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EDM: Earned Duration Management, a new approach to schedule performance management and measurement

Homayoun Khamooshi *, Hamed Golafshani [1]

Department of Decision Sciences, School of Business, The George Washington University, Washington, D.C. 20052, United States

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Abstract

The concept of schedule monitoring and control as one of the most important functions of project and program management has not been fully exploited. One possible explanation could be the dominance of the Earned Value Management System (EVMS, also known as EVM). EVM was originally developed as a cost management and control tool which was extended to track the schedule as well. EVM and its derivatives (e.g. Earned Schedule) use cost as a proxy to measure schedule performance to control the duration of the project. While there is a correlation between schedule, cost, quality, and scope of a project, using cost to control duration has proven to be misleading. In contrast to Earned Value and Earned Schedule, the authors have developed the Earned Duration Management (EDM) in which they have decoupled schedule and cost performance measures and developed a number of indices to measure progress and performance of schedule and cost, as well as the efficacy and efficiency of the plan at any level of the project. These new indices are easy to understand, have wider applications, and can be used by contractors, clients and the scheduling offices to assess and measure schedule performance. The newly developed duration performance measures are all schedule-based and can be used for forecasting the finish date of the project.

Keywords: Earned Value; EVM; Earned Schedule; Earned Duration; Earned Duration Management; EDM; Schedule management; Monitoring and control; Efficiency; Performance measurement; Forecasting; Estimation index; Performance and progress index; Project management

1. Introduction

Project management is about being in control, making sure that the risk of failure is minimized by keeping the project in alignment with the developed project plan. It is also about making informed decisions for adjustments to the plan when required.

Project monitoring and control, on the other hand, is the process of observing the implementation of the project plan, collecting data on implementation, conducting analysis by comparing the planned values against the actual implementation records, and using this information to keep the project on track. One of the most widely accepted control systems used by practitioners in project management field is referred to as the Earned Value Analysis (EVA) or Earned Value Management System (EVMS) or in short EVM.

The evolution of EVM, for the most part, has been focused on cost management, control, and financial analysis for decades (Brandon, 1998; Fleming and Koppelman, 2004; Kim et al., 2003). This analysis mechanism was developed based on a set of 35 criteria, called the Cost/Schedule Control Systems Criteria (C/SCSC). Later the C/SCSC method was modified to accommodate ease of use and pragmatism simply because the original version was too bureaucratic and complicated. Also, the organizations were reluctant to spend a lot of time and money on setup costs for its implementation (GAO, Significant Changes Underway in DOD's Earned Value Management Process, 1997). The U.S. government and the associated agencies opted for making the use of EVM a requirement of government contracting

* Corresponding author at: Department of Decision Sciences, Funger Hall, Suite 415, The George Washington University, Washington, D.C. 20052, United States. Tel.: +1 202 994 4862; fax: +1 202 994 2736.
E-mail addresses: hkh@gwu.edu (H. Khamooshi), gol@gwmail.gwu.edu (H. Golafshani).
[1] Federal Aviation Administration.

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and bidding for projects (General Service Administration, Department of Defense, and National Aeronautics And Space Administration, 2006). There is abundance of literature on EVM and its basic principles and definitions (e.g. see Anbari, 2003; Fleming and Koppelman, 2010).

In short, a clear project scope, a well-defined schedule, and detailed budget lay the foundation for implementing EVM and its derivatives for a project. The budget plan and schedule are to be set for the lowest level of Work Breakdown Structure (WBS) elements to be monitored and controlled. Such a plan will be considered a baseline for the project and the progress will be assessed against that baseline (Cioffi, 2006).

EVM defines parameters to enable monitoring and controlling of projects. EVM defines the Planned Value (PV) as the value that is planned to be spent for executing the work according to the original schedule at any point in time. Previously, PV was denoted as BCWS or Budgeted Cost of Work Scheduled. Earned Value (EV) is the monetary value of the progress made (work completed) at a certain point in time. Previously, EV was denoted as BCWP or Budgeted Cost of Work Performed. Actual Cost (AC) represents the monetary value of what has been expensed to achieve the progress made at a certain point in time. Previously, AC was denoted as ACWP or Actual Cost of Work Performed.

Prior to the dominance of EVM, PV and AC were mainly the determinant factors in measuring project progress. However, these measures were not enough for showing the entire picture and determining whether the project was getting the worth of what it was expending. EVM provides various performance measures that are designed to assist with monitoring and controlling the project depending on the type of information needed. For instance, Cost Variance (CV) is utilized to represent the difference between how much was actually spent and the value earned (EV) through the work performed. In that case, CV is defined as:

$$CV = EV - AC \tag{1}$$

Hence, a negative value points out that the project has spent more for the executed activities than what it is worth. To the contrary, a positive value indicates that the project has spent less to gain the value of the executed work. In general, EVM and its derivatives use positive values to represent favorable signs of progress and negative values as unfavorable signs. The Schedule Variance (SV) per EVM has traditionally been used as an indicator which represents whether the project is on schedule or not:

$$SV = EV - PV \tag{2}$$

Similar to CV, a negative SV means that the project is behind the planned schedule, whereas a positive SV represents a project that is ahead of schedule. It is to be noted that, this schedule performance measure is not very reliable when the cost of delayed critical activities is a fraction of the cost of other activities. Hence, the delay in completion of these critical activities does not present much of a variance! Additionally, when the activities finish, SV equals to zero as both EV and PV are the same upon completion of the activity. This outcome is irrespective of whether the actual duration of the activity happened before or after its planned completion date. There are other widely used performance measures that calculate project efficiency, or forecast a future state of the project, among other things. These include, Cost Performance Index:

$$CPI = \frac{EV}{AC} \tag{3}$$

and Schedule Performance Index:

$$SPI = \frac{EV}{PV} \tag{4}$$

Despite EVM's numerous benefits and its widespread use, there are some concerns with utilizing EVM as the only tool for monitoring and controlling cost and schedule of a project. Paige in a lucid paper some 50 years ago proposed the separation of concerns with schedule from concerns with budgetary matters (Paige, 1963). It was not till a few years ago where researchers and practitioners brought up the issues with use of EVM for schedule management. The cost management component of EVM is considered to be very effective whereas its schedule aspect has been questioned conceptually in the last few years. Fleming and Koppelman (Fleming and Koppelman, 2004) recommend that Schedule Performance Index should be used just as a warning mechanism and not as a real tool to analyze how the project is performing with regard to schedule.

Lipke argued (Lipke, 2003) that "from the time of the development of the EVM indicators, it has been known that the schedule indicators are flawed and exhibit strange behavior over the final third of the project when performance is poor". He introduced the concept of Earned Schedule, ES, as an extension to EVM. This research shows that SPI is not an accurate or reliable measure of schedule performance. The reason given is the fact that any finished activity has an SPI equal to one. This perfect score is irrespective of the actual performance of the completed activity. To improve the performance of SPI, the Earned Schedule method converts the Earned Value at a given point in time into its equivalent duration (on the PV or planned value graph) required to achieve that Planned Value. Fig. 1 demonstrates this conversion on a conceptual EVM graph.

