements that need to be appropriately incorporated in, and – more importantly – observed under, the construction contract, in order to allow a more informed schedule performance measurement and assessment by the engineer.

The difference between the project planned duration (PD) and any EAC(t) figure newly computed using any of the available duration forecasting methods may turn to be representative of the amount of delay that the project is likely to incur. If this difference is negative (i.e., EAC(t) > PD), the engineer may rely on a set of schedule recovery indices that are shown in Figure 49, with specified thresholds for each indicator, in order to assess the degree of achievability of the project planned duration. A full comparison of the relevant duration forecasting techniques and metrics along with a proposed framework for their application are discussed in the following section.

To this effect, the calculated EAC(t) figure together with the specified tolerance limits can be used as a tool to support the engineer in determining whether or not the enforcement of liquidated damages shall be effectuated. As such, the aim of these tolerance limits is to produce warning signals when the monitored project progress exceeds a specified threshold, signifying that it is probable that the project surpasses its project duration target. These signals can subsequently serve as a trigger for the initiation of an appropriate action by the engineer. Accordingly, in the case where the contractor is delayed during project execution due to events that do not entitle him to an extension of time, the engineer may instruct the contractor to submit a revised schedule and a supporting method statement highlighting the methods that the contractor intends to follow in order to accelerate progress and complete the works on time. Alternatively, it may then be justifiable, after the performance of a traditional schedule delay analysis is performed, for the employer to collect liquidated damages from money that has otherwise become due to the contractor, due to his failure to maintain that the project delivery is expected to be in accordance with the planned completion date.

9.8 Encountered Duration Forecasting Methods

In recent years, a variety of methods have been provided to monitor schedule performance and forecast the EAC(t) figure. As such, six deterministic methods for project duration forecasting are encountered in the literature over the past two decades, namely:

a. the planned value method (PVM), established by Anbari (2003);
b. the earned duration method (EDM), developed by Jacob (2003) and further extended by Jacob and Kane (2004);
c. the earned schedule method (ESM) (Lipke 2003);
d. the work rate prediction method (WRPM), adopted by PMI (2011);
e. the earned duration management method (EDM(t)), developed by Khamooshi and Golafshani (2014); and
f. the earned time method (ETM), established by Chang and Yu (2018).

9.8.1 *Description of Methods*

Schedule performance management shall be measured in terms of time (i.e., usually in weeks or months). At the end of the project, the actual execution duration is usually different than the baseline planned duration. Building on this basis, project duration management typically tackles the planning, monitoring, and forecasting of a project's work progress. To this effect, this section reviews the main concepts of the proposed duration forecasting methods that are commonly used to control construction project schedule. To facilitate the discussion of these methods, a number of EV-related metrics, relied upon in the formulations offered by the concerned methods, are offered in Table 35.

Anbari (2003) developed the planned value method (PVM) based on the assumption of linear planning distribution (i.e., PV_{rate}), which is budget at completion divided by the total planned duration. This technique calculates the schedule variance in time units by dividing the variance of the schedule by the PV_{rate}, which yields TV. To this effect, PVM did not directly tackle the concept of ED, but its concept is implied in the underlying formulae. However, Jacob (2003) and Jacob and Kane (2004) proposed the earned duration management (EDM) technique to determine the ED of a project or activity. In conditions in which the actual project duration exceeds the planned project duration, the AD (i.e., actual time) replaces the PD in the corresponding formulae. Later, Lipke (2003) developed the earned schedule method (ESM) to overcome the limitations of the traditional earned value schedule indicators. To this effect, the ES expresses the time at which the amount of EV accrued should have been earned, satisfying the following relationship: $PV[ES(t)]=EV(t)$ or $ES(t)=PV[EV(t)]^{-1}$. To this effect, the three techniques developed by Anbari (2003), Jacob (2003), and Lipke (2003) allowed for the computation of variations in project duration figures in time units, albeit using cost data.

The practice standard for earned value management (PMI 2011), which is one of the highly significant EVM references worldwide, presents the work rate prediction method to predict the ED and consequently the project completion time, using "schedule-averaging" formulae. The work rates, historically utilized as performance factors, are shown in Table 36. To this effect, the forecast is too pessimistic in the project early stages. Additionally, the inspection of the corresponding formulae unveils limitations with the performance factors utilized. That is, when a project is still under execution past its planned duration, the value of $PV_{cumulative}$ equals its maximum value, which is the budget at completion (i.e., BAC). In this case, there will be no value for $PV_{current\ period}$ to utilize as performance factor. Moreover, in case of the commonly improbable condition of zero EV being accrued in a period (i.e., $EV_{current\ period}=0$), the calculation also becomes undefined.

Khamooshi and Golafshani (2014) claimed that project duration forecasting using ESM could still produce unreliable results since the ES value is calculated from PV and EV, which are both expressed in monetary values. As such, their novel approach, the earned duration management method or EDM(t), advocates the exclusive dependence on duration data to compute project physical progress, making the schedule performance analysis free from any reliance on cost values (Vanhoucke et al. 2015). The computation of ED(t) is very similar to the calculation of ES, which is calculated as the projection of the total earned duration TED (i.e., the sum of the earned durations of all the in-progress and completed activities at the status time) on the total planned duration TPD (i.e. the sum of the planned durations of all the planned activities at AD according to the baseline schedule), instead of the projection of EV on PV. As such, the duration forecasting formula adopted the use of the duration performance index (DPI) as a performance factor, which allows the measurement of the time-based progress of the project with respect to the actual duration elapsed.

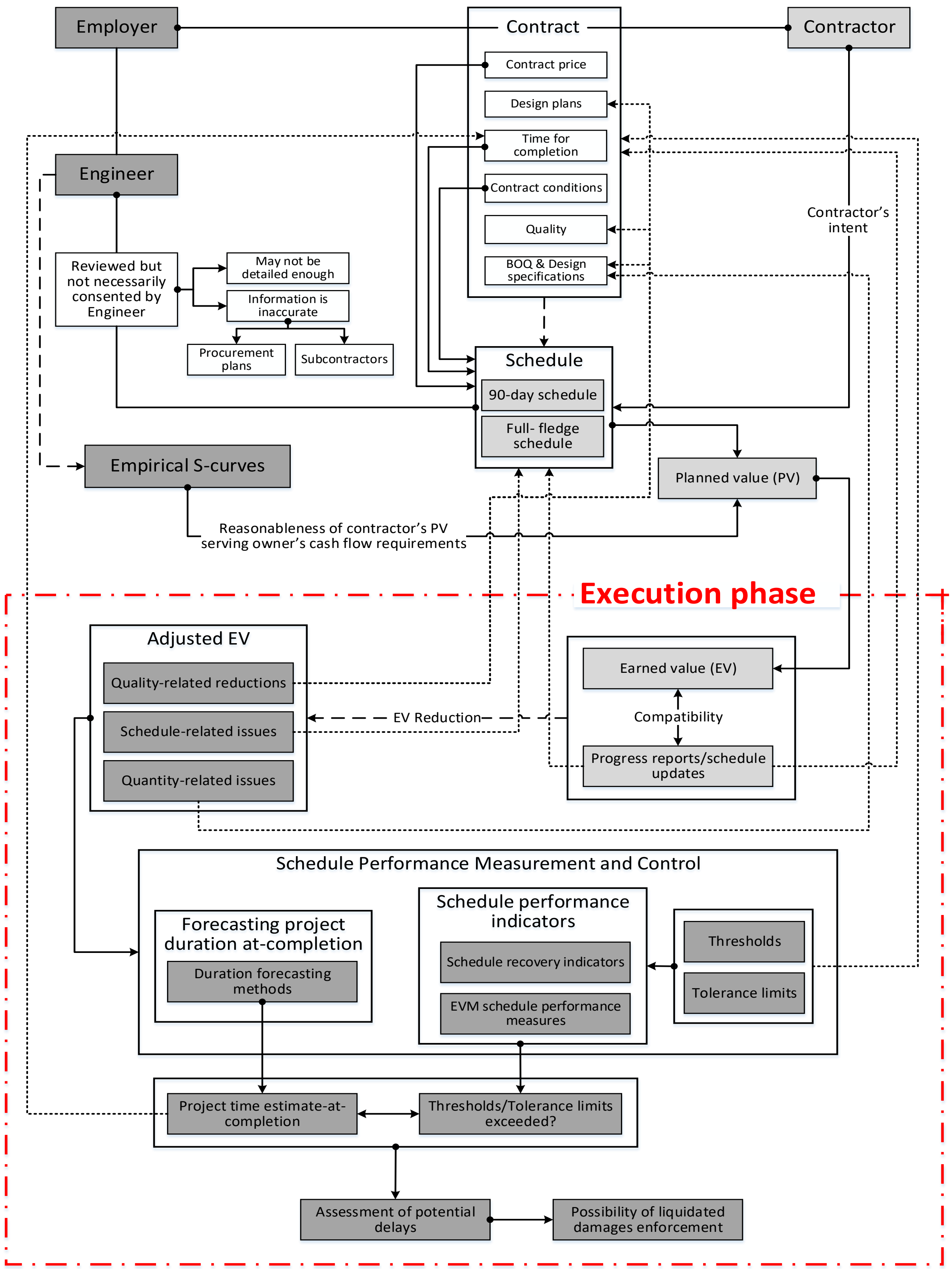

Figure 49. Reasons for the adoption of schedule duration forecasting methods

Table 35. Definitions of the EVM Forecasting Methods' Main Metrics

Symbols	**Nomenclature**	**Formula**
AD or AT	Actual duration or actual time	---
BAC	Budget at completion, the budgeted cost of the project	---
CPI	Cost performance index	EV/AC
DPI	Duration performance index	ED/AD
ED or ET	Earned duration or earned time	Table 36
EV	Cumulative earned value at the status date (i.e., AT)	---
EV_1	Cumulative earned value at an observation point t_1	---
N	Number of elapsed time periods	---
PD	Planned duration, the planned total duration of the project	---
PF	Performance factor	---
PV_0	Cumulative planned value at an observation point t_0	---
PV_1	Cumulative planned value at an observation point t_1	---
PV_N	Planned value at time instant N	---
PV_{N+1}	Planned value at time instant N+1	---
PV_{rate}	Planned value rate	BAC/PD
SCI	Schedule cost index or critical ratio	$SPI \times CPI$
SPI	Schedule performance index	EV/PV
SPI(t)	Schedule performance index (in time units)	ES/AT
SV	Schedule variance	$EV - PV$
TED	Total earned duration	---
TPD_N	Total planned duration at time instant N	---
TPD_{N+1}	Total planned duration at time instant N+1	---
TPI	Time performance index	ET/AT
TV	Time variance	Table 36
WR_M	Mean work rate of the project from beginning to end	BAC/PD
WR_p	Planned average work rate from the beginning of the project to the observation point	PV_1/t_1
WR_s	Average work rate between 2 observation points	$\frac{PV_1 - PV_0}{t_1 - t_0}$

According to Chang and Yu (2018), SV and SPI in the traditional EVM are typically misinterpreted as time performance measures, and the use of their physical meaning is recommended for reestablishing their original significance as work performance indicators. Thus, once a project becomes overdue, work performance is no longer the same as time performance. The duration forecasting results of ETM using WR_p (i.e., planned average work rate from the beginning of the project to the observation point) are similar to those prediction obtained using EDM, however, the time prediction results using WR_S (i.e., scheduled average work rate between two observation points) are almost the same as those obtained using ESM.

The six project duration forecasting methods, along with their corresponding formulations, are chronologically presented in Table 36. Furthermore, their various underlying assumptions and corresponding performance factors are summarized in Table 37. As it can be inferred from Table 37, four methods, namely PVM, EDM, ESM, and EDM(t) relied on a specific cost and/or schedule performance factor (PF) for calculating the EAC(t) duration forecast, with a corresponding assumption expressed about the expected performance of future work. On the other hand, the WRPM utilizes the work rate as a performance factor in their generic duration forecasting formulae. However, the ETM uses the work rate as a performance factor in the calculation of the earned time (ET) and a schedule performance factor (i.e., TPI) for forecasting the EAC(t) duration figure.

9.8.2 *Integrative Methods Representation*

A holistic visualization is offered under Figure 50 that shows the various parameters used for obtaining the time's estimate-at-completion in the formulae summarized in Table 37. The actual duration (AD) represents the status date at the current measurement or tracking period, whereas the planned duration (PD) expresses the project completion duration according to the baseline schedule. The earned duration (ED) is the time at which the amount of the already accrued project progress (i.e., EV) should have been earned according to the plan. However, it should be noted that this integrative diagram (Figure 50) does not respect a proportional relationship among the various measurements obtained using the proposed formulations of each duration forecasting method.

9.8.3 *Methods Criticisms*

Most criticism against EVM-based duration forecasting methods revolves around two main properties of the traditional EVM method. Firstly, while the PV and EV being expressed in monetary terms, they are used to measure the duration-based project progress. To this effect, five of the proposed methods embrace EV and/or PV values in their formulations in order to compute the project time's estimate-at-completion. Jacob and Kane (2004) argued that most duration forecasting methods have the same level of estimation accuracy due to the fact that they adopt the same basic parameters (i.e., PV and EV), though EV is not normally a reliable measure of the progress in project duration. Thus, forecasting formulae using cost-based metrics are not necessarily accurate in dealing with duration performance measurement, especially in case of the low correlation between cost and time profiles throughout the project lifecycle (Khamooshi and Golafshani 2014). Secondly, using the traditional SV or SPI for schedule performance is usually deceptive, since they are insensitive to the progress of critical activities. (Short 1993). Additionally, these schedule metrics do not reveal whether or not scheduled milestones are achieved given that some performed work may have been executed out of sequence or ahead-of-schedule (Short 1993).

Lipke (2003) considered that the EVM schedule indicators fail to offer reliable information on schedule performance over the final third of the project. Additionally, they undeniably collapse if the project is overdue. That is, as a project nears its completion date, its SPI value tends to approach the value of one (SPI=1.0), irrespective of its actual performance. To this effect, several duration forecasting methods defeat this limitation by using other indices. As an illustration, the SPI(t) used in the ESM, is considered to be a favored index for measuring project duration performance, in comparison to the traditional SPI.

Furthermore, EVM was mainly established to focus on the project total duration at each reporting period, disregarding the build-up of these figures and measures (Khamooshi and Golafshani 2014). Specifically, time overruns by a certain activity could be rewarded by other activities. This could be satisfactory at the macro-level but could generate critical problems at the micro-level, where the performance of teams, units, or departments are inspected. As a solution to this dilemma, Khamooshi and Golafshani (2014) developed a variety of indices to measure project progress and schedule performance at the project macro and micro levels.