Using this approach, the method provides the Earned Schedule, $ES(t)$, for the project. Therefore, Earned Schedule could mathematically be defined as adapted from (Jacob, 2006) as:

$$\text{Find t such that } EV \geq PV_t \text{ and } EV < PV_{t+1(calendar\ unit)}$$
$$ES(t) = t + \frac{EV - PV_t}{PV_{t+1(calendar\ unit)} - PV_t} \times 1\ (calendar\ unit) \tag{5}$$

where $ES(t)$ is Earned Schedule at the status date, EV is the Earned Value at the status date, PV_t is the Planned Value at time instant t, and the calendar unit represents the unit in which duration t is measured. The corresponding duration from the beginning of the project till status date is generally defined as Actual Time (AT) or elapsed time. We use the term Actual Duration (AD) in place of Actual Time for consistency and accuracy in this paper.

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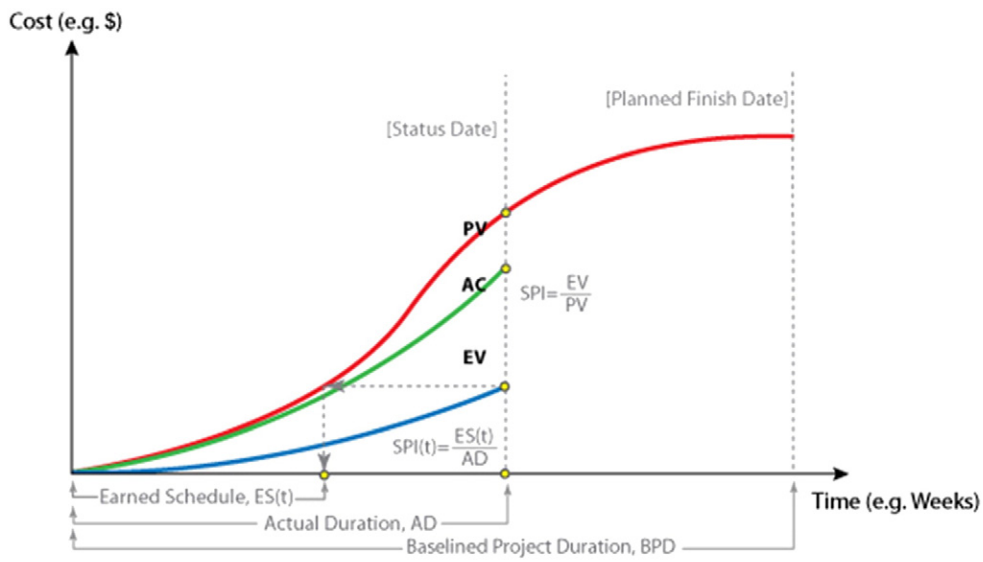


Fig. 1. Conceptual EVM graph.

The resulting $ES(t)$ is then compared to Actual Duration (AD). The Earned Schedule defines Schedule Performance Index denoted by $SPI(t)$ as:

$$SPI(t) = \frac{ES(t)}{AD} \tag{6}$$

While we agree that ES and consequently $SPI(t)$ is a better schedule/duration performance measure of the progress compared to SPI, we argue that still there are some issues associated with the use of this method for schedule performance measurement as well.

In this paper, we first present a critical evaluation of Earned Value and Earned Schedule as a tool for assessing schedule performance. We then introduce a comprehensive set of new indices which are easy to measure, understand and calculate with wider applications and implications in managing projects. These indices can be used to measure progress and performance of the project. As an example, the Duration Performance Index introduced measures the duration/time-based progress of the project compared to the actual duration passed. We also discuss the potential advantages of these measures over Earned Value and Earned Schedule indices. Additionally, we develop duration and cost estimation performance measures which can be used by contractors, clients, and the scheduling offices to assess the efficiency and efficacy of the estimated and planned durations and costs. These new measures are then applied to a real life project and the results are compared with Earned Value and Earned Schedule.

The list of acronyms and symbols which are used in this paper is given at the end of the paper for ease of reference. In addition, we have provided a separate table listing all the formulas.

2. Review of existing schedule and cost progress and performance measures

The Earned Schedule performance measure which was introduced by Lipke (W. Lipke, 2003) and later reinforced by Lipke et al. (2009) uses Earned Value which is measured in monetary terms (cost-based) to capture duration-based level of progress made in the project. Please refer to Fig. 1 and the overview of Earned Schedule in the previous section.

Vandevoorde and Vanhoucke (2006) and Vandevoorde and Vanhoucke (2007) in their comparative analysis of schedule performance measures came to the conclusion that $SPI(t)$ is a better measure of project schedule performance compared to all the other measures including the classical Schedule Performance Index (SPI) and Cost-Schedule Index defined as:

$$CSI = SPI \times CPI \tag{7}$$

Thus, when ES is used as a measure to predict the remaining duration or completion of the project, it provides a more reliable forecast at different stages of the project. Lipke et al. (2009) also conducted a similar research comparing the accuracy and reliability of a number of indices which could be used for forecasting the duration of a project, at different stages of progress toward completion, presumably based on past performance. They claimed that SPI has shown to produce reasonably good predictions only for large projects like those of the United States Department of Defense projects where the duration of the project is long and the volume of data used in the forecasting process is large, whereas $SPI(t)$ generally performs better.

Though $SPI(t)$ is argued to be a preferred option to measure duration/time performance compared to SPI, it has some conceptual shortcomings and could not be validated as a general method which is applicable to all scenarios. The main drawback of $SPI(t)$ is the fact that, similar to SPI, it measures schedule performance using monetary terms of Earned Value (EV) and Planned Value (PV). According to “Schedule is Different” where the idea of ES is introduced, “the cumulative value of $ES(t)$ is found by using BCWP to identify in which time increment of BCWS the cost value occurs” (Lipke, 2003). In other words, the Earned Schedule method uses EV as a proxy to get to corresponding duration. EV is not necessarily an accurate measure of schedule/duration progress made. It is, on the other hand, generally considered the best measure of "value earned" monetarily.

Even though we might see correlations between duration and cost profiles throughout the life of a project, these profiles are not generally the same. Hence, performance measures which use a cost profile to offer a schedule measure will not be accurate. Consequently, ES, similar to any method which uses EVM's cost-based measures, will inherently be deficient in dealing with duration performance measurement. In using such models, the higher the disparity between time and cost profiles of a project, the more inaccurate the schedule performance offered will be. In such instances, *SPI*(*t*) and *SPI* will both show inaccurate results, and at times, *SPI*(*t*) could even perform worse than *SPI*. Any section of a project which shows disproportionate duration and cost profiles can demonstrate such inaccuracy, as shown in the following example: A completed procurement activity with a high *PV* and short duration could dramatically change *SPI*(*t*) by overshadowing large delays of inexpensive activities on the critical path. This deficiency is illustrated in the sample project below.

In this example, there are two parallel paths. One path is longer, therefore is the critical path for the project. The critical path activities include A, B, and E. The other path contains the remaining activities, including activity D which has the highest value. This activity resembles long lead procurement activities that happen during the initial stages of a project. In this example and for simplicity, we have assumed that all activities are on time and on budget, except activity B that is not started. The marker on Fig. 2 shows the status date.

EVM output of the Microsoft Project report is provided in Table 1 below:

Using the given information, we calculate:

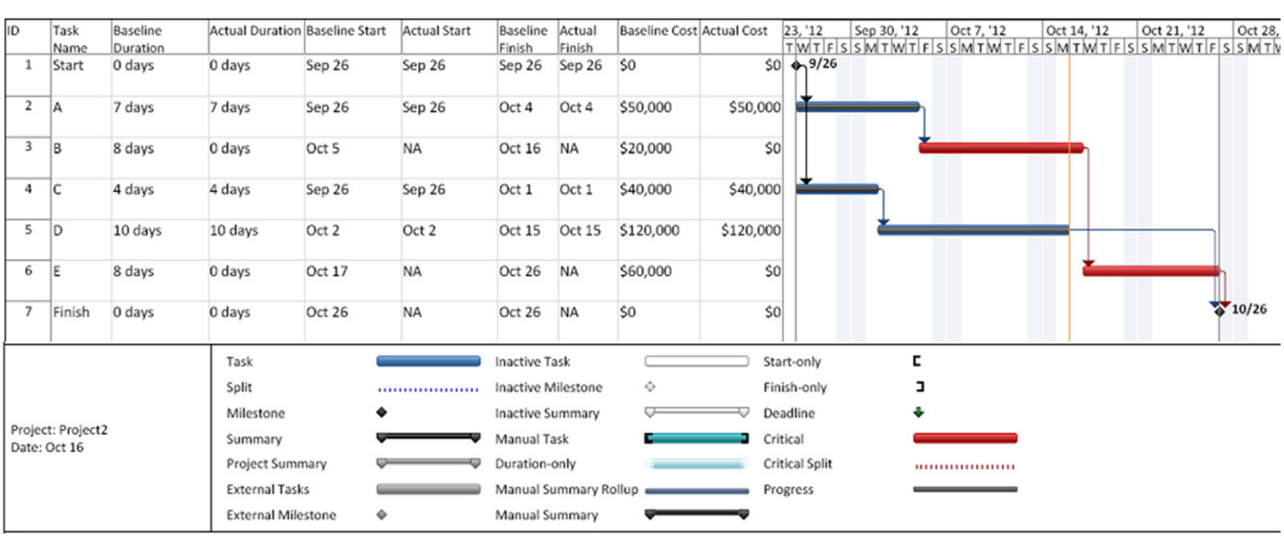
$$\text{EVM} \rightarrow SPI = \frac{EV}{PV} = \frac{\$210,000}{\$227,500} = 0.92$$

$$\text{ES} \rightarrow SPI(t) = \frac{ES(t)}{AD} \sim \frac{13}{14} = 0.93$$

As shown in the example above, schedule efficiency based on EVM is 92% and based on Earned Schedule method is 93%. It is evident that because a critical activity is not even started according to the plan, the project duration performance must not be at either of these two high performances.

EVM is recognized as the most widely used and accepted project cost control system today. In spite of this widespread acceptance of EVM, still a high percentage of projects fail to achieve baseline schedule and cost objectives (GAO, GAO Cost Estimating and Assessment Guide, 2009; Standish Group, 2011). While there could be many reasons contributing to failure of projects, lack of focus on duration planning and control, and reliability of estimates used in planning/scheduling is frequently within the mix. Nevertheless, EVM does not take advantage of the available data to assess the performance and accuracy of estimates developed by contractors and their planning offices. EVM was primarily developed to emphasize on the big picture, i.e. total duration and cost at each stage, ignoring the build-up of these figures and measures. In other words, as long as the total planned and actual figures of cost and duration match, "the project status is portrayed as green". This approach as explained above ignores the dynamics of occurrence of events within the system and has been debated by other practitioners and researchers as well (Jacob and Kane, 2004). That is, schedule and cost overruns by one element could be compensated by other elements. This could be fine at the macro level but could create serious issues at the micro level where the performance of teams, sections, or departments are scrutinized.

We, therefore, suggest that a more rigorous and comprehensive assessment of estimation performance is also needed. Only focusing on the duration of the critical path and the associated planned cumulative cost curve (known as Performance Measurement Baseline, or S-curve) is not necessarily enough for assessing



ID	Task Name	Baseline Duration	Actual Duration	Baseline Start	Actual Start	Baseline Finish	Actual Finish	Baseline Cost	Actual Cost
1	Start	0 days	0 days	Sep 26	Sep 26	Sep 26	Sep 26	$0	$0
2	A	7 days	7 days	Sep 26	Sep 26	Oct 4	Oct 4	$50,000	$50,000
3	B	8 days	0 days	Oct 5	NA	Oct 16	NA	$20,000	$0
4	C	4 days	4 days	Sep 26	Sep 26	Oct 1	Oct 1	$40,000	$40,000
5	D	10 days	10 days	Oct 2	Oct 2	Oct 15	Oct 15	$120,000	$120,000
6	E	8 days	0 days	Oct 17	NA	Oct 26	NA	$60,000	$0
7	Finish	0 days	0 days	Oct 26	NA	Oct 26	NA	$0	$0

Fig. 2. Schedule of a sample project with high value non-critical activities.

Table 1
EVM results, example project.

Work day	*EV*	*PV*	*AC*
1	17,143	17,143	17,143
2	34,286	34,286	34,286
3	51,429	51,429	51,429
4	68,571	68,571	68,571
5	87,714	87,714	87,714
6	106,857	106,857	106,857
7	126,000	126,000	126,000
8	138,000	140,500	138,000
9	150,000	155,000	150,000
10	162,000	169,500	162,000
11	174,000	184,000	174,000
12	186,000	198,500	186,000
13	198,000	213,000	198,000
14	210,000	227,500	210,000

the schedule performance of the project. The focus on big picture using S-curve only accounts for some of the monitoring and controlling aspect of project management.

The government of the United States of America and many other authorities all around the world have imposed EVM as the prime tool for managing contracts with regard to meeting schedule and cost targets (GAO, Significant Changes Underway in DOD's Earned Value Management Process, 1997; GAO, GAO Cost Estimating and Assessment Guide, 2009). However, in mostly all cases, the use of this control system as a tool for reflecting on benchmarking and documenting lessons learned based on collected performance data is ignored. We believe that the data collected for EVM reporting, is valuable and, can be utilized in other ways to provide better and more accurate information about the progress and performance of the project. It also can offer new beneficial insights about the project which were not necessarily available before.

In the next section, schedule and cost dimensions are decoupled and the above ideas are expanded and used to develop some new indices for monitoring schedule and cost separately. These measures, as a minimum, do not possess the deficiency of EVM and ES mentioned earlier.

3. New progress and estimation performance measures

Few methods have been suggested to measure duration/schedule performance of a project (Turner, 2010; Vanhoucke, Measuring Time: Improving Project Performance Using Earned Value Management, 2012). In most of these measures, if not all, the attention is focused on the Performance Measurement Baseline and where the project stands using EVM parameters (all cost-based, monetary measures). The authors argue that these methods can be improved to provide better and more reliable performance measures. Also, additional measures could be designed to use the available data resulting from existing monitoring processes for benchmarking, reflection on original estimated durations and lessons learned upon completion of activities, assessing the performance of planning and scheduling departments, and measuring efficiency and efficacy of estimation methods used.