Furthermore, all the proposed duration forecasting methods adopt the linear approach. For instance, in the ESM, one must assume that the cumulative PV and EV curves are both linear, but with dissimilar slopes. Thus, it is worth pointing out that the earned schedule duration formula is essentially based on a veiled hypothesis that assumes a linear slope in the local area, which is not acceptable at the macro (global) level (Evensmo and Karlsen 2006). Similarly, the PVM adopts the concept of PV_{rate}, which is equal to the average planned value per time period, assuming linear PV distribution over the project lifecycle. However, this assumption is not generally valid, where the project PV S-curve is flatter at the beginning and steeper in the middle. As such, and since most real-life project cost curves are nonlinear, this inconsistency raises a question about the theoretical implementation of those formulae (Warburton and Cioffi 2016).

Lastly, EVM forecasting formulas are not suggested to be used in the project early stages because of large prediction errors (Fleming and Koppelman 2006). Here, the stabilization period needed to obtain consistent EVM estimates is variable from one project to another, and no research study has been conducted about how to determine the period after which the EVM forecasting formulations can be adopted with adequate accuracy (Kim and Reinschmidt 2009).

By way of summarizing, while there are many shortcomings to using EVM data for schedule performance measurement and analysis, those duration forecasting methods have been established to be used for supplementing and enhancing the effectiveness of schedule analysis of the construction project.

9.9 Emergent EVM Extensions

This section presents several emergent techniques related to schedule performance measurement and analysis, which were identified from the related literature and summarized in Table 38. They aim at:

a. measuring and analyzing the probability of the schedule recovery, and
b. removing the false warning effects generated from the non-critical activities.

A brief discussion of each of the proposed extensions, as indicated in the second column of Table 38, is hereunder provided as follows.

Table 36. EVM Duration-Forecasting Methods' Formulations

Authors	Duration prediction methods	Earned duration (ED) /earned schedule (ES) in time units	Time variance (TV)	Time estimate at completion (EAC(t))
Anbari (2003)	Planned value method (PVM)	----	$\frac{SV}{PV_{Rate}}$	$\frac{PD}{PF}$ or $PD - TV$
Jacob (2003) & Jacob and Kane (2004)	Earned duration method (EDM)	$ED = AD \times SPI$	$ED - AD$	$AD + \frac{Max(PD; AD) - ED}{PF}$
Lipke (2003) & Henderson (2004)	Earned schedule method (ESM)	$ES = N + \frac{EV - PV_N}{PV_{N+1} - PV_N}$	$ES - AT$	$AT + \frac{PD - ES}{PF}$
PMI (2011)	Work rate prediction method (WRPM)	$ED = \frac{BAC - EV}{PF}$	$ED - AD$	$AD + ED$
Khamooshi and Golafshani (2014)	Earned duration management method (EDM(t))	$ED = N + \frac{TED - TPD_N}{TPD_{N+1} - TPD_N}$	$ED - AD$	$\frac{PD}{PF}$
Chang and Yu (2018)	Earned time method (ETM)	$ET = \frac{EV}{(WR_S \text{ or } WR_P \text{ or } WR_M)}$	$ET - AT$	$\frac{PD}{PF}$

Table 37. Duration-Forecasting Methods Performance Factors

Duration forecasting method(s)	**Performance factor (PF)**	**Assumption**
PVM, ESM and EDM	1.0	Duration of remaining work follows the planned time performance (i.e., according to plan)
	SPI or SPI(t)	Duration of remaining work follows the current time performance
	SCI	Duration of remaining work follows the current time/cost performance
WRPM	$\text{PV}_{\text{current period}}$	Duration of remaining work follows the planned value performance corresponding to the current period
	$\text{PV}_{\text{average}}$	Duration of remaining work follows the average planned value performance
	$\text{EV}_{\text{current period}}$	Duration of remaining work follows the earned value performance corresponding to the current period
	$\text{EV}_{\text{average}}$	Duration of remaining work follows the average earned value performance
EDM(t)	DPI	Duration of remaining work follows the current time performance
ETM	TPI	Duration of remaining work follows the current time performance

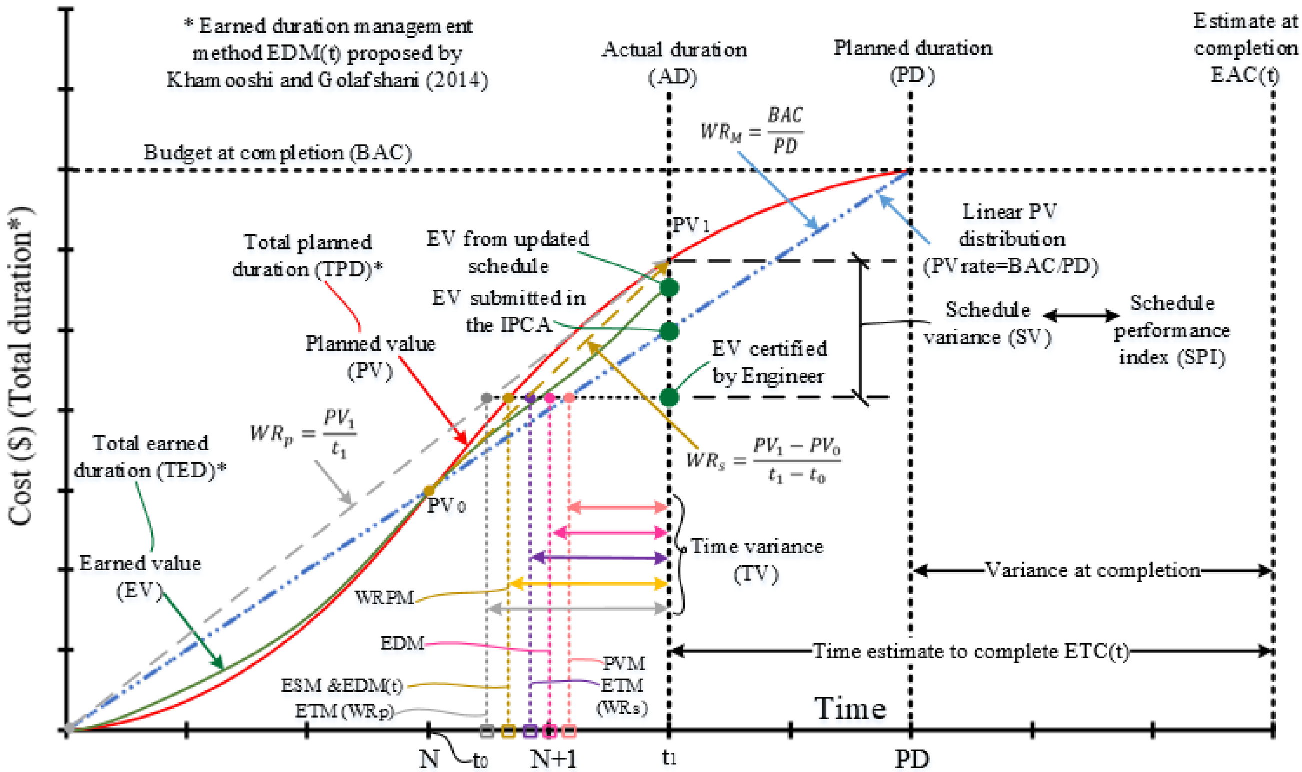

Figure 50. Parameters of duration-forecasting methods

9.9.1 *Schedule Recovery Indicators*

To finish in accordance with its originally planned duration, a project that is not achieving its schedule targets needs enhanced performance in the remaining work. To this effect, three schedule recovery indicators are proposed in order to determine the future schedule efficiency required to achieve projected schedule outcomes, including:

a. the to-complete schedule performance index (TSPI),

b. the to-complete schedule compression ratio (TCSCR), and

c. the EV improvement index.

The to-complete schedule performance index (TSPI) is the ratio of the planned remaining duration to the actual remaining duration (PMI 2011), and it as such measures the achievability of a target project duration. For instance, a TSPI greater than 1.0 implies that the project is running behind schedule, and higher values of TSPI indicates that the target duration is less reachable.

Additionally, Cioffi (2006) proposed a new improvement index (Ξ) that calculates the required increase in productivity to finish the project according to the original planned schedule duration. Given only an EV performance factor (i.e., the inverse of the traditional schedule performance index) and the fraction of tasks executed-to-date (or alternatively an S-curve equation and the standardized time), the completed task fraction where schedule recovery is impossible is then computed, and a point in time beyond which recovery is highly improbable is proposed. For instance, an improvement index Ξ of 1.34 implies that the productivity of the work shall increase by 34% over the average performance in order to finish the project on time, i.e., according to the baseline duration.

A novel EV performance measure has been proposed by Kim (2014) that also specifies the degree of achievability of a project schedule target. To this effect, the to-complete schedule compression ratio (TCSCR) is the reciprocal of TSPI, defined as the ratio of the actual remaining duration to the planned remaining duration. It is important to note that the TCSCR is positive only in the case where the actual elapsed time is less than the planned duration. however, when a project is overdue (AT > PD), the necessity for evaluating the degree of achievability of the schedule target is useless. The use of TCSCR is easy and straightforward; for instance, TCSCR=0.9 implies that the planned duration for the outstanding works shall be crashed to 90% of its current value to achieve the project planned duration.

9.9.2 *Critical Path Influence*

The traditional EVM method disregards the difference between critical and non-critical project activities, which both contribute to measuring the overall project progress (Zhong and Wang 2011). More specifically, a delay in a non-critical activity might provide false warning signals to the project management, possibly leading to the wrong corrective measures being taken. Thus, in order to highlight the critical and non-critical path effects on the schedule performance, the weight earned value (WEV), developed by Zhong and Wang (2011), is introduced, with the aim of proposing an improvement to the traditional SV and SPI. This method assigns a weight value to each of the project activities depending on their respective total floats, in order to reduce the false effect of non-critical activities. The total time difference (TF), or total float, is the amount of time an activity can be delayed without affecting the project completion time. To this effect, the smaller the TF value is, the more crucial is the work involved in that activity. As such, a TF equal to zero is assigned to the project critical activities. Furthermore, Najafi and Azimi (2016) proposed the active floating time (AFT) method, which applies EV, PV, and floating time concept for schedule performance measurement and analysis, allowing the calculation of schedule variance with minor probability of error due to the false warning from non-critical activities in the project network. The solution derived from this method is equivalent to the schedule status obtained from the CPM-based scheduling method.

Table 38. Proposed EVM Emergent Extensions

Authors	Proposed Extension	Formulation	Symbols	Explanation
Henderson (2004)	To-complete schedule performance index	$TSPI = \frac{PD - ES}{PD - AT}$ $TSPI = \frac{PD - ES}{EAC(t) - AT}$	PD ES AT EAC(t)	Project planned duration Earned schedule Actual time Time estimate at completion
Kim (2014)	Dynamic control thresholds	$TCSCR = \frac{PD - t}{PD - ES}$ $TCSCR = \frac{1 - \%E(t)}{1 - SPI(T)(t) \times \%E(t)}$ $SPI(T)(t) = \frac{TCSCR - 1 + \%E(T)}{TCSCR \times \%E(t)}$ $SPI(T)(t) = \frac{1 - TSPI[1 - \%E(T)]}{\%E(t)}$ $\frac{SV(T)(t)}{PD} = \frac{(TCSCR - 1)[1 - \%E(T)]}{TCSCR}$ $\frac{SV(T)(t)}{PD} = (1 - TSPI)[1 - \%E(T)]$	PD t ES %E(t)	Planned duration Status date Earned schedule Time percent elapsed at the status date, defined as t/PD
Zhong and Wang (2011)	Weight earned value	$k_i = \frac{e^{(-TF_i)}}{\sum_{i=1}^{n} e^{(-TF_i)}}$ $BCWP_k = BCWP \times k$ $BCWS_k = BCWS \times k$ $SV_k = BCWP_k - BCWS_k$ $SPI = \frac{BCWP_k}{BCWS_k}$	TF k_i	Total time difference, means the maneuver time from the beginning to the ending of the project (i.e. the smaller the TF, the more critical is the work) Weight of work i
Najafi and Azimi (2016)	Active floating time method	If $EV = 0, AFT = PFT - (DT - PS)$ If $EV > 0$, $AFT = PFT - ((AS - PS) + (DT - AS)(EV/B) - D)$	AFT PFT DT AS PS	Active floating times Planned floating times Data time or time of data gathering Activity actual starting time Activity planned starting time

			B D	Activity budget Activity duration
Cioffi (2006)	EV improvement index	$x_p = \frac{1}{\bar{F}_i[x_n]}\left[1 - \sqrt{\bar{F}_i[x_n](\bar{F}_i[x_n] - 1)}\right]$ $x_S \equiv \frac{1}{\bar{F}_i[x_n]}$ $\Theta = \frac{1 - \gamma(\beta_n)}{\gamma(\beta_n)} \frac{z}{1 - z}$ $z = \gamma(\beta_n) \times \bar{F}_i[\beta_n]$ $y(\beta) = y_\infty \frac{1 - \exp(-8r_{0.67}\beta)}{1 + \gamma\exp(-8r_{0.67}\beta)}$ $\ln(\gamma + 2) \equiv 8r_{0.67}\beta_{1/2}$ $\beta_p = \frac{1}{8r_{0.67}} \ln\left[\frac{\gamma_\infty + \gamma x_p}{\gamma_\infty - x_p}\right]$	$\bar{F}_i[x_n]$ x_p x_s Θ $r_{0.67}$ $\beta_{1/2}$ $y(\beta)$ β γ	Reciprocal of standard schedule performance index Probable recovery limit Strict limit on recovery Improvement Index Slope of the rise in the middle part of the S-curve Time at which approximately half the funds have been expended Project progress (S-curve) equation Standardized time Equation constant

9.10 Proposed Metrics Applicability Framework

Conventionally, the contractor usually depends on the CPM-based schedule for assessing schedule performance measurement and controls. To this effect, this schedule incorporates activity-level duration estimates and reflects logical sequencing relationships connecting the project's concerned activities. The schedule software adopted by the contractor forecasts the project duration at completion and variance at completion, by assuming that the reasons that affected previous activities are not to affect the future ones. In order to highlight the practical implications of how the various identified methods and metrics may be relied upon by the engineer, the framework, shown in Figure 51, has been developed. It forms an expansion, or a detailed representation, of the framework presented in Figure 49, consisting of three main cohorts that include proposed steps that may suitably be followed by the engineer. These involve:

a. deciding on the realistic EV amount that may be deemed representative of the value of work claimed by the contractor to have been accomplished;
b. making informed evaluations of schedule performance measurements; and
c. taking decisions under the construction contract for controlling progress and/or advising on the levying of delay damages by the owner against delays that can be methodologically assessed as no longer recoverable.