We would like to start by differentiating between two potential groups of duration (schedule) and cost performance measures:

- One set of measures are focused on progress and performance of duration and cost at the project level, and the ability to deliver the project on time and on budget, e.g. *SPI* (or *SPI*(t), etcetera) and *CPI*. These measures usually compare the actual progress of the project on the performance measurement baseline against the planned/scheduled progress. These performance measures are indicators of project being on schedule or on budget, or alternatively, ahead or behind schedule or budget.
- The second type of measures focus on estimation performance. These measures consider the accuracy of the original estimates and the capability of the project team delivering the work (activity, work package, or larger elements) within the allocated time or cost. These measures compare the planned duration or cost to the actual duration or cost spent to finish the work. These measures have the potential to be used for benchmarking, documenting lessons learned, improving estimation process, etc.

We need to make a distinction between these two separate performance measures. While a project may have a perfect score of finishing on time, it could end up showing overall poor duration estimation accuracy. Therefore, we suggest utilizing the estimation performance measures defined in Section 3.4 which provide such insight and fill the current void.

Also, as it was discussed earlier, overemphasis on EVM and using cost as a proxy for schedule performance could provide misleading information to project team in assessing the schedule. Therefore, to provide more accurate performance measures there is a need to decouple schedule and cost dimensions. With that in mind, we developed the following duration-based performance measures along with their analogues EVM (cost-based) counterpart measures to more accurately present schedule and cost status for the following two categories:

a) Progress and performance measures, and
b) Estimation performance measures.

Each of these two types of performance measures can be defined at various levels of project within telescopic Work Breakdown Structure. In this paper, we focus on two levels only, micro or activity level and macro or project level.

The following definitions and notations are used to formulate the equations for the proposed approach which we call Earned Duration Management (EDM).

3.1. Notations used at the micro level

In defining these notations, EVM descriptions are adapted from A Guide to the Project Management Body of Knowledge (Project Management Institute, 2013).

At micro, activity, level we define and use:

Baseline Planned Duration of scheduled activity i: BPD_i, is the authorized duration assigned to the scheduled work to be accomplished for activity i. BPD_i is independent of the status date. Some may refer to it as the baseline duration for activity i.

Planned Duration of scheduled activity i: PD_i, at any point in time, is the authorized duration assigned to the scheduled work to be accomplished for activity i. This variable for EDM method is the duration counterpart or equivalent to PV of an activity in EVM.

Activity Progress Index, for activity i: API_i, at any point in time, measures the progress of activity. The schedule progress of an activity could be defined in two ways. In cases where the progress made on the activity has a linear relationship with time, one can assume percentage complete to be an accurate measure of progress. However, when this is not the case, physical progress could be used as a medium (e.g. labor hours, material quantities, lines of code, etc.) (Project Management Institute, 2005a, 2005b). We understand that there could be challenges in measuring progress. For EDM purposes, one can use progress of an activity similar to EVM. However, an alternative method of calculating schedule progress is through estimating the remaining duration to complete activity i (i.e. Estimated Duration To Complete for scheduled activity i — $EDTC_i$) by subject matter experts, then:

$$API_i = \frac{AD_i}{AD_i + EDTC_i} \tag{8}$$

Calculating API_i using this equation is completely duration based.

Considering that API_i measures the schedule progress of an activity, it will always have a value of less than or equal to one. Value of API_i starts from zero and as the activity nears completion, its value approaches one, and becomes one upon completion of the activity.

Earned Duration of scheduled activity i: ED_i, at any point in time, is the value of work performed expressed as proportion of the approved duration assigned to that work for activity i (e.g. days). This variable for EDM is the duration counterpart or equivalent to EV of an activity in EVM.ED_i can normally be calculated as:

$$ED_i = BPD_i \times API_i \tag{9}$$

Actual Duration of scheduled activity i: AD_i, at any point in time, is the time in calendar units between the actual start of the activity and either that point in time if the activity is in progress or the actual finish date if the activity is complete. This measure for EDM method is the duration counterpart or equivalent to AC of an activity in EVM.

Baseline Planned Value of scheduled activity i: BPV_i, is the authorized budget assigned to the work to be accomplished for activity i. BPV_i is independent of the status date. Some may refer to it the baseline cost for activity i.

Planned Value of scheduled activity i: PV_i, at any point in time, is the authorized budget assigned to the scheduled work to be accomplished for the activity up to that time as defined in EVM.

Earned Value of scheduled activity i: EV_i, at any point in time, is the value of work performed expressed in terms of the approved budget assigned to that work for a schedule activity as defined and used in EVM.

Actual Cost of scheduled activity i: AC_i, at any point in time, is the total costs actually incurred and recorded for accomplishing work performed during the AD_i for the activity as defined by EVM.

It is to be reiterated that PD_i, ED_i, and AD_i for EDM are counterparts or equivalent twins of PV_i, EV_i, and AC_i for EVM and are all dependent on the status date. BPD_i and BPV_i are indepedant of the status date and are the authorized duration and cost of activity i per baseline schedule.

3.2. Notations used at the macro level

At the macro level we define and use the following terms:

Baseline Planned Duration: BPD, is the authorized duration assigned to the scheduled work to be accomplished for the entire project irrespective of the status date.

Total Planned Duration: TPD, for the project, at any particular point in time, is the sum of PD_i for all the planned activities at that time according to baseline plan. It needs to be said that for activities crossing over the status date, only the duration of the activity to the left of the vertical status date line counts toward TPD.

$$TPD = \sum_{i=1}^{n} PD_i \tag{10}$$

where n is the number of in-progress and completed activities up to that time.

Total Earned Duration: TED, for the project, at any particular point in time, is the sum of ED_i for all the in-progress and completed activities at that time. Or

$$TED = \sum_{i=1}^{n} ED_i \tag{11}$$

where n is the number of in-progress and completed activities up to that time.

Earned Duration: ED(t), for the project, at any point in time, is the duration corresponding to Total Earned Duration (*TED*) on Total Planned Duration S-curve, which mathematically could be expressed as:

$$\text{Find t such that } TED \geq TPD_t \text{ and } TED < TPD_{t+1(calendar\ unit)}$$
$$ED(t) = t + \frac{TED - TPD_t}{TPD_{t+1(calendar\ unit)} - TPD_t} \times 1\ (calendar\ unit) \tag{12}$$

where $ED(t)$ is Earned Duration at status date or Actual Duration (*AD*). *TED* is the Total Earned Duration at *AD* and TPD_t is the Total Planned Duration at time instant t, and the calendar unit represents the unit in which time instant t is measured. At the end of the project $ED(t)$ is the same as *BPD* (Baseline Planned Duration). Fig. 4 presents a conceptual graph which depicts calculation of $ED(t)$. Table 2 depicts $ED(t)$ calculation for the example project.

Total Actual Duration: TAD, at any point in time, for the project is the sum of AD_i for all the in-progress and completed activities at that time. Or

$$TAD = \sum_{i=1}^{n} AD_i \tag{13}$$

where n is the number of in-progress and completed activities up to that time.

Planned Value: PV, for the project (as used in EVM terminology) at any point in time, is the authorized budget assigned to all the activities or scheduled work to be accomplished up to that point. It can be defined and calculated as:

$$PV = \sum_{i=1}^{n} PV_i \tag{14}$$

where n is the number of planned activities up to that time.

Earned Value: EV, for the project (an EVM terminology) at any point in time, is the value of work performed expressed in terms of the approved budget assigned to all the in-progress and completed activities at that time. Earned Value for the project can be defined and calculated as:

$$EV = \sum_{i=1}^{n} EV_i \tag{15}$$

where n is the number of in-progress and completed activities at that time.

Table 2
EDM results for the example project.

Day	Total earned duration	Total planned duration	Total actual duration
1	2	2	2
2	4	4	4
3	6	6	6
4	8	8	8
5	10	10	10
6	12	12	12
7	14	14	14
8	15	16	15
9	16	18	16
10	17	20	17
11	18	22	18
12	19	24	19
13	20	26	20
14	21	28	21

Actual Cost: AC, (an EVM terminology) at any point in time, for the project is the total costs actually incurred and recorded in accomplishing work performed. Actual Cost for the project can be defined and calculated as:

$$AC = \sum_{i=1}^{n} AC_i \tag{16}$$

where n is the number of in-progress and completed activities at that time.

Actual Duration: AD, for the project at any particular point in time, is the period of time from the start of the project till that time.

It is to be noted that *TPD*, *TED* and *TAD* for EDM are counterparts or equivalent twins of *PV*, *EV* and *AC* for EVM.

3.3. Progress and Performance Measures for Duration and Cost

The measures defined below, classified into micro and macro levels, will assist project managers in monitoring, evaluation, and control of duration/schedule and cost progress and performance and the ability to deliver the project on time and on budget.

3.3.1. Micro level progress and performance measures for duration and cost

Duration Performance Index, for activity i: DPI_i, at any point in time, is a measure of schedule performance in delivering the activity. In other words, it shows how well the activity is doing in achieving the target completion date. It can be calculated as:

$$DPI_i = \frac{ED_i}{AD_i} \tag{17}$$

DPI_i can have values of greater than one presenting a better performance than planned, lower than one indicating worse performance compared to plan, or one which suggests performance is according to plan. The higher or lower performance will result in the activity being seen as ahead or behind schedule respectively. Thus, DPI_i is an indicator of the activity being on, ahead, or behind schedule.

Upon completion of the activity: DPI_i represents the overall performance in delivering the activity compared to the plan. From a different perspective, this end value of DPI_i for activity i represents the accuracy of the original duration estimate. We call the value of DPI_i at completion of activity i the Duration Estimation Index for that activity (DEI_i) and define that index in the next section and explain its applications.

Earned Duration Index, for activity i: EDI_i, at any point in time, is a measure of duration earned (e.g. number of days) compared to what was planned to be done up to that point in time. We define:

$$EDI_i = \frac{ED_i}{PD_i} \tag{18}$$

At any point in time, an activity might have achieved more, less, or the same amount of work in comparison with the plan up to that point in time. Thus, this measure can have values of higher than one, lower than one, or equal to one, respectively.

Adapting directly from EVM, at the activity level, we define:

Schedule Performance Index, for activity i: SPI_i, at any point in time, could be formulated as:

$$SPI_i = \frac{EV_i}{PV_i} \tag{19}$$

The value of SPI_i, similar to API_i, is zero before the activity starts and reaches maximum value of one when the work is complete. However, despite the similarity in starting and finishing values of these two performance indices, SPI_i does not measure the overall duration focused progression of the activity. It, rather, measures the monetary value of the work done compared to the plan up to that time. Another difference between these two indices is in their range of possible values. Unlike API_i, SPI_i can take on values of greater than one when the activity is in progress and cost-wise has achieved more than what has been planned, or lower than one when the activity is underperforming. This characteristic might suggest SPI_i is similar to Duration Performance Index for activity i, DPI_i, due to the resemblance in the values possible. However, SPI_i is actually more similar to Earned Duration Index, for activity i, EDI_i. At the same time, we argue that SPI_i is not a direct schedule progress or performance measure. Hence, it may not necessarily provide the insight that either API_i, DPI_i, or EDI_i offer.

Adapting directly from EVM, we next define:

Cost Performance Index, for scheduled activity i: CPI_i (an EVM terminology), at any point in time, as:

$$CPI_i = \frac{EV_i}{AC_i} \tag{20}$$

3.3.2. Macro level progress and performance measures for duration and cost

At the macro, project, level we define:

Project Progress Index: PPI, at any point in time, is a measure of overall duration progress of the project. It measures $ED(t)$ against the baseline planned duration as:

$$PPI = \frac{ED(t)}{BPD} \tag{21}$$

It is to be noted that because PPI represents the schedule progress, at macro level, its value is always less than or equal to one. PPI's value starts from zero and as the project nears completion, the value of $ED(t)$ approaches to BPD which results in the value of PPI approaching one. At the end of the project, $ED(t)$ is the same as BPD. Hence, PPI value will be one upon completion of the project.

Duration Performance Index, for project: DPI, at any point in time, represents the overall schedule progress performance toward the completion of the project. In other words, it shows how well the project is doing in achieving the target completion date in consideration of the critical path. Duration Performance Index is defined as:

$$DPI = \frac{ED(t)}{AD} \tag{22}$$

The value of DPI will be less than one, if the project schedule is not performing at the same level as planned, hence it will be perceived as being behind schedule. DPI will be equal to one, if project is overall performing at the same level as planned. Thus, the project will be seen as on schedule. And DPI will be greater than one when the project schedule is overall performing better than planned which will result in project being ahead of the schedule. Similar to $SPI(t)$, Duration Performance Index for project provides the measure of progress performance on the critical path and toward completion of project.

Earned Duration Index, for project: EDI at any point in time, is a duration-based measure of overall work performed in terms of Earned Duration, in comparison with the work planned up to that point in time. This measure does not consider activity dependencies and is irrespective of their interactions to achieve the end date of the project. We define:

$$EDI = \frac{TED}{TPD} \tag{23}$$

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At any point in time duration-wise a project might have achieved more, less, or the same amount of work in comparison with the work planned to be achieved by that time. Thus, this measure can have values of greater than one, lower than one, or equal to one respectively.

To demonstrate the difference between *DPI* and *SPI*(t) on one hand, and *EDI* and *SPI* on the other, we have prepared two similar conceptual graphs. Fig. 3 is the familiar EVM or ES graph whereas Fig. 4 is its EDM counterpart showing *TPD*, *TAD*, and *TED* in an EDM graph. Comparing these two graphs shows that *DPI* is a measure similar to *SPI*(t), and *EDI* is similar to *SPI*.

To demonstrate the use of these indices we calculate and present *TED*, *TPD*, and *TAD* for the example project above in Table 2 below:

From Table 2 one can see that *TED* at the status date or day 14 (i.e. $AD = 14$) is equal to 21 days. According to the *TPD* column, the project was planned to earn this duration by the end of day 11. Thus, *ED*(t) is roughly 11 days. Considering that the actual duration passed from the start of the project is 14 days, *DPI* will be calculated as:

$$DPI = \frac{ED(t)}{AD} \sim \frac{11}{14} = 0.79$$

For this sample project we can calculate the Earned Duration Index as:

$$EDI = \frac{TED}{TPD} = \frac{21}{28} = 0.75$$

Earlier, we found that $SPI(t) = 0.93$, and $SPI = 0.92$ for this example project. That is, schedule or duration performance suggested by ES or EVM is at 92 or 93 percent level. Comparing these values with $DPI = 0.79$ and $EDI = 0.75$ respectively and knowing the status of the project, it can be seen that in both cases, *DPI* and *EDI* present much more valid information about the schedule compared to *SPI*(t) and *SPI* for a project where a critical activity is severely behind schedule.