9.10.1 *EV Adjustments*

The first (top) cohort under Figure 51 tackles the possible effectuation by the engineer of possible reductions to the EV amount purported by the contractor in the monthly progress report, as deduced from the accompanying construction schedule updates. To this effect, a recent study by the authors (Demachkieh and Abdul-Malak 2019) has discussed several scenarios as to why work estimated by contractors to have been completed turn out to be denied certification by the engineer. As such, the engineer may exercise withholding or setting-off certain sums from amounts presented by the contractor as reflecting the value of executed work allegedly earned by the owner at the time of reporting. Accordingly, this discordancy is likely to yield an inconsistency between:

a. on one side, the EV inferred from the updated version of the schedule, and
b. on the other side, the EV certified to date (i.e., data date of the updated schedule in question), as incorporated in the latest payment certificate issued by the engineer.

The inconsistency in quantity measurement is considered to be the first reason justifying the reduction applied by the engineer to the EV amount reflected in the construction schedule. This may lead to effecting withholdings related to:

a. difference in the method of measurement for taken-off quantities, and
b. executed work that is yet to be inspected by the engineer.

To this end, the contractor reflects in the project updated schedule the amount equivalent to the full quantity executed to date. However, the engineer opts to deduct the sum associated with uninspected quantities that are viewed as not yet eligible for incorporation in the IPCA. Another reason for effecting EV reductions may be in connection with integrative work items, where an item's unit rate covers many stages of work progress for the item in question. The subjectivity usually inherent to work progress valuations pertaining to such work items can be diminished through the reliance on proposed methods (Demachkieh and Abdul-Malak 2019), such as the "fuzzy EV" (Moslemi-Naeni and Salehipour 2011; Moslemi-Naeni et al. 2011; Mortaji et al. 2013; Naeni et al. 2014) and "interval EV" (Forouzanpour et al. 2016) techniques, as shown in Figure 51. The fuzzy EV method is applicable in the case where a schedule of value (SOV), in which percent unit rate values associated with the concerned progress stages are specified, is not stated in the contract. As for the interval EV method, it can be used in the case where several decision-makers are requested to jointly help in producing a valuation of the accomplished progress based on the stages specified in the work item's SOV. Essential to this process is the condition that any work being assessed shall have previously been inspected by the engineer and, consequently, cleared for inclusion in the payment certification.

Additionally, in case the contractor fails to deliver the performed works according to the specified technical performance or quality requirements, the engineer may resort to provisionally decreasing the EV amount, either by reducing the quantities executed to date or the item's subtotal, until the contractor remedies the defective work in compliance with the contract requirements. To this end, a number of techniques can be used for assessing the achieved quality of executed work (Demachkieh and Abdul-Malak 2019), namely: (1) performance-based EV (PBEV) (Hernández et al. 2013), (2) quality EV (Dodson et al. 2015), and (3) earned quality (Paquin et al. 2000). To be noted is that the application of the earned quality technique is dependent on the consented construction schedule, with its fundamental principle being based on providing a sturdy connection between the schedule's work breakdown structure and the quality breakdown structure.

Finally, the resulting EV amount, deemed by the engineer to have been correctly or objectively measured and assessed, may eventually undergo additional reductions with respect to schedule-related criteria (Demachkieh and Abdul-Malak 2019). That is, when any performed work, as duly reported by the contractor, is found to have been executed out of the planned sequence stipulated in the consented construction schedule, or not to have suitably served other activities of the schedule with which interdependencies exist (i.e., internal customers), the adopted EV figure may accordingly be decreased further by the engineer. This can be done through the employment of the "effective EV" (Lipke 2004) and "customer EV" (Kim et al. 2015) methods, by reducing the total EV amount, in the case of the former, or the EV subtotal for concerned work items, in the case of the latter.

In summary, when work, considered to have been executed by contractors, turns out to be denied certification by the engineer, this results in a delay of receipt, if not partial or full denial, of payment to the contractor. The final EV figure, ultimately certified by the engineer in every payment cylce, is used in the second cohort for allowing the generation of duration forecasts, as subsequently discussed.

9.10.2 *Schedule Performance Measurement and Control*

After the determination of the total value earned for executed works, the engineer, under the second (middle) cohort of the framework proposed in Figure 51, may refer to the "weight EV" or the "active floating time" methods for the purpose of removing the false warning signals generated by the non-critical activities. As such, the proposed schedule duration forecasting methods allow the calculation of SV and/or SPI, which are used in combination with the cumulative PV and total certified EV to forecast the duration estimate-at-completion figure. Noting that four of the methods, including ESM, EDM(t), WRPM and ETM, do not rely on SV and SPI in their underlying formulations, they cannot thus benefit from the improvement proposed by the weight EV method. To this effect, Elshaer (2013) proposes considering activity sensitivity information in the forecast of at-completion project duration. More precisely, activity-based sensitivity measures are suggested as weighing parameters for the activities PV and EV, leading to a more reliable schedule performance by eliminating or lessening the negative impact of false warning signals due to non-critical activities. The role of the engineer is therefore to select an accurate and reliable forecasting method in order to estimate the project duration based on the total certified EV and – when applicable – the schedule performance measures, calculated from one of the two proposed methods (i.e., weight EV or active floating time), or – alternatively – employing activity sensitivity analysis.

Realistically, after falling behind schedule, catching up is at best tough. Therefore, the engineer may rely on one or more of the three schedule recovery indicators, in the third (bottom) cohort of the proposed framework, in order to determine the future schedule efficiency required to achieve projected schedule outcomes, including: (1) TSPI, (2) TCSCR, and (3) EV improvement index. The use of TCSCR can also be applied as a pre-established threshold for satisfactory performance restrictions during project execution. Suppose that an organization enforces a schedule-control threshold at TCSCR = 85%. To this end, when the TCSCR becomes equal to or less than 0.85 during project execution, a warning signal must be established to raise the red flag about a possible schedule slippage. Accordingly, a new concept of an iso-TCSCR curve is defined, and two types of dynamic control thresholds for schedule analysis are usually generated for the control of the SV and the SPI(t). The iso-TCSCR curve is a curve of a schedule performance assessment with an equal TCSCR value, using the formulations shown in Table 38. Having the values of SV or SPI(t) and the percent complete for the project on hand, the engineer can directly extrapolate the value of TCSCR from the iso-curves.

Furthermore, based on the value of ED calculated from the duration forecasting methods, the TSPI, the reciprocal of TCSCR, is calculated with the purpose of judging the achievability of the planned duration at the status date. Accordingly, the practice standard for earned value management (PMI 2011) recommends that a cautionary TSPI threshold can be provided at TSPI = 1.1, and when TSPI exceeds this threshold, the projected duration (EAC(t) or PD) is "likely to be unachievable". By way of closing, the EV improvement index provides a measure of the required increase in productivity, using an analytic approximation for an S-curve, in order to recover the original target duration. According to Cioffi (2006), the schedule is unrecoverable for any project that has a performance index of around 1.6 (i.e., SPI $\approx$ 0.625).

At the end of each reporting period, the engineer is faced with three lines of actions, namely: disregard, monitor prudently, or take prompt measures. To this effect, the engineer can decide on taking certain measures when the general project performance status drops below a certain critical threshold (e.g., TCSCR<0.8), as it may already be stipulated in the contract conditions. Additionally, the engineer can use control charts to monitor the variation in SPI, SV, TSPI, or any other indicator over time with upper and lower control limits (i.e., UCL and LCL). If the specified index goes beyond those limits, then usually there is a need for possible intervention by the engineer. In other words, the expected at-completion project duration, along with selected schedule recovery indicator and its specified allowed threshold or control limit, can aid the engineer in triggering and justifying actions (i.e., liquidated damages enforcement) that are warranted by the projected schedule performance, methodologically assessed in accordance with the framework's proposed steps.

9.10.3 *Liquidated Damages Enforcement*

Time represents an essential aspect to the parties of the construction contract, and schedule delays are reported to be the most common issue encountered on construction projects (Birgonul et al. 2014). To this effect, in case of a project delay by reasons attributed to the contractor, the employer could suffer losses due to the delays incurred in running the intended facility, which may ultimately lead to reduced profit. As such, the purpose of delay analysis is to assess the causes of the project incurred delay (Menesi 2007), in addition to the liability of each party to such delay (Fawzy and El-adaway 2012), in order to judge whether an extension of time shall be awarded to the contractor (Menesi 2007). However, the analysis of delays in construction projects is a challenging task due to the bulky number of different activities that have to be analyzed, even for a fairly small project (Menesi 2007). Regular documentation of progress-related information, together with start and finish activities times, work deemed to be completed, resources assigned, idle periods, work interruption phases, delivery of materials, and variation orders, are of major importance for effective delay analysis (Fawzy and El-adaway 2012). Generally, the as-planned and as-built schedules are the main components used for delay analysis (Menesi 2007). While the as-planned schedule is a graphical illustration of the contractor's intents in respect of how the works are to be executed, the as-built schedule displays the actual activities sequence and progress, incorporating the "slowdowns, suspensions, and accelerations"(Fawzy and El-adaway 2012). Accordingly, delay damages (or liquidated damages) provisions are incorporated by the employer in the contract conditions to provide a pre-assessment of all losses that are expected to be experienced due to the overdue execution of the works (Fawzy and El-adaway 2012).

In order to highlight the mechanism that may be employed for the recovery of liquidated damages, the standard conditions for the construction contract issued by the International Federation of Consulting Engineers (known as the FIDIC), which are vastly used on international projects and adopted by the World Bank, were prudently reviewed (FIDIC 1999). According to Sub-clause 8.6 (Rate of Progress) of these conditions, if the contractor is delayed during project execution due to reasons that do not enable him to an extension of time, the engineer is authorized to instruct the contractor to submit a revised schedule and a report describing the methods which the contractor shall follow to accelerate the project progress in order to complete the works within the contractual project duration, subject to the provisions of Sub-clause 8.3 (Programme). To this effect, the contractor shall tolerate the corresponding acceleration costs. As a result, if the employer incurs extra costs (e.g., supervision costs), the contractor shall pay the employer these costs, pursuant to Sub-clause 2.5 (Employer's Claims). However, if the contractor fails to complete the project within the time for completion, the contractor shall pay to the employer delay damages, in accordance with Sub-clause 8.7 (Delay Damages). To this end, a determination by the engineer of the sums that have become due to the employer shall be made, following a notice to this effect served on the contractor either by the owner or, on his behalf, by the engineer in accordance with Sub-clause 2.5.

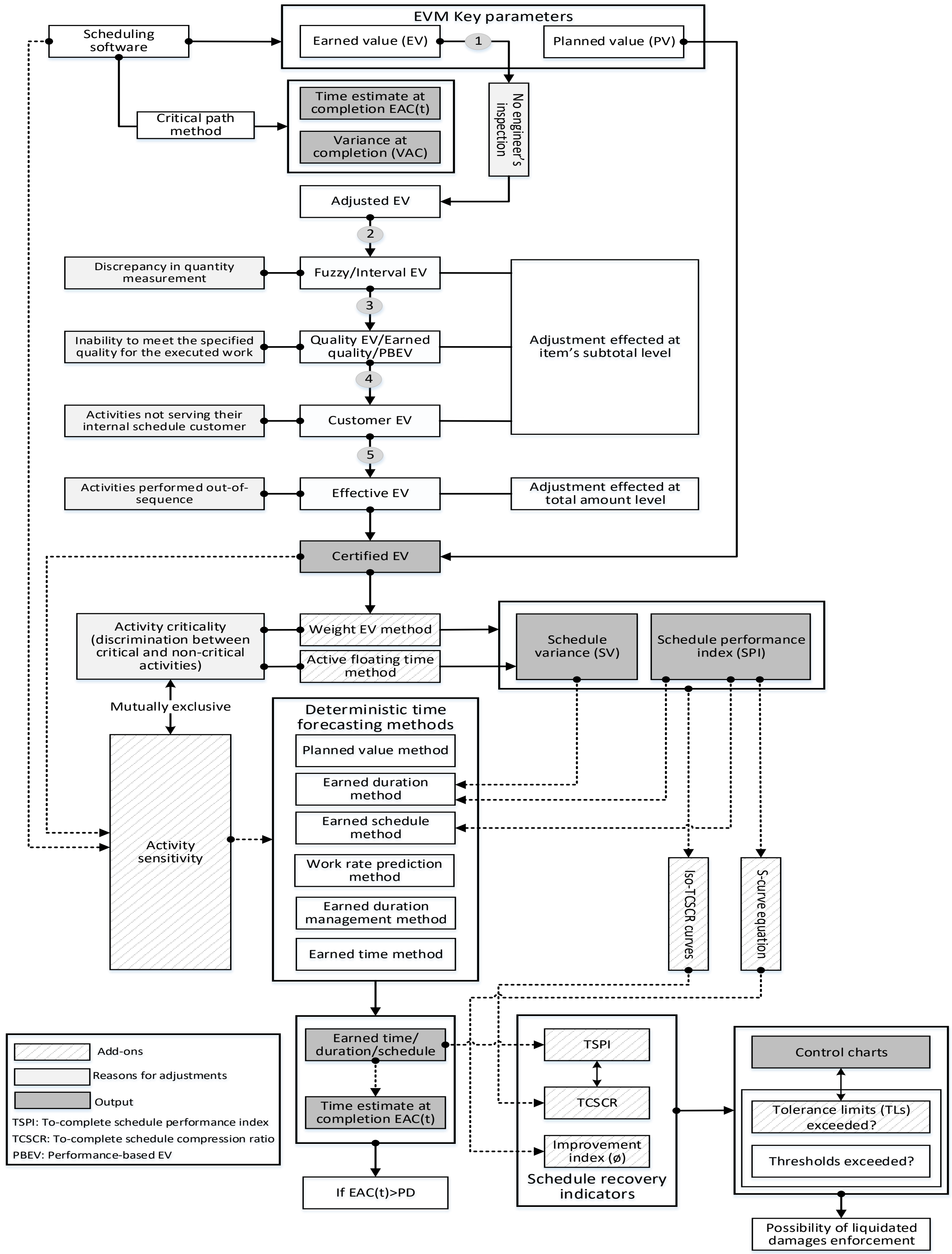

Figure 51. Schedule performance measurement and control framework

9.11 Comparative Prediction Capabilities of Emergent Metrics

In this section, a case study example has been developed, in order to demonstrate the practicable application of the proposed framework and check the reliability of the encountered duration estimation methods. The aim is to specifically compare and interpret the results obtained from the employment of the proposed schedule duration forecasting formulations against those generated by conventional CPM-scheduling software. Accordingly, two scenarios are built, including: work performed according to the baseline schedule (scenario 1), and work performed out of the originally planned sequence, coupled with a discrepancy in quantity measurement for a certain project schedule activity (scenario 2).