Cost Performance Index: for project, CPI, is the classical EVM index defined as:

$$CPI = \frac{EV}{AC} \tag{24}$$

The value of *CPI* will be less than one, if the project is over budget, equal to one, if on budget, and greater than one when under budget.

Project managers can use control charts to monitor *DPI*, *EDI*, and *CPI* over time with upper and lower control limits (UCL and LCL). If the index goes beyond these limits, then generally there is a need for investigation and possibly intervention, either to maximize and take advantage of an opportunity or to minimize the risks.

The progress and performance measures defined above, separate duration and cost performance measures to deliver more accurate information on the status of a project and its activities.

3.3.3. Forecasting and other uses

Similar to EVM, one other potential usage of the progress performance measures is forecasting the future state of the project. We believe that the performance of the project at each stage is a function of the nature of the project and the context and content of that stage (characteristics of the S curve) of project as supported by Bower (2007). We also believe that using any performance measure developed at one stage of a project as a proxy to forecast performance of the project many periods away in the future is questionable. As an example, in Engineering, Procurement, Construction (EPC) type contracts, assuming the entire contract will be behind schedule because the engineering stage is delayed, may not necessarily be an accurate prediction. The authors' experience shows that spending a little bit more time and resources on the engineering stage when deemed necessary could reduce the cost and duration of installation and commissioning activities (part of the construction stage) drastically. Such minimal delay, in those cases, could actually help achieve huge time and cost savings for the overall contract. Hence, if the stages

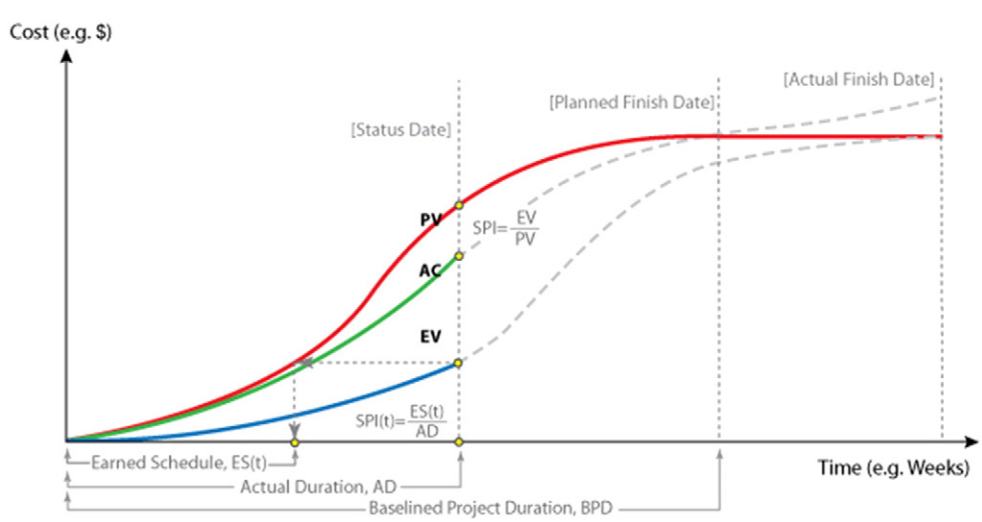

Fig. 3. Conceptual EVM graph.

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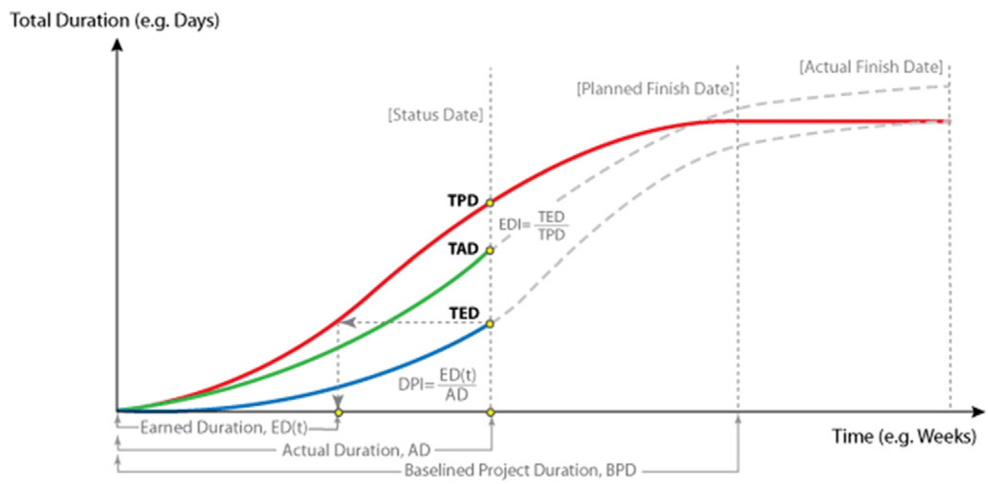

Fig. 4. Conceptual EDM graph.

of the project are different and heterogeneous, which normally is the case, there is no rationale for assuming past performance is a good predictor of the future.

In all these forecasts we assume the current performance continues and remains the same for the remainder of the project. However, we know that if the performance is not according to the plan, as a minimum the project manager normally tries to influence the project to bring it back on track, and consequently resulting in a change in performance. Thus, the performance of the project in the future is not necessarily constant and the same as the past but most probably is flexible and dynamic and responsive to past performance (Cooper, 1994; Cioffi, 2006; Moslemi Naeni et al., 2011).

In spite of the difficulties and issues mentioned earlier, one could reasonably use any of the many simple forecasting models (e.g. moving average, exponential smoothing), and or more advance and complex approaches (fuzzy time series etcetera) to predict the value of the index for the next few periods. Forecasting project completion cost using *CPI* which uses *EV* has shown to be a relatively good choice (Vandevoorde and Vanhoucke, 2006). On the other hand, to forecast the duration of the project, we suggest utilizing *DPI* which is based on EDM data and does not have the computational difficulties and potential errors of cost/value-based models (EVM, ES) as discussed earlier.

Despite the above, one can formulate a forecasting equation for EDM similar to the classical forecasting approaches for EVM (considering a constant performance for the remainder of the project). We define:

Estimated Duration at Completion, (*EDAC*), as:

$$EDAC = \frac{BPD}{DPI} \tag{25}$$

Alternatively, one can use the following formula to estimate the duration at completion:

$$EDAC = \frac{AD}{PPI} \tag{26}$$

Or we can calculate the *Estimated Duration To Complete*, for project, *EDTC* as:

$$EDTC = \frac{BPD}{DPI} - AD = \frac{AD \times (1 - PPI)}{PPI} \tag{27}$$

Additionally, similar to EVM, we can define a duration variances for EDM. At the activity level, *Duration Variance for activity i*, (DV_i), can be calculated as:

$$DV_i = ED_i - PD_i \tag{28}$$

And at the project level *Total Duration Variance for Project*, (*TDV*), is defined as:

$$TDV = TED - TPD \tag{29}$$

TDV shows the sum total of all the deviations from the plan which is a measure of the accuracy of the planning. In other words, it is a measure of total deviation of all the activities planned up to any point in time.

To measure the deviation from the plan on the critical path, we define *Duration Variance for a project*, *DV*, as:

$$DV = ED(t) - AD \tag{30}$$

Considering that we used cost parameters similar to EVM, there will be no changes to the cost variance performance measures. Hence, at the activity level:

$$CV_i = EV_i - AC_i \tag{31}$$

And at the project level:

$$CV = EV - AC \tag{32}$$

3.4. Duration and cost estimation performance measures

As discussed earlier, one aspect of control is to use the collected information for benchmarking, lessons learned, and assessing the performance of planning and scheduling departments. Therefore, we use the data collected as part of monitoring and controlling processes of project management to develop these measures. As this required data is currently available to project management teams for generating EVM reports, there will be no additional costs for data collection to produce EDM reports.

Once again, these measures can be defined at both micro, and macro levels.

3.4.1. Micro level duration and cost estimation performance measures

At the micro, e.g. activity, level we define:

Duration Estimation Index of scheduled activity i: DEI_i, as a measure to gain a better understanding of the accuracy of the original estimated duration of the activity. DEI_i compares the duration originally planned (authorized) for the activity versus what was the actual duration upon completion of the activity:

$$DEI_i = \frac{BPD_i}{AD_i} \tag{33}$$

Similarly, we define:

Cost Estimation Index of scheduled activity i: CEI_i, as a measure to gain a better understanding of the accuracy of the original estimated cost of the activity:

$$CEI_i = \frac{BPV_i}{AC_i} \tag{34}$$

DEI_i and CEI_i should be used to report duration and cost estimation accuracy or performance for activities only after they are completed.

Based on experience, these indices are usually less than one due to notional rules such as Parkinson's Law which states that "work expands so as to fill the time available for its completion". These indices could occasionally be more than or equal to one as well.

3.4.2. Macro Level Duration and Cost Estimation Performance Measures

Now that estimation performance measures at the micro level have been established, we discuss macro or project level estimation performance measures. We define:

Duration Estimation Index for project: *DEI*, as the average DEI_i of all the *completed* activities (m) at any stage of the project. At the completion of the project, m is equal to M or total number of activities in the Project.

$$DEI = \frac{\sum_{i=1}^{m} DEI_i}{m} \tag{35}$$

where m is the number of activities which are finished.

We use the average function at the project level, with some reservations. This averaging produces better performance measure for the activities within similar functions or departments such as engineering, design, development, etc. This index can be used for benchmarking or any kind of comparative analysis with the previously executed projects. One can use other methods such as weighted average (based on duration, cost, effort, etcetera, as most appropriate) to get a more accurate Duration Estimation Index at higher levels depending on the activity types. The weighted average version of Duration Estimation Index for project could be formulated as:

$$DEI = \frac{\sum_{i=1}^{m} (w_i \times DEI_i)}{m} \tag{36}$$

where w_i is the designated weight for the activity i and m is the number of activities which are finished.

Cost Estimation Index for project: CEI, is the cost counterpart of *DEI* and measures average cost estimation performance for the project based on all *completed* activities (m).

$$CEI = \frac{\sum_{i=1}^{m} CEI_i}{m} \tag{37}$$

where m is the number of activities which are finished.

Similar to *DEI*, one can use weighted averages to get a more accurate Cost Estimation Index at higher levels depending on the element types, size, breakdown or based on duration, cost, effort, etc. In which case the following formula can be used:

$$CEI = \frac{\sum_{i=1}^{m} (y_i \times CEI_i)}{m} \tag{38}$$

where y_i is the designated weight for the activity i and m is the number of activities which are finished.

Knowing that the planned durations are not always one hundred percent reliable, we expect some variation in the values for *DEI* and *CEI* for different types of projects. For deterministic projects we expect higher reliability of duration and cost estimates and less risk of delays or over-runs. This is in contrast to probabilistic projects (Research, Engineering, and Development projects) in which the estimates are less reliable and performance variation is expected (Khamooshi and Cioffi, 2013).

3.4.3. Possible values of defined estimation measures

The value of DEI_i, CEI_i, *DEI*, *CEI* could be higher or lower than one. For these indices, a value of more than one is a sign of better performance compared to what has been agreed on during development of plan. To the contrary, values less than one are indicative of worse than expected performance. One can use control charts to monitor *DEI* and C *EI* over time with upper and lower control limits (UCL and LCL) for evaluation of estimation. This process could provide us with the opportunity for taking advantage of any opportunity for improving the estimation process and minimizing the risks associated with estimates.

Using a project management software with built-in functionality to input and process performance management data, all the aforementioned measures can be developed and reported by filtering the relevant activities or work packages for each section, department, or part of project. This filtering operation, i.e. separating homogenous activities, could provide very valuable information for assessing the schedule and estimation performance of any particular section or department.

In addition to providing more accurate information about the duration status of the project and its activities, another benefit

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of EDM is its estimation performance measures. These performance measures provide us better tools to control the project, document lessons learned by comparing estimates against actuals, and improve the estimation for future projects. Consequently, EDM empowers the project manager to have a better handle on project duration control and higher chance of delivering a project successfully.

4. EDM applied to the United States Coast Guard (USCG) project

In this section we apply the suggested performance measures to a real life United States Coast Guard (USCG) project. This project upgrades the capacity and capability of an old storage garage boat management facility to that of a modernly equipped boat handling and maintenance facility. We have proportionally reduced the costs to maintain the confidentiality of project data while keeping the baseline schedule data intact.

We will first demonstrate EVM, ES, and EDM data when 18 out of 46 weeks of the planned project duration has passed. We show this information at the end of week 37 as well. Later, we will show the performance measures at project completion.

The calculations below are fairly straightforward and are accommodated by using a project management software package (Microsoft Project in this case).

Fig. 5 shows EVM graph at the end of week 18 for this project (Table 1.A in Appendix 1 presents the same data in a tabular format).

EVM calculates *SPI* as:

$$\text{EVM} \rightarrow \qquad SPI = \frac{EV}{PV} = \frac{\$467,789}{\$685,890} = 0.68$$

Using Table 1.A containing the data extract of the Microsoft Project EVM report makes it easier to calculate *ES*(*t*). *EV* at the end of week 18 is equal to $467,789. According to the *PV* column, the project was planned to earn this value roughly during week 11. Thus, *ES*(*t*) is approximately 11 weeks. Considering that *AD* is 18 weeks, *SPI*(*t*) will be calculated as follows:

$$\text{ES} \rightarrow \qquad SPI(t) = \frac{ES(t)}{AD} \sim \frac{11}{18} = 0.61$$

Using USCG project data available for generating EVM graphs, we can produce the EDM graph as shown in Fig. 6. This figure depicts a noticeably different profile for EDM compared with the one presented in Fig. 5 for ES.

The same data can be shown in a tabular format presenting *TED*, *TPD*, and *TAD* (Table 2.A in Appendix 2).