9.11.1 *Scenario 1*

The Gantt chart in Figure 52 shows the baseline schedule results for a notional project, generated using the Primavera P6 scheduling software. This exercise was established for the purpose of determining the forecasting accuracies of the various duration forecasting methods when applied to the same project schedule. Table 39 shows the predecessor(s), duration, and budgeted cost of each involved activity. The total project budget is shown to be $14,600, spreading over a period of 31 days. The distribution of the budget over the baseline duration forms the PV used in the EVM computations.

To reflect some hypothetically-achieved schedule progress, Figure 53 shows the project status at the end of the 14^{th} day (i.e., reporting date), where (for this scenario) all project activities were assumed to have been executed according to the work's planned execution sequence. As shown in Figure 53, some activities have already begun, while others have been completed. Table 41 shows the actual scheduling results for each activity, as derived from the scheduling software, and stated at the reporting date. As such, the planned value for each activity is computed as its planned percentage of completion multiplied by its planned value figure. Consequently, the cumulative planned value, equal to $6020, is the sum of the individual planned values for all concerned activities. Similarly, the earned value of each activity is calculated as the actual percentage of completion multiplied by its budgeted cost. To this effect, the cumulative EV, equaling $5,460, is then computed by summing up the individual earned value figures for all concerned activities.

As it can be inferred from Table 40, the project is experiencing a $560.0 negative schedule variance. Consequently, the time variance is 2 days, which implies that the project estimated duration at completion predicted by the CPM-scheduling results is 33 days. This is assumed to be an accurate estimate because the time forecasts are first made at the activity-level.

9.11.1.1 Forecasting Accuracy

The accuracy of the proposed duration forecasting methods is tested using the absolute percentage error or APE, as follows:

$$APE = \left| \frac{EAC(t) - EAC(t)_{CPM}}{EAC_{CPM}} \right| \times 100$$

Equation 3. Absolute Percentage Error (APE)

Where EAC(t) is the estimated at-completion project duration produced by any of the proposed models, and $EAC(t)_{CPM}$ is the estimated duration at completion provided by the CPM-scheduling computations.

Logically, the lower the APE for a specific forecasting formula, the higher the corresponding accuracy offered by the method in question. As such, the overall accuracy results of the EVM duration forecasting formulations are presented in Table 41. However, it is important to note that the grey-shaded cells in Table 41 do reflect the forecasting formulae that were originally proposed by (Jacob 2003; Lipke 2003; Henderson 2004; Jacob and Kane 2004) , but, instead, those that have been added by Vandevoorde and Vanhoucke (2006).

It should be noted that the use of the EDM(t) formulations require some computational steps in order to allow the exclusive usage of time-based data in the generation of a project's duration forecast. To this effect, the concepts underlying this method were used to generate the actual and earned duration numbers shown in

Table 44 for the notional project. The planned numbers are the result of assigning one-time unit to each day of each activity and adding up those numbers for each working day to obtain the total planned duration numbers (i.e., daily and cumulative) at the bottom of Table 42. Accordingly, each planned day of an activity is assigned a weight of one, irrespective of the costs incurred. The actual duration is the number of days actually taken to execute the activity. To compute the daily earned duration for each activity, the planned duration of the activity is divided by its actual duration. For instance, activity A was planned to be executed in 10 working days and was executed in 12 days. This implies that activity A effectively contributes to the project's earned duration with 10/12=0.83 day for each day of its execution period, when calculating the project's total earned duration (TED).

9.11.1.2 Interpretation of Results

As seen in Table 41, it is clearly confirmed that ESM-1 (i.e., deriving a forecast using ESM with a corresponding PF=1.0) represents the best method for providing accurate time forecasts, based on the APE results. The ESM-1 show the lowest APE of 1.31%, and thus dominates the other methods, thereby confirming the indications offered by previous work (Vanhoucke and Vandevoorde 2007; Elshaer 2013; Batselier and Vanhoucke 2015; Batselier and Vanhoucke 2015; Batselier and Vanhoucke 2015). For instance, the EAC(t) calculated from the ESM-1 is projecting a period of execution of 32.4 days, compared to the CPM-scheduling estimated duration of 33 days, predicting an earlier project finish time of around 0.6 days. Moreover, it is important to note that the time prediction results of ETM using WR_s (i.e., EAC(t)=34.9 days) are the same as the prediction results obtained using ESM-SPI(t), as demonstrated with this example. However, since the work rate is low at period 14 (i.e., $PV_{current}$ = \$280), the results show that the project is taking longer to be completed (i.e., EAC(t)=46.6), when using the formulations proposed by WRPM.

Moreover, it can be inferred from Table 41 that the unweighted methods (i.e., methods using PF=1), which assume that future performance will be according to the plan are more accurate than the performance-based counterparts. This is due to the fact that the former take into account the effect of corrective actions taken by management to remedy lagging schedule performance, whereas the latter do not. Moreover, those unweighted methods are built on the same principle as that of CPM, the historically preferred approach for forecasting the expected at-completion project duration (Anbari 2003); therefore, there is no valid cause why these methods should not be applied in the construction industry (Batselier and Vanhoucke 2015). In other words, the obtained results, showing the sovereignty of the unweighted methods, are not completely surprising. Thus, the current poor schedule performance expressed by SPI(t), DPI, or TPI, does not effectively echo the future performance, which should ideally reflect corrective measures. However, since EDM(t)-DPI slightly outdoes ESM-SPI(t) for the project on hand, the introduction of an unweighted EDM(t) (i.e., PF=1) might surpass the forecasting accuracy of

ESM-1, thus leading to a new preferred duration forecasting method (Batselier and Vanhoucke 2015). Thus, applying an unweighted EDM(t)-1 yields a forecast of 32.4 days, representing a major improvement compared to the figure of 34.4 days, already included in Table 41. By way of closing, the statements concerning the inferiority of EVM for forecasting the project expected-at-completion duration are basically addressed through the ESM introduction by Lipke (2003), whose dominance (with a PF=1) has been verified through the example used herein.

Table 39. Activities Relationships, Durations, and Budgeted Costs

Activity Name	Predecessors	Duration	Budgeted cost
A	---	10	$2,000.0
B	---	5	$1,200.0
C	A	5	$1,400.0
D	B	8	$1,700.0
E	C,D (FS=2)*	3	$800.0
F	E	2	$600.0
G	E	5	$1,300.0
H	E	4	$1,600.0
I	F,G	7	$1,900.0
J	H	9	$2,100.0

*Finish-to-start relationship with a lag time of 2 days

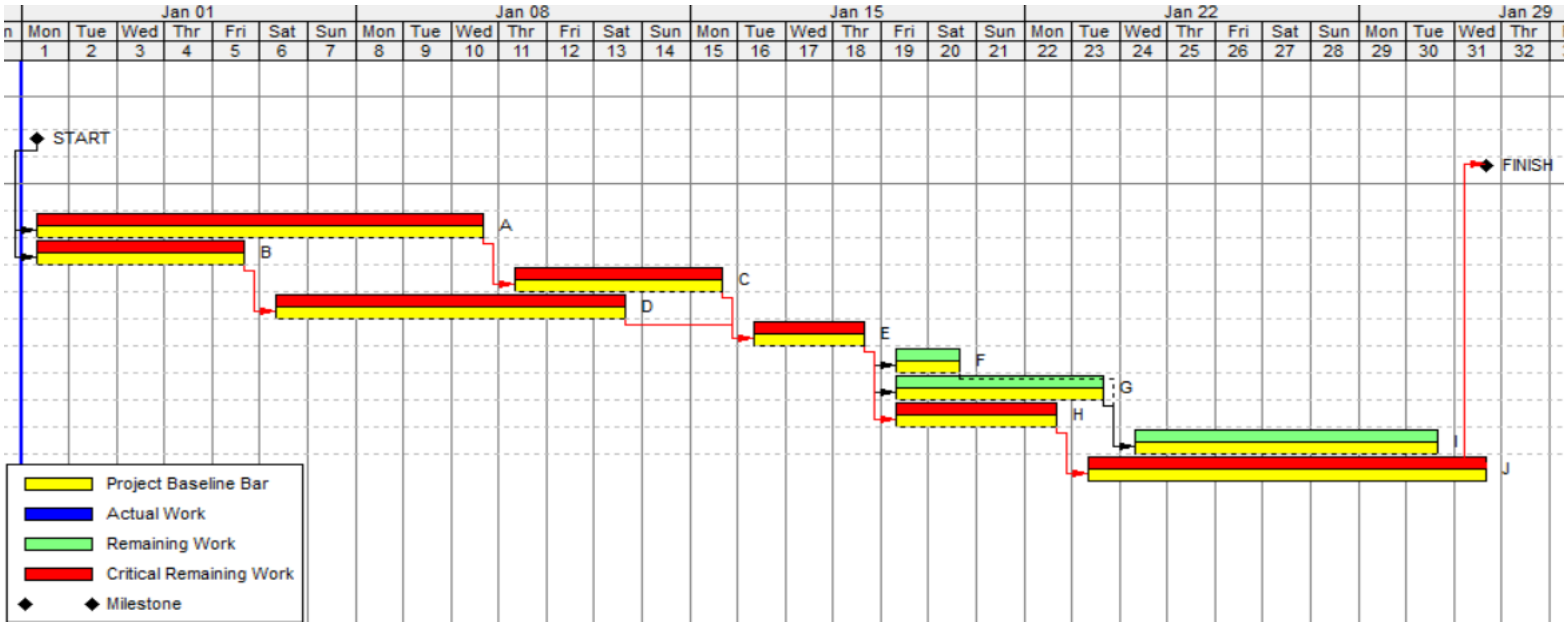

Figure 52. Project as-planned schedule

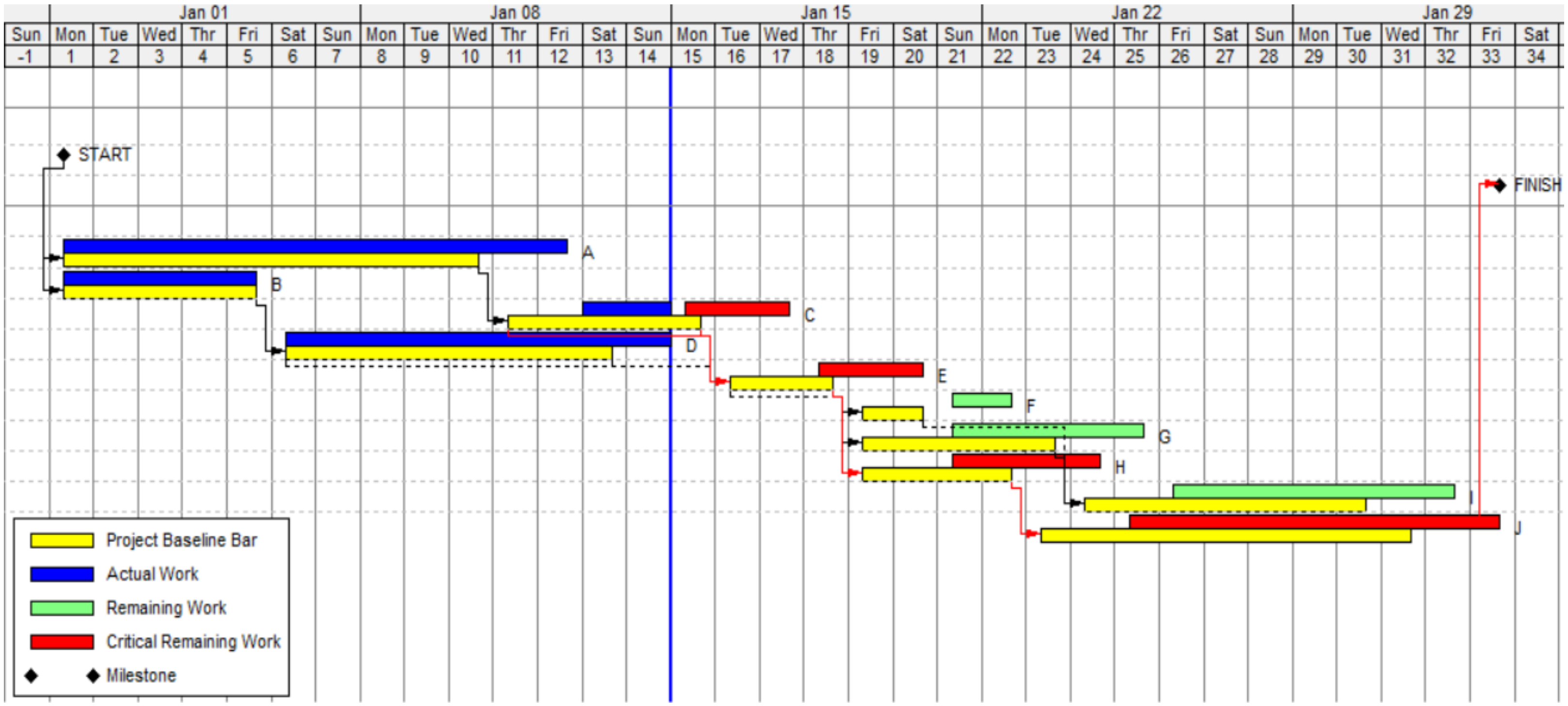

Figure 53. Project updated schedule at the end of the 14th day

Table 40. Project Data Extracted from the Scheduling Software (Scenario 1)

Activity Name	Baseline Project Duration	Actual Duration	At Completion Duration	Remaining Duration	Time Variance	PV	EV	AC	CPI	SV	SPI
	31	14	33	19	-2	$6,020.0	$5,460.0	$5,500.0	0.99	($560.0)	0.91
A	10	12	12	0	-2	$2,000.0	$2,000.0	$2,000.0	1.00	$0.0	1.00
B	5	5	5	0	0	$1,200.0	$1,200.0	$1,200.0	1.00	$0.0	1.00
C	5	2	5	3	0	$1,120.0	$560.0	$600.0	0.93	($560.0)	0.50
D	8	9	9	0	-1	$1,700.0	$1,700.0	$1,700.0	1.00	$0.0	1.00
E	3	0	3	3	0	$0.0	$0.0	$0.0	0.00	$0.0	0.00
F	2	0	2	2	0	$0.0	$0.0	$0.0	0.00	$0.0	0.00
G	5	0	5	5	0	$0.0	$0.0	$0.0	0.00	$0.0	0.00
H	4	0	4	4	0	$0.0	$0.0	$0.0	0.00	$0.0	0.00
I	7	0	7	7	0	$0.0	$0.0	$0.0	0.00	$0.0	0.00
J	9	0	9	9	0	$0.0	$0.0	$0.0	0.00	$0.0	0.00

Table 41. Accuracies of Duration-Forecasting Methods

Performance factor (PF)	Time estimate-at-completion EAC(t) [Absolute percentage error APE %]					
	PVM	EDM	ESM	WRPM	EDM(t)	ETM
1.0	32.2	32.3	32.6	---	---	---
	2.46%	2.11%	1.31%	---	---	---
SPI or SPI(t)	34.2	34.2	34.9	---	---	---
	3.57%	3.57%	5.79%	---	---	---
SCI	34.4	34.3	35.1	---	---	---
	4.33%	4.02%	6.26%	---	---	---
$PV_{current}$	---	---	---	46.6	---	---
	---	---	---	41.34%	---	---
$PV_{average}$	---	---	---	36.8	---	---
	---	---	---	11.44%	---	---
$EV_{current}$	---	---	---	37.4	---	---
	---	---	---	13.44%	---	---
$EV_{average}$	---	--	---	37.4	---	---
	---	---	---	13.44%	---	---
DPI	---	---	---	---	34.4	---
	---	---	---	---	4.29%	---
TPI	---	---	---	---	---	34.9
	---	---	---	---	---	5.79%
	---	---	---	---	---	35.1
	---	---	--	---	---	6.35%

Table 42. EDM(t) Results for the Example Project

Activities		Total Duration	Working days															
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Activity A		Planned	1	1	1	1	1	1	1	1	1	1						
			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
		Actual	1	1	1	1	1	1	1	1	1	1	1	1				
		Earned	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83				
Activity B		Planned	1	1	1	1	1											
			1.0	1.0	1.0	1.0	1.0											
		Actual	1	1	1	1	1											
		Earned	1.0	1.0	1.0	1.0	1.0											
Activity C		Planned											1	1	1	1		
													1.0	1.0	1.0	1.0		
		Actual													1	1	1	1
		Earned													1.0	1.0	1.0	1.0
Activity D		Planned						1	1	1	1	1	1	1	1			
								1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0			
		Actual						1	1	1	1	1	1	1	1	1		
		Earned						0.89	0.89	0.89	0.89	0.89	1.0	1.0	0.89	0.89		
Total Duration	Planned	Daily	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0		
		Cumulative	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0	26.0	27.0		
	Actual	Daily	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0		
		Cumulative	2	4	6	8	10	12	14	16	18	20	22	24	26	27		
	Earned	Daily	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	2.00	1.00		
		Cumulative	1.83	3.67	5.50	7.33	9.17	11.00	12.83	14.67	16.50	18.33	20.17	22.00	24.00	25.00		

9.11.2 *Scenario 2*

The second scenario represents the case where it is assumed that there is a disagreement between the contractor and engineer regarding the assessment of percent complete of activity D; additionally, activities E and F are assumed to have been performed not in accordance with the original planned schedule. As such, the Gantt chart in Figure 54 shows the updated schedule at the end of the 14th day.

In case the engineer applies the interval EV for work measurement (Forouzanpour et al. 2016), the resultant percent complete of activity D is 71% (whose calculation presentation is outside the scope of this work). This results in an EV amount equal to $1207, compared to $1275, the value reflected in the construction schedule update, as shown in Table 43. In addition, since activities E and F are violating the planned work execution sequence, the p-factor (calculated as the ratio of the cumulative EV corresponding to the original plan up to the status date to the total EV) (Lipke 2004) applicable to the example shows that 87% of the accrued EV has been realized in accordance to the schedule; as such, 13% of the accrued EV has occurred out of the correct activities sequence. The amount of rework projected by the end of period 14 as a result of poor sequencing adherence is therefore estimated to be $538 (whose calculation presentation is also outside the scope of this work). As such, this factor (i.e., p-factor=0.87), in combination with the engineer's assessment of completed work, can then be used to adjust the EV amount to a lesser amount, named "effective EV," which is estimated to be equal to $5,542.5, compared to the amount of $6,148.3, shown in the progress report submitted by the contractor.

The EVM method, as stated above, does not identify activities that belong to the critical path (or critical chain).

Table *44* assembles the data related to the application of the weight EV to the example shown in Figure 52. Accordingly, the weight EV method is used as a way to overcome this limitation. When applied to this example, it gives an SPI value of 0.90, compared to a figure of 0.92 when using the traditional EVM approach, while noting that both indicate a behind-schedule condition. (Demachkieh and Abdul-Malak 2018)

Since the ESM-1 is considered the most reliable method to forecast project duration, as demonstrated by this offered example and several research studies (Vanhoucke and Vandevoorde 2007; Elshaer 2013; Batselier and Vanhoucke 2015; Batselier and Vanhoucke 2015; Batselier and Vanhoucke 2015), its formula was adopted to forecast the expected-at-completion project duration, using the cumulative PV and certified EV amounts. To this effect, the EAC(t) is equal to 32.4 days, signifying a delay of 1.4 days. However, the CPM method yields an EAC(t) equal to 28 days, which indicates an ahead-of-schedule condition.

The values for the relevant metrics and indicators are calculated using the EAC(t) obtained from the ESM-1, in addition to the SV and SPI produced from the weight EV, shown in Table 45. At the end of period 14, the TSPI indicator has been calculated by reference to 31 days. Its value of 1.08 proposes, as it is less than 1.1, that the schedule delay may be recoverable if appropriate and effective corrective measures are applied, as recommended by the practice standard for earned value management (PMI 2011). Finally, a TCSCR value of 0.92 implies that the baseline duration for the outstanding works shall be crashed to 92% of its current value to achieve the project planned duration. Moreover, in order to finish this project according to the original baseline schedule, the productivity of the work must increase by 19% over the average performance.

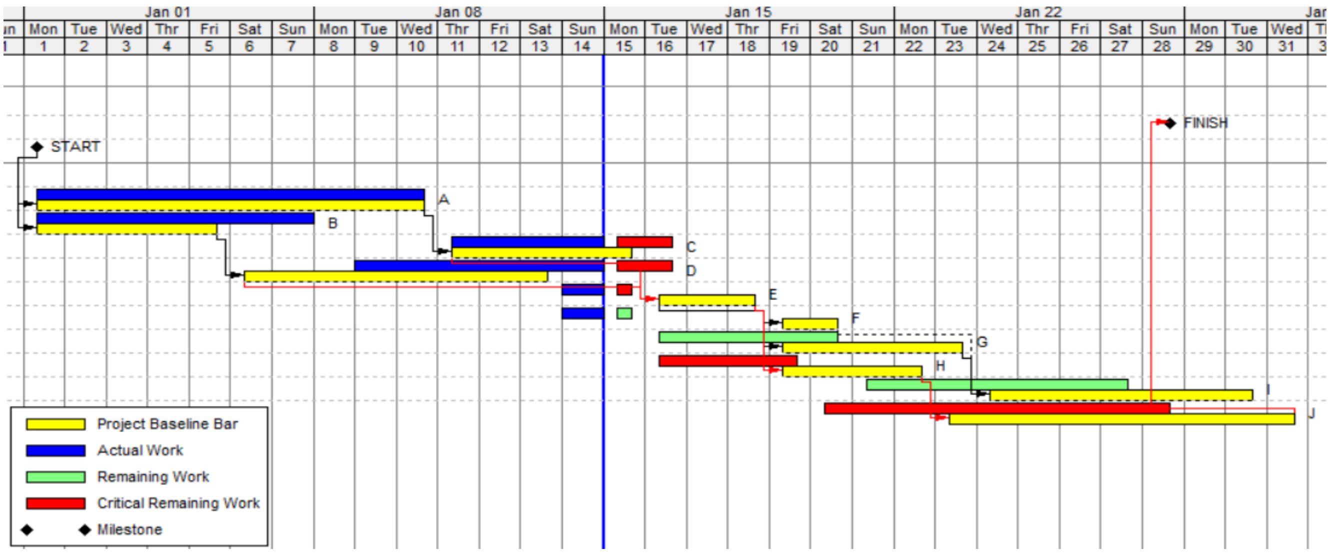

Figure 54. Project updated schedule at the end of period 14

Table 43. Project Data Extracted from the Scheduling Software (Scenario 2)

Activity Name	Baseline Project Duration	Actual Duration	At Completion Duration	Remaining Duration	Time Variance	PV	EV	AC	SV	SPI
	31	14	28	14	3	$6,020.0	$6,148.3	$6,250.0	$128.3	1.02
A	10	10	10	0	0	$2,000.0	$2,000.0	$2,000.0	$0.0	1.00
B	5	7	7	0	-2	$1,200.0	$1,200.0	$1,300.0	$0.0	1.00
C	5	4	6	2	-1	$1,120.0	$840.0	$1,000.0	($280.0)	0.75
D	8	6	8	2	0	$1,700.0	$1,275.0	$1,150.0	($425.0)	0.75
E	3	1	2	1	1	$0.0	$533.3	$500.0	$533.3	0.00
F	2	1	2	1	0	$0.0	$300.0	$300.0	$300.0	0.00
G	5	0	5	5	0	$0.0	$0.0	$0.0	$0.0	0.00
H	4	0	4	4	0	$0.0	$0.0	$0.0	$0.0	0.00
I	7	0	7	7	0	$0.0	$0.0	$0.0	$0.0	0.00
J	9	0	9	9	0	$0.0	$0.0	$0.0	$0.0	0.00

Table 44. Weight EV Calculations

Activity	Duration	TF_i	e^{-TF_i}	Weight (K_i)	BCWS	BCWP	Percent complete	Planned value	BCWP (k)	BCWS (k)	Traditional EV		Weight EV	
											SV	SPI	SV	SPI
A	10		1.00	12.90%	$2,000.0	$2,000.0	100%	$2,000.0	257.9	257.9	0.0	1.00	0.0	1.00
B	5		1.00	12.90%	$1,200.0	$1,200.0	100%	$1,200.0	154.8	154.8	0.0	1.00	0.0	1.00
C	5		1.00	12.90%	$1,400.0	$840.0	60%	$1,120.0	108.3	144.4	-280.0	0.75	-36.1	0.75
D	8		1.00	12.90%	$1,700.0	$1,207.0	71%	$1,700.0	155.7	219.2	-493.0	0.71	-63.6	0.71
E	3		1.00	12.90%	$800.0	$189.1	24%	$0.0	24.4	0.0	189.1	---	24.4	---
F	2		0.02	0.24%	$600.0	$106.4	18%	$0.0	0.3	0.0	106.4	---	0.3	---
G	5		0.37	4.74%	$1,300.0	$0.0	0%	$0.0	0.0	0.0	0.0	---	0.0	---
H	4		1.00	12.90%	$1,600.0	$0.0	0%	$0.0	0.0	0.0	0.0	---	0.0	---
I	7		0.37	4.74%	$1,900.0	$0.0	0%	$0.0	0.0	0.0	0.0	---	0.0	---
J	9		1.00	12.90%	$2,100.0	$0.0	0%	$0.0	0.0	0.0	0.0	---	0.0	---
Total	---	---	7.75	100%	$14,600.0	$5,542.5	---	$ 6,020.0	701.3	776.4	-477.5	0.92	-75.1	0.90

Table 45. Calculations of EVM Indicators

Input data	PD	31.0
	ED	12.6
	AD	14.0
	SPI	0.90
S-Curve parameters	$\beta_{1/2}$	0.60
	$r_{0.67}$	0.50
	γ	9.02
	y_∞	1.19
	y	0.40
	z	0.44
Schedule recovery indicators	EV improvement index	**1.19**
	TSPI	**1.08**
	TCSCR	**0.92**

CHAPTER 10

IMPLICATIONS OF EARNED VALUE ASSESSMENT AND MEASUREMENT IN CONSTRUCTION CONTRACT ADMINISTRATION

10.1 Preamble

The research outcomes revealed an opportunity for developing a number of particular provisions that can be adopted by contract administration practitioners when deciding on or drafting the construction contract conditions. As such, this chapter summarizes the related requirements to be met by contractors and the types of authority to be entrusted with the engineer for facilitating the employability of the proposed frameworks, thereby potentially minimizing the likelihood of conflicts and disputes to arise between owners and contractors on construction projects.

10.2 Introduction

Disputes are one of the leading causes which avoid the successful delivery of construction projects as they have antagonistic effects on cost, schedule, and quality (Fenn et al. 1997). As such, current studies dealing with construction disputes in North America, Europe, Asia and the Middle East, revealed that the main cause of disputes between owners and contractors is poor contract administration (ARCADIS 2014; ARCADIS 2015). Similarly, Kumaraswamy and Yogeswaran (1998) enumerated the main causes of disputes in construction projects, mainly related to contractual matters, to include variation orders, extension of time, failure of payment provisions, administration and management of contract clauses, and quality of technical specifications. Moreover, a comprehensive list of causes of disputes is established by Chan (2003). To this effect, the adopted sources of disputes were classified into three main categories: (a) contractual matters to include change orders, extension of time, quality of contract specifications, unfeasible owner expectations, and unclear contractual terms; (b) cultural matters, for instance, poor communication between the parties to the contract, and the confrontational approach in resolving disputes; and (c) legal matters including the conflict of laws, and the deficiency in the local legal system.

Construction projects are highly exposed to a large spectrum of uncertainties and the contract is inevitably incomplete due to its incapability to include procedures that tackle all the conceivable contingencies likely to be experienced during project execution stage. This calls for the need to have shared efforts between the project owner and contractor in order to solve the anticipated problems. To this effect, any unsettled issue arising there, which may escalate into a dispute, is considered as one of the most detrimental relationship destroyers between the parties to the contract (Cheung and Yiu 2006). Accordingly, it is claimed that the effective preparation of well-drafted contracts helps in achieving success of the delivery of the construction project in question (Podvezko et al. 2010). However, given that projects are nowadays more complex, there is an urgent necessity to prepare more inclusive contracts dealing with several financial, technical, and legal contingencies of the construction project (Bubshait and Almohawis 1994).

A well-prepared construction contract decreases the probability of disputes between owners and contractors to a great level by dealing with various possible risks, likely to be experienced during the construction stage (El-Hoteiby et al. 2017). In practice, numerous international forms of the standard general conditions are extensively used on international projects, for instance, the International Federation of Consulting Engineers (FIDIC), American Institute of Architects (AIA), and many others; though, they necessitate various add-ons/adjustments through contract particular conditions with the purpose of dealing with the precise conditions of each construction project (El-Hoteiby et al. 2017). In its most rudimentary form, a contract aims to reaffirm the duties, obligations, rights, responsibilities, and liabilities of each party to the construction contract (Demachkieh and Abdul-Malak 2019). That comprises setting out the provisions to enable the delivery of the construction projects, while respecting the project goals (Hughes and Greenwood 1996). Furthermore, in order to tackle the uncertainties expected to be experienced throughout the project construction phase, contract conditions are becoming more expounded with the purpose of having provisions to handle all probable contingencies and their impacts (Cheung and Yiu 2006).

Many of the recent international standard forms of contracts used in different areas of the world have facilitated the process of the contract drafting and helped in preventing possible risks likely to be experienced during the construction of the intended facility. Nevertheless, adjusting these general conditions by the addition of particular conditions is essential to help in serving the uniqueness of each construction project, with the purpose of preventing, or at least lessening possible construction disputes that might consume projects' resources (El-Hoteiby et al. 2017). To this effect, it is claimed that many project owners adopt standard conditions for preparing the construction contracts in order to decrease the possibility of misinterpretations, unjustifiable reimbursements, variation orders, and claims and disputes to ascend out of contractual performance (Bubshait and Almohawis 1994). Standard conditions of contract are likewise reported to decrease the inefficiencies connected with the repetitive process of contracts drafting and reviewing (Jergeas and Hartman 1994). Nevertheless, those general conditions can be modified or adjusted by the contract drafter, i.e. the project owner. This is achieved by providing particular conditions that are used to alter the general ones in order to match the contract conditions with the project's goals as regarded by the project owner, which potentially cause the owner's interests being well attended to with respect to those of the contractor (Laryea and Hughes 2009).

10.3 EV Significance for the Construction Contract Engineer

The construction schedule is needed by each participant involved in the construction project. As such, it is a necessity for the construction contract's engineer to monitor and control the project progress and for the owner and contractor to plan the project and construction financing obligations, respectively. As such, the schedule depicts the contractor's best intent for the construction of the works, including the contractual project planned duration, activities' logical sequencing restrictions, accompanied by resource and cost loading. Moreover, both the owner and his appointed engineer plan the required personnel during the course of construction, using the schedule prepared by the contractor (Booen 2000).

10.3.1 *Consenting the Contractor's Schedule*

Succeeding the contract award and shortly after getting the notice of commencement with the works, the contractor submits to the engineer a high-level preliminary schedule including satisfactory details for the project activities intended to be achieved in the first ninety days of the contractual planned project duration.

Consequently, and before the end of the 90-day period, the contractor is required to submit a comprehensive schedule. To this effect, this full-fledge schedule should embrace sufficient details for all activities that are planned to be executed during the overall project duration. Per se, the engineer, while not required to express his explicit consent to the submitted schedules, is nonetheless to alert the contractor of the degree to which any of those schedules are claimed to be not in compliance with the contract provisions. That being said, the engineer may show no disapproval to the schedule but without undertaking obligation for it (Bunni 2013). To be highlighted here is that there is no definite specification stipulating the review process that shall be conducted by the engineer, even though such a process is predicted to be completed within a reasonable time. Nevertheless, empirical S-curve prediction formulas and models have been developed (Cioffi 2005; Mavrotas et al. 2005; Blyth and Kaka 2006; Chao and Chien 2009; Chao and Chen 2015; San Cristóbal 2017), with the aim of judging the reasonableness of the time-phased expenditures curve, which is derived from the contractor's submitted schedules, being impartially evaluated against industry-accepted measures. Here, the curve of interest is the owner's cash flow prediction curve; which is produced by multiplying the work item's unit rate or price by the quantity of the work item that is planned to be executed in each of the contractor's schedule activities. As such, the investigation of the employability and forecasting accuracy of the proposed cash flow prediction models from the viewpoint of the project owners and their appointed engineers is detailed in Chapter 9. By way of closing, one can conclude that the consented schedule is the main instrument used by the engineer to understand the plan proposed by the contractor for delivery of the construction facility.

10.3.2 *Project Schedule Measurement and Control*

During project construction, the contractor is under the obligation to submit a monthly progress report incorporating a thorough description of the work progress along with a comparison between the planned (i.e., PV) and actual (i.e., EV) progress values, along with sufficient particulars of any events or circumstances which may endanger the project completion in accordance with the contract requirements, and the corrective or anticipated actions that are or shall be implemented to overcome schedule delays. Nevertheless, there are many scenarios justifying the effectuation of the reductions applied by the engineer to the sums proposed by the contractor in an interim payment certificate application (IPCA), including: (1) discrepancy on the measurement of executed work (i.e., quantity-related reductions), (2) technical performance or achieved quality of performed work (i.e., quality-related reductions), (3) possible rework in relation to the violation of the planned work schedule (i.e., schedule-related reductions), and (4) the failure of transferring the executed work to their respective schedule successors or internal customers (i.e., schedule-related reductions).

That is, work considered to have been executed by the contractor, as shown in the IPCA and reflected in the updated project schedule, which are both in congruence with the monthly progress report, is refused approval by the construction contract engineer, either by way of withholding or setting off sums from the sums to be certified by the engineer for successive settlement by the owner to the contractor (Demachkieh and Abdul-Malak 2019). That being said, the EV sum that was earned from the work executed by the contractor and being certified by the engineer up to a certain time instant, is used by the project owner for project progress monitoring purpose (Demachkieh and Abdul-Malak 2019).

Accordingly, the incompatibility between the EV sums that are certified by the engineer and those that are shown and mirrored in the project schedule updates generated by the contractor and which are usually accompanying the monthly progress reports is the primary motive that prompts the necessity for the construction contract's engineer to autonomously calculate an at-completion project duration figure (i.e., EAC(t)), with the aim of evaluating the project schedule performance. To this effect, several duration forecasting methods are proposed in the literature and may be relied upon by the engineer for this purpose. As such, the hypothesized framework shown in Figure 55 summarizes the various needs that shall be pertinently included in, and – more prominently – observed under, the construction contract, in order to permit a more informed EV measurement and assessment by the project owner or his appointed engineer.

The difference between the computed EAC(t) figure by using any of the proposed duration forecasting techniques and the project contractual planned duration (i.e., PD) is claimed to be reflecting the amount of expected delay. If this difference is positive (i.e., EAC(t) is greater than PD), the engineer may have the discretion through the contract, to depend on a group of schedule recovery indicators, as shown in Figure 55, along with specified thresholds for each index, with the aim of evaluating the extent of achievability of the project PD, and ultimately abetting the engineer in determining whether or not the recovery of liquidated damages (i.e., LD) shall be initiated. To this effect, the purpose of these tolerance limits is to generate warning signals in the case where the project progress surpasses a stated threshold, suggesting the possibility that the project exceeds its contractual duration, which may eventually prompt the effectuation of any suitable measure taken by the engineer. A detailed assessment of the proposed duration forecasting methods and metrics and their potential practical application are discussed in Chapter 10. Consequently, in the case where the contractor is incurring delays owing to events not enabling him to an extension of time, he is required to submit a revised schedule and an updated method statement incorporating the methods followed tor to expedite progress in order to finish the project in accordance with the PD. Otherwise, it could be reasonable for the owner to enforce the recovery of LD, due to the contractor's failure to respect the contractual completion duration.

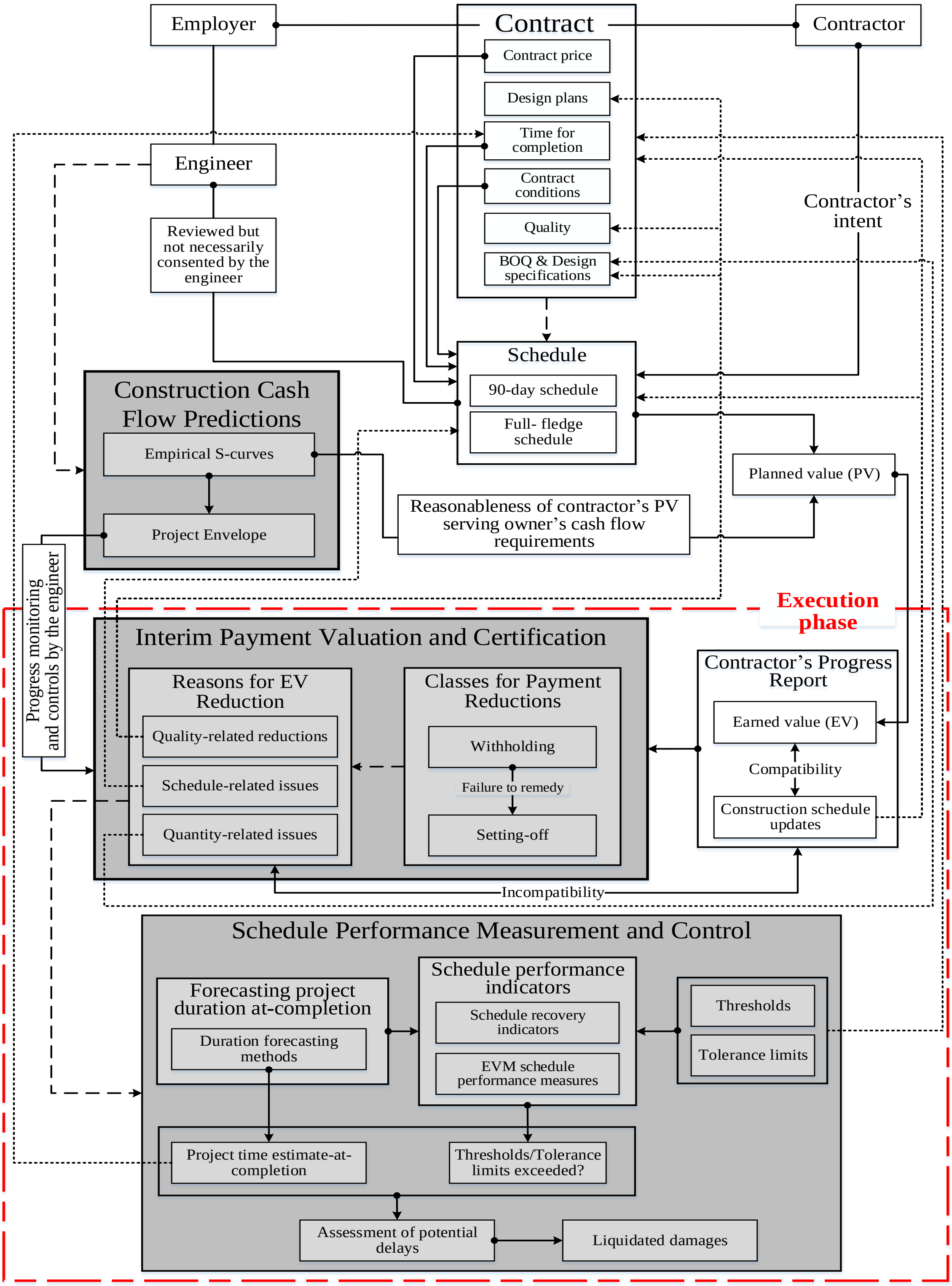

Figure 55. EV assessment and measurement framework

10.4 Requirements to be met by the Contractor

In practice, subsequent to the contract award and soon after receiving the notice of commencement with the works, the contractor is usually required to submit to the engineer a high-level preliminary schedule reflecting enough details for the activities that are planned to be executed in the first 90 days of the project duration. A full-fledge schedule is later submitted before the end of the first 90-day period, incorporating adequate details for all activities intended to be executed during the contractual construction duration. To this effect, the contractor is required to provide with the schedule submissions the rationale behind the “start-to-start” relationships between activities, if any, in order to support the engineer in the application of the customer EV method during the course of work execution, which is based on the inability to transfer the executed works to the internal schedule customers.

As such, the engineer, while not being under obligation to give an explicit consent to the schedule, is however to inform the contractor to the extent of which he finds any of these schedule submissions to be not compliant with the contract requirements. Aside from other specific checks the engineer may – by the virtue of observing due diligence – be required to perform in respect of the submitted schedule, assessing the reasonableness of the deduced cash flow associated with the inherent planned time-phased progress is a core task, viewed in practice as a prerequisite to the engineer ultimately consenting, or otherwise not objecting to, the schedule. Thus, the contractor is required to submit, along with the schedule-generated S-curve, various inputs, to include: (a) slope of the curve, (b) time at which half of the costs will be spent, (c) two values of costs and their respective occurrences, and (d) position of the inflection point. These inputs are adopted by the engineer to predict the construction work progress S-curve in the preconstruction stages, using the various empirical S-curves models and formulations encountered in the reviewed literature.

During project construction, the contractor is required to submit a monthly progress report incorporating a thorough description of the work progress along with a comparison between the planned (i.e., PV) and actual (i.e., EV) progress values, along with sufficient particulars of any events or circumstances which may endanger the project planned completion date, and the corrective or anticipated actions that are or shall be implemented to overcome schedule delays. To this effect, the engineer may instruct the contractor to submit, along with the construction schedule updates accompanying the monthly report, the following: (a) achieved progress on the "start-to-start" activities, (b) PV corresponding to the tasks associated with ES, (c) EV at actual reporting time corresponding to and limited by the planned tasks, and (d) cumulative PV amounts.

Figure 57 shows the related requirements to be met by contractors and the types of authority to be entrusted with the engineer for facilitating the employability of the proposed frameworks, thereby potentially minimizing the likelihood of conflicts and disputes to arise between owners and contractors on construction projects.

10.5 Inputs determined by the Engineer

During project execution, there are many reasons, summarized in Figure 56, as to why the engineer may resort to possible reductions to the EV amount purported by the contractor in the monthly progress report, as deduced from the accompanying construction schedule updates. As such, the engineer may exercise withholding or setting-off certain sums from amounts presented by the contractor as reflecting the value of executed work allegedly earned by the owner at the time of reporting.

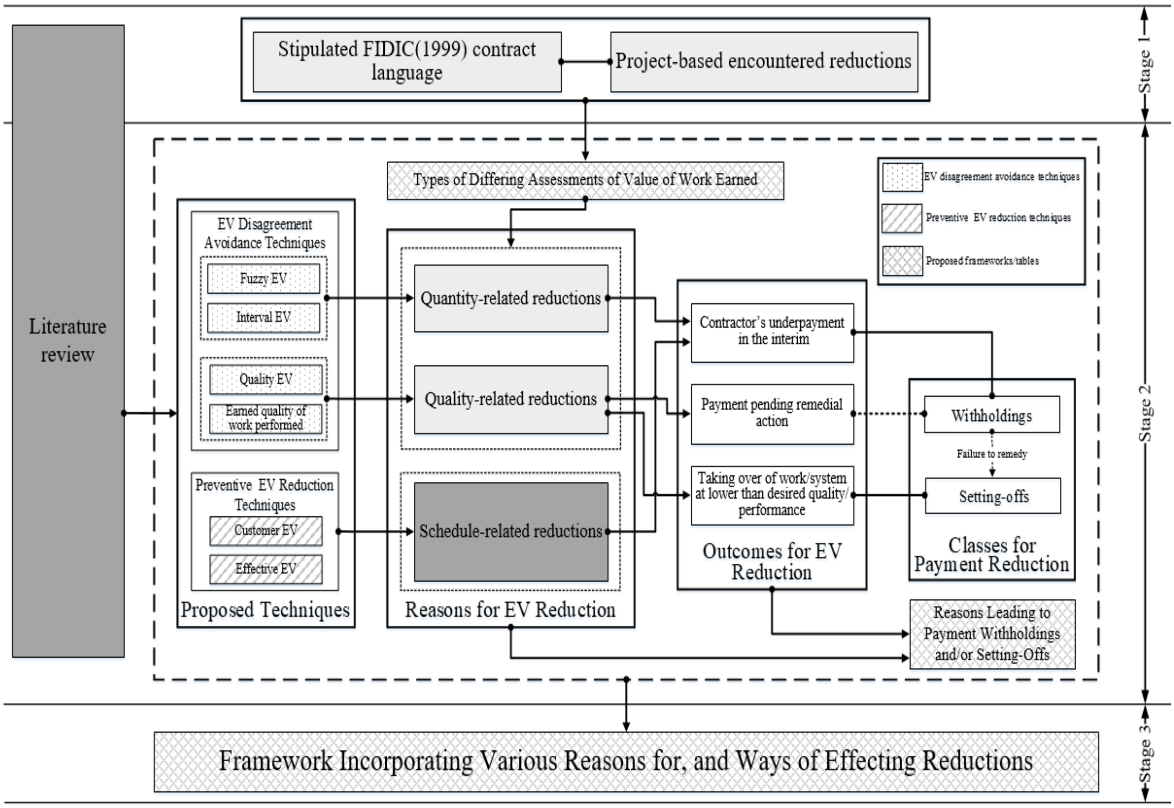

Figure 56. Tactics for avoiding EV disagreements and techniques for mitigating preventive EV reductions

The inconsistency in quantity measurement is considered to be the first reason justifying the reduction applied by the engineer to the EV amount reflected in the construction schedule, as summarized in Chapter 8. This may lead to effecting withholdings related to: (a) difference in the method of measurement for taken-off quantities, (b) executed work that is yet to be inspected by the engineer, and (c) overstated BOQ quantities in a lump-sum type of contract. Figure 56 summarizes the various sources of information used to deduce the various classes of possible reduction to be applied by the engineer while certifying the amount due to the contractor.

The measurement of work shall be considered as a continuous process to be jointly performed by the contractor in preparation for submitting an IPCA and by the engineer with the aim of certifying the payment due to the contractor, in order to lessen probable discrepancy in evaluated progress/quantities that may arise when measurements are made independently. Integral to this process is that any work being measured have been properly examined and inspected by the engineer, and consequently, approved to be included in the payment statement in the cycle on hand. As such, inspecting the work by the engineer shall be performed without unreasonable delay. In this case, more accurate contract language shall be introduced in the contract particular conditions or specifications requirements, determining the authority of the engineer to legitimately permit payments for the quantities that are yet to be inspected, to read as follows:

For work executed in timely and duly fashion by the Contractor and whose inspection has been unduly delayed by the Engineer, no withholding shall be effected by the Engineer to the uninspected works as per Sub-Clause 14.6 [*Issue of Interim Payment Certificates*]. However, no such activity shall relieve the Engineer from his authority to allow an Interim Payment Certificate to be corrected or modified in any subsequent Payment Certificate, as per the terms stipulated under Sub-Clause 14.6 [*Issue of Interim Payment Certificates*], in case the quality of accomplished work being deemed unsatisfactory, as per Sub-Clause 7.5 [*Rejection*].

The risk induced from such an action is alleviated by the fact that the engineer is eligible to make any proper modifications or rectifications to the previously issued payment certificates. To be noted is that such a practice, when articulated in the construction contract, has the potential to contribute in preventive extreme project financing costs and decrease the possibility of those additional costs to be the issue of future claims requested by the contractor. This can also assist in eliminating the incompatibility between the quantities used for evaluating the total earned value and those used for reflecting the progress in the activities of the project schedule. to conclude, this practice will have the effect of discouraging the engineer from intentionally postponing the inspection of performed work, given that the notices for inspections have been appropriately and timely made by the contractor and respecting the contract requirements with respect to the construction schedule regularly updated by the contractor.

Similarly, when it is mutually recognized that the total field quantity of a certain work item has undeniably been completed, it will be only impartial that the work item contract lump-sum price's subtotal be fully included in the contemporary interim payment certificate. Such a practice may reduce the likelihood of a deceptive underestimation to the owner of the total EV depicting the achieved progress. However, if it is obvious that there has been an error, and more work is still being needed for the work item on hand, the risk of contractor's overpayment is reduced again by the right of the engineer to correct any previously issued payment certificate. The following shall be prescribed in the contract conditions:

If the whole actual measured quantities of an item of work included in the Contract, as per the terms stipulated under Sub-Clause 12.1 [*Method of Measurement*], is changed in a reasonable negative fashion from the estimated total quantity of this item in the Bill of Quantities or other Schedule, the Engineer shall include in the interim payment Statement the contract lump-sum price's subtotal corresponding to the work item in question, that is, the quantity of this item in the Bill of Quantities or other Schedule multiplied by the specified rate for this item. However, this does not affect the authority of the Engineer to make further deductions or to correct any subsequent Payment Certificate, as per the terms stipulated under Sub-Clause 14.6 [*Issue of Interim*

Payment Certificates]. Yet, the Contractor is not relieved from the onus of verifying the quantities for the said item of work.

Another reason for effecting EV reductions may be in connection with integrative work items, where an item's unit rate covers many stages of work progress for the item in question. The subjectivity usually inherent to work progress valuations pertaining to such work items can be diminished through the reliance on proposed methods (Demachkieh and Abdul-Malak 2019), such as the "fuzzy EV" (Moslemi-Naeni and Salehipour 2011; Moslemi-Naeni et al. 2011; Mortaji et al. 2013; Naeni et al. 2014) and "interval EV" (Forouzanpour et al. 2016) techniques. In the case where the fuzzy EV is to be adopted, the engineer shall specify the α-cut value and the membership function that transforms the linguistic term used to express the progress of a certain activity into a fuzzy number. The fuzzy EV method is applicable in the case where a schedule of value (SOV), in which percent unit rate values associated with the concerned progress stages are specified, is not stated in the contract. As for the interval EV method, it can be used in the case where several decision-makers, having assigned weights determined by the engineer, are requested to jointly help in producing a valuation of the accomplished progress based on the stages specified in the work item's SOV.

Additionally, in case the contractor fails to deliver the performed works according to the specified technical performance or quality requirements, the engineer may resort to provisionally decreasing the EV amount, either by reducing the quantities executed to date or the item's subtotal, until the contractor remedies the defective work in compliance with the contract requirements. To this end, a number of techniques can be used for assessing the achieved quality of executed work (Demachkieh and Abdul-

Malak 2019), namely (1) quality EV (Dodson et al. 2015), and (2) earned quality (Paquin et al. 2000). To be noted is that the application of the earned quality technique is dependent on the consented construction schedule, with its fundamental principle being based on providing a sturdy connection between the schedule's work breakdown structure and the quality breakdown structure. The earned quality method requires that a formal approach be agreed to between the parties, in order to quantify the (1) criteria's subjective values, (2) relative weight of each criterion with respect to the overall quality objective, (3) estimated contribution of each schedule activity to its related quality criterion, (4) value function for each criterion, and (5) number of schedule-embedded control points.

Finally, the resulting EV amount, deemed by the engineer to have been correctly or objectively measured and assessed, may eventually undergo additional reductions with respect to schedule-related criteria (Demachkieh and Abdul-Malak 2019). That is, when any performed work, as duly reported by the contractor, is found to have been executed out of the planned sequence stipulated in the consented construction schedule, or not to have suitably served other activities of the schedule with which interdependencies exist (i.e., internal customers), the adopted EV figure may accordingly be decreased further by the engineer. This can be done through the employment of the "effective EV" (Lipke 2004) and "customer EV" (Kim et al. 2015) methods. The application of the customer EV requires that the contractor submits, as shown in Figure 57, the following: (a) the rationale behind the "start-to-start" relationships between activities, if any, (b) the achieved progress on those activities. however, the application of the effective EV requires that the contractor provides the engineer with the following input data: (a) PV corresponding to the tasks associated with ES, and (b) EV at actual reporting time corresponding to and limited by the planned tasks.

In summary, when work, considered to have been executed by contractors, turns out to be denied certification by the engineer, this results in a delay of receipt, if not partial or full denial, of payment to the contractor. The final EV figure, ultimately certified by the engineer in every payment cylce, in addition to the cumulative PV amounts that was planned to be achieved by that time, is used for allowing the generation of duration forecasts. Table 46 lists the related requirements to be met by contractors and the types of authority to be entrusted with the engineer, along with proposed EVM-based techniques and tools.

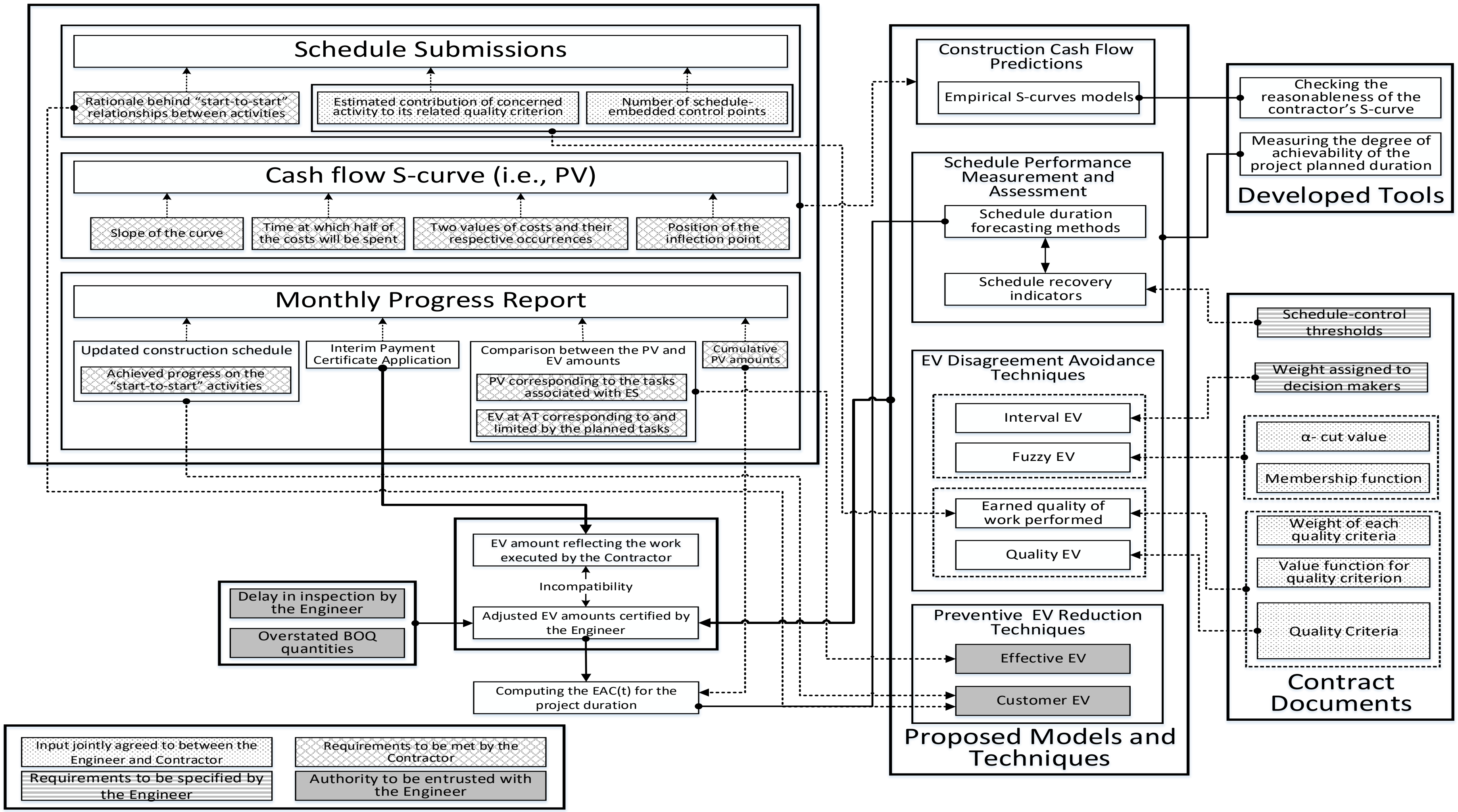

Figure 57. Implications of EV assessment and measurement in construction contract administration

Table 46. Requirements to be Met by the Contractor and Engineer for EV Assessment and Measurement

Project Stages	**Requirements to be met by the Contractor (√)**	**Construction Flow Predictions Using Empirical S-Curves**	**Interim-Payment Valuation and Certification**								**Schedule Performance Measurement and Assessment**		**Inputs determined by the Engineer or agreed to between the Contracor and Engineer (x)**
			Discrepancy in quantity measurement				Quality- related reasons		Schedule-related reasons		Computation of EAC(t)	Degree of achievability of PD	
			Fuzzy EV	*Interval EV*	*Overstated BOQ quantities*	*Delay in inspection*	*Quality EV*	*Earned Quality*	*Customer EV*	*Effective EV*	*Schedule forecasting methods*	*Schedule recovery indicators*	
Preconstruction Stage	Rationale behind the "start-to-start" relationships between activities							x	√				Estimated contribution of concerned activities (i.e., related to specific work items) to their related quality criteria
	Number of schedule-embedded control points for specific activities (i.e., related to specific work items)							√					
	Slope of the curve	√											
	Time at which half of the costs will be spent	√											
	Two values of costs and their respective occurrences	√											
	Position of the inflection point	√											
Construction Stage	Achieved progress on the "start-to-start" activities								√			x	Schedule-control thresholds
	PV corresponding to the tasks associated with ES			x						√			Weight assigned to decision makers
	EV at AT corresponding to and limited by the planned tasks		x							√			α- cut value
	Cumulative PV amounts		x								√		Membership function
								x					Weight of each quality criteria
								x					Value function for quality criterior
							x	x					Quality criteria
									√				
Authority to be entrusted with the Engineer					●	●			●	●	●	●	

CHAPTER 11

SUMMARY, CONCLUSIONS AND FUTURE WORKS

11.1 Preamble

This chapter summarizes the main outcomes of this thesis in addition to the research limitations and the intended future works.

11.2 Summary and Conclusions

The earned value management (EVM) method is a well-established tool intended for monitoring, evaluating, and controlling the progress of projects of several types and sizes. However, the literature has steadily revealed limitations related to the employability of this technique in the construction industry. To this effect, this research explores and verifies the significance of project controls in relation to project success. Whether from the perspective of all 62 adopted studies or that of the 33 studies concerned with the construction-type projects, the project controls CSF was found to have received the highest citation frequency and to have been ranked with a high level of criticality by 50 percent of those studies that offered any form of ranking. Accordingly, this calls for the continued need for improving the efforts, systems, or mechanisms needed for endorsing suitable planning, monitoring, and controls for projects in various industries, and more especially in the construction sector.

This research work further provides a review of the historical genesis, evolution, and standardization of the EVM technique, along with a thorough in-depth analysis of the limitations and challenges reported in 81 reviewed studies to be hindering EVM application. In addition, it specifically investigates the chronological evolvement of the EVM limitations, while shedding light on those still cited – over the past five years – as remaining unresolved. Twelve general headings were ultimately adopted to reflect the deduced EVM limitations, with the headings linked to the quality of inputs (namely, faulty results in calculating the percent complete of executed work) and outputs (namely, mistaken results of estimate-at-completion forecasts) receiving the highest citation frequencies of 21 and 24, respectively. Furthermore, this research presents a proposed classification of the gleaned literature-based limitations into six classes of barriers, four of which are found to be related to EVM technical aspects, whereas the other two are found to be concerned with EVM practical implementation issues. These limitations offer an elaborate critical synthesis of EVM main shortcomings, which was used as the foundation for mapping the improvements encountered in the literature, as a step towards better packaging the enhanced capabilities of the technique for extending its employment on construction projects of various organizational deliverance structures and contractual frameworks.

Moreover, this research work presented the breakdown of the encountered improvements, reflecting their distribution over the three main EVM sets of metrics: “key parameters”, “performance indicators”, and “forecasting parameters”. The analysis offered descriptions of these relevant improvements, while reflecting their classification into three main areas of “information management”, “graphical representation,” and “expressions or formulae”. It further filtered and classified the main EVM proposed improvements encountered in 137 adopted studies and mapped them to the identified limitations. The exceptional significance of the top two limitations to achieving better EVMS employability was confirmed by the fact that the top two frequencies (16 percent and 14 percent) of reported improvements were found to have been associated with these two top-ranked limitations.

As such, numerous improvement studies have been found to tackle the forecasting of the project-level cash flow in the preconstruction stages, that may be used to support that provided from the traditional schedule-based approach, using prediction techniques involving neural network and regression analyses as well as third-degree polynomial and sigmoid functions. The encountered models rely on an array of input variables, including the type of work and location, degree of project simplicity, team competence, curve slope and inflection point, and specific time-money milestones, among others. The applicability and prediction accuracy of the proposed planned progress estimation models from the perspectives of construction project owners and their appointed contract engineers are investigated. In this regard, data related to the earned value figures achieved from work progress actually made on a completed residential project were used for forecasting the contractor's S-curve using the adopted models. The performed sensitivity analyses allowed the determination of those ranges of the input factors that satisfy an acceptable degree of prediction accuracy. The use of the progress estimates models and mathematical formulae shall be of value to the contract engineer involved in administrating construction contracts, through stipulating a reasonable approach for checking the schedule-based S-curve (i.e. planned value curve) submitted by the contractor. The ultimate implication is intended to be one that better helps in owners' initial financial planning and more objectively judging the analytical schedule-based cash-flow estimate, thereby serving the ultimate critical task of conducting project monitoring and control.

During project execution, the contractor is required to submit a monthly progress report that includes: (1) a comparison between planned (i.e., PV) and actual progress (i.e., EV), (2) a description of any events or situations which may endanger the project planned completion date, and (3) a summary of the mitigation actions taken in order to overcome schedule delays, if any. However, there are many reasons as to why work considered to have been accomplished by contractors, as presented in the interim payment certificate application (IPCA) and reflected in the updated schedule (both accompanying the monthly progress report), is denied certification by the engineer. Accordingly, this research work addresses the conditions that could trigger the potential withholding or setting-off by the engineer of amounts that are otherwise viewed as due by the contractor. A framework highlighting a set of practices that are conducive to avoiding disagreements as to the measurement of executed work is offered. Also incorporated in the formulated framework are several reasons or conditions that can be viewed as justifying the effectuation of payment reductions, either by way of withholding or setting off sums from the amounts to be certified on a periodical basis by the engineer for subsequent reimbursement by the owner to the contractor. These have been identified to include: (1) disagreement on the quantification of executed work, (2) quality or technical performance of executed work, (3) potential rework caused by the violation of the planned work execution sequence, and (4) the inability to transfer the performed work to internal schedule's customers. The outcome of the proposed framework is one that emphasizes the need to impart cooperation between the involved participants and to instill transparency and objectivity into the processes and techniques that may be adopted for the purpose of administrating the issuance of interim payment certificates, with the anticipated benefit ultimately being the avoidance of payment-related disputes.

As such, the incompatibility between the EV amounts certified by the engineer and those that are reflected in the construction schedule update submitted by the contractor in congruence with the monthly progress report is the main reason that triggers the need for the engineer to independently compute an EAC figure for the construction duration (EAC(t)), for the purpose of assessing the project schedule performance. Several duration forecasting methods may be relied upon in this regard. As such, an extensive number of techniques dealing with ways and means that improve the forecast of the at-completion project duration have been proposed in the reviewed literature. That said, a framework that can systematically guide the construction contract engineer in measuring and controlling project schedule performance is then developed. The proposed framework aims at making this control tool better accustomed and suited for exercising construction schedule control. In that respect, it accounts for the several emergent extensions, involving variant metrics that have been developed in complement to other proposed EVM-compatible methods, in order to offer better means for studying the project schedule performance and measuring the total expected delays. A notional project has been used to demonstrate the practicability of the majority of the steps incorporated under the proposed framework. The proposed framework shall be of value to the contract engineer involved in administrating construction contracts, through stipulating an integrated set of methods and metrics for more reasonably forecasting the remaining project duration. The ultimate implication is intended to be one that helps in justifying a fair initiation of the recovery of liquidated damages (LD) in case of schedule delays, thereby minimizing the likelihood of conflicts and disputes to arise between owners and contractors on construction projects as a result of such LD-enforcement actions.

As such, the hypothetical example provided in this analysis track does not intend to verify that the proposed time forecasting methods produce more accurate forecasts than the CPM-based results. However, it clearly appears that ESM-1 outdoes the other proposed EVM forecasting methods by providing duration figures satisfactorily accurate to be usable. To be noted is that the network schedule remains the main and most reliable source of schedule analysis, in case there is no effectuation of reductions by the engineer to the sums proposed by the contractor in a submitted IPCA.

All of the techniques discussed in this analysis track ultimately have the same purpose, which is measuring anticipations or expected delays in project schedule by predicting at-completion duration in time units. The literature assessments of these methods when used as a tool to control project schedule offer minor advantages for one method over another, depending on the construction project circumstances. No better or best method was certainly confirmed to be applicable to all probable scenarios for the project's progress over the complete duration lifespan. Therefore, given that no project forecasting method is confirmed as being robust in terms of always providing satisfying and reliable results over each stage of the whole project construction stage, the engineer should prudently select the forecasting method deemed most practicably appropriate, as further explained below, given the circumstances on hand, in order to decide when the current schedule project performance is to be viewed as acceptable or not. As such, only when delays are deemed unrecoverable, a fair initiation by project owners of the recovery of liquidated damages can then be justified, as it shall be analytically deduced from the analysis of the contractor's schedule and supported by the completion predictions as proposed in this work.

For the example project, it was found that the ESM generally outperforms other project duration forecasting methods. This is not altogether surprising because ESM adopts an instantaneous metric (i.e., ES), and the engineer frequently measures the schedule performance based on the project data to date. However, it is advisable to use smaller time increments for the reporting periods to verify the assumption of linearity, thereby decreasing the possible forecasting errors.

Furthermore, one could conclude that in the project middle and late execution stages, the use of PVM is not preferable (due to the assumption of linear planning distribution), given the fact that, in a real project environment, it is rarely true that the planned value is linear, but – instead – it follows the famous S-shaped curve. The PVM provides inaccurate completion time figures that are less than the actual time once the planned duration is surpassed, i.e., once the project becomes overdue. To be noted is that, in the early execution stages, the duration forecasting is too pessimistic when using the WRPM, since the work rates (i.e., PV and EV) are usually low in a project's S-curve. Moreover, the WRPM fails to provide an accurate duration forecast in two cases: (1) $PV_{t+1}=PV_t=BAC$ (i.e., overdue project) and (2) $EV_{t+1}=EV_t$. In such cases, the denominator, i.e., work rate, is zero, and ED is undefined. As such, the ETM can serve as a suitable approach to estimate the at-completion project duration in case the project surpasses its duration target. In addition, the time prediction results using ETM of WR_P are the same as the prediction results obtained using EDM. Furthermore, the duration prediction results using ETM of WR_S are approximately the same as the prediction results obtained using ESM. To this effect, both EDM and ESM provide reasonably stable and adequately accurate predictions.

Additionally, it is the authors' belief that EDM(t) is bound to produce reliable forecasts of at-completion project duration. However, the authors also recognize the challenges involved with the difficulty in the understanding of the new EDM concepts (i.e., TED and TPD) by construction practitioners; that is, the use of EDM(t) is tedious and a time- and resource-consuming process, especially in real construction projects where a huge number of schedule activities is involved.

By way of summarizing, this analysis track tackles one of the critical schedule-related aspects of construction contract administration, being that related to the project schedule performance measurement and control. It offers a framework highlighting the several requirements that need to be properly incorporated in, and – more prominently – observed under the construction contract, in order to allow a more informed schedule performance measurement and control by the contract engineer. Also incorporated in this chapter are several scenarios that can be viewed as assisting the engineer in deciding on the realistic EV amount that may be deemed representative of the value of work claimed by the contractor to have been accomplished; with the purpose of making informed evaluations of schedule performance measurements. The outcome of the presented research work is one that emphasizes the need to benefit from the presented integrated set of methods and metrics, with the aim of more judiciously predicting the at-completion project duration. The ultimate implication is intended to be one that supports a systematic and transparent evaluation for justifying a fair initiation by project owners of the recovery of liquidated damages in case of expected schedule delays. By employing such a sensible approach in support of considering the levying delay LDs sums, the possibility of conflicts and disputes to arise between owners and contractors on construction projects are prone to be diminished.

By way of concluding, this research work offers an accurate verbalization of the terms that may be included under the contract particular conditions, addressing the attributes of the prescribed roles of both the engineer and contractor. By introducing such adjustments, the interests of the parties to the contract may possibly end up being better served, ultimately helping in diminishing (or even preventing) the likelihood of disagreements and disputes to emanate between owners and contractors during the course of construction.

11.3 Limitations

The main limitations encountered in this research work are the following:

- The generalizability of the research findings depends upon the suitability of the research methods adopted. A limitation of this study is the significant reliance on questionnaire as the dominant data collection methodology in the adopted publications and ultimately the limited number of case studies and interviews in validating the importance of project controls in relation to project success. Questionnaires do not give the researcher the advantage to follow up concepts and illuminate concerns, one of the main strengths of interviews. In brief, while using questionnaires, there is some level of researcher imposition, in a way that allow the researchers to make decisions and assumptions as to what is and is not significant. To this effect, a "multi-method" method, which allows the combination of questionnaires with, for example, interviews or case studies for better data collection, is thus proposed. As such, integrating combined data collection methodologies could have improve the generalizability of the research findings. Moreover, this study does not specify the type of organization in which the data collection process occurred, namely public or private.
- Four high-end building projects completed in the Middle East region were used in order to demonstrate the practicable application of the decision-aid frameowks. To be noted is that those projects are medium-size projects and executed in the same geographical area. Thus, it will be benefical to consider the

applicability of the propsoed frameworks on megaprojects (i.e., projects having a budget greater than $1 billion), and projects completed in a different geographical area (i.e., Europe or North America).

11.4 Future Works

During the course of conducting this research, the following issues were recognized as prospective areas for future investigation:

- Software applications that integrate the functions of generating the project cash flow estimates, and computing the project time estimate-at-completion into one earned value management tool, that can be used by the engineer to exercise project monitoring and controls during the course of work execution.
- The results of the study show the significant potential for investigating the applicability of the decision-aid frameworks for untraditional project delivery methods (integrated project delivery approaches, design-build projects, public private partnership projects, multiple trade contractors).

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