TED at the status date of week 18 is equal to 180 days. According to the *TPD* column, the project was planned to earn this duration during week 16. Thus, *ED*(*t*) is roughly 16 weeks. Considering that the actual number of weeks passed from the start of the project is 18 weeks, *DPI* and *EDI* will be calculated as:

$$DPI = \frac{ED(t)}{AD} = \frac{16}{18} = 0.89$$

$$EDI = \frac{TED}{TPD} = \frac{180}{198} = 0.91$$

The Project Progress Index measures the time-based (duration) progress of the project compared with the baseline planned duration and is calculated as follows:

$$PPI = \frac{ED(t)}{BPD} = \frac{16}{46} = 0.35$$

The status of the project according to EVM at the end of week 37 is presented in Fig. 7. Table 3.A in Appendix 3 presents the same data in a tabular format.

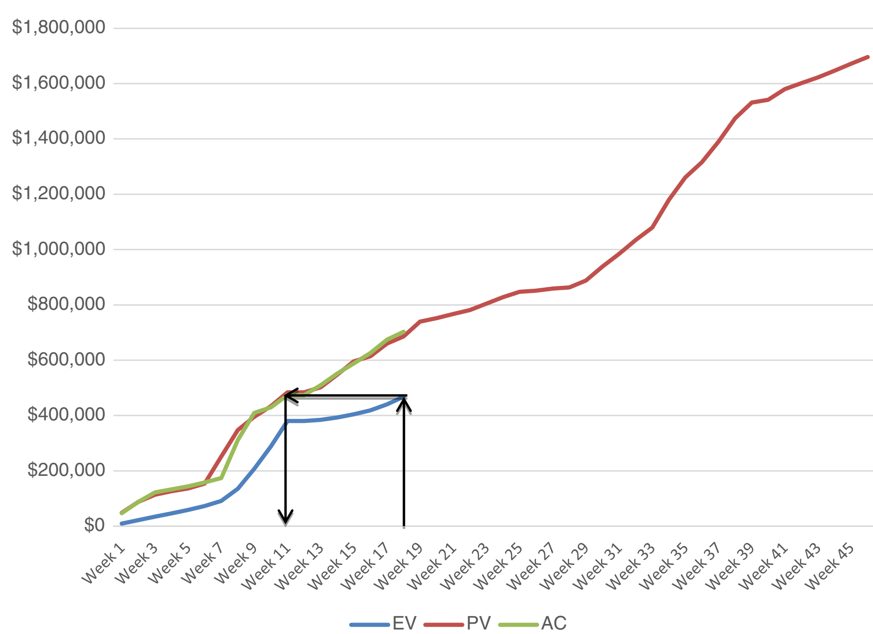

Fig. 5. EVM graph at the end of week 18.

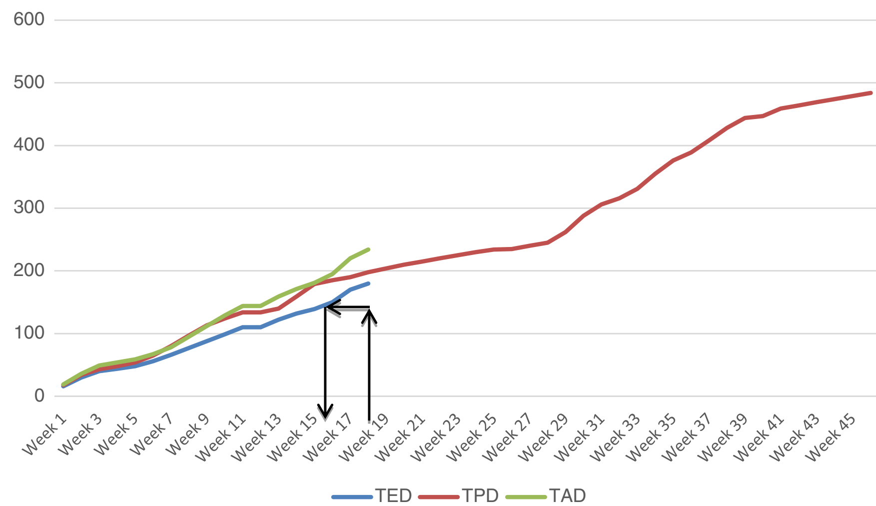

Fig. 6. EDM graph at the end of week 18, the total duration (y axis is in days) whereas the project duration/progress is in weeks.

EVM calculates *SPI* as:

$$\text{EVM}: \qquad SPI = \frac{EV}{PV} = \frac{\$870,915}{\$1,390,280} = 0.63$$

Using Table 3.A containing the data extract of the Microsoft Project EVM report makes it easier to calculate *ES*(*t*). *EV* at the end of week 37 is equal to $870,915. According to the *PV* column, the project was planned to earn this value roughly during week 29. Thus, *ES*(*t*) is approximately 29 weeks. Considering that *AD* is 37 weeks, *SPI*(*t*) will be calculated as follows:

$$\text{ES}: \qquad SPI(t) = \frac{ES(t)}{AD} \sim \frac{29}{37} = 0.78$$

EDM graph at the end of week 37 is shown in Fig. 8. This figure depicts a noticeably different profile for EDM compared with the one presented in Fig. 7 for ES. The same data is shown in a tabular format presenting *TED*, *TPD*, and *TAD* Table 4.A, Appendix 4.

TED at the status date of week 37 is equal to 282 days. According to the *TPD* column, the project was planned to earn this duration during week 30. Thus, *ED*(*t*) is roughly 30 weeks. Considering that the actual number of weeks passed from the start of the project is 37 weeks, *DPI* and *EDI* will be calculated as:

$$DPI = \frac{ED(t)}{AD} = \frac{30}{37} = 0.81$$

$$EDI = \frac{TED}{TPD} = \frac{282}{408} = 0.69$$

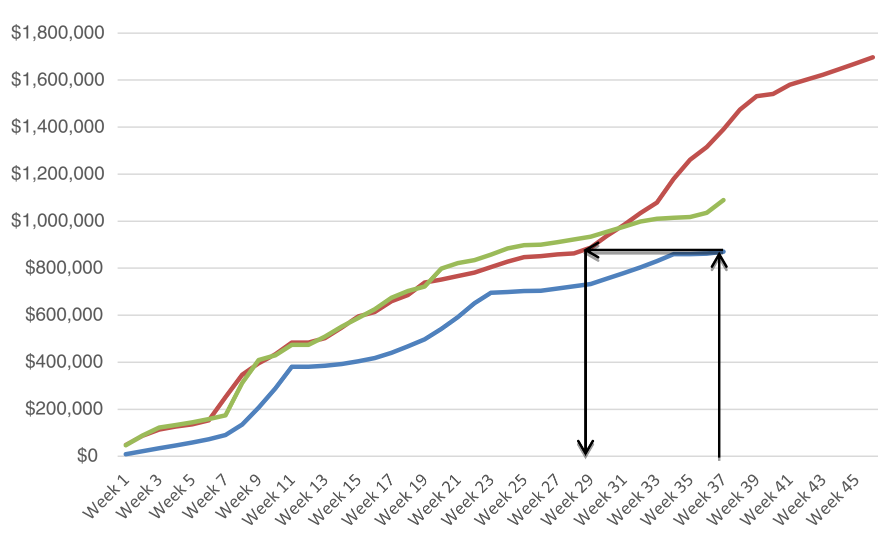

Fig. 7. EVM graph at the end of week 37.

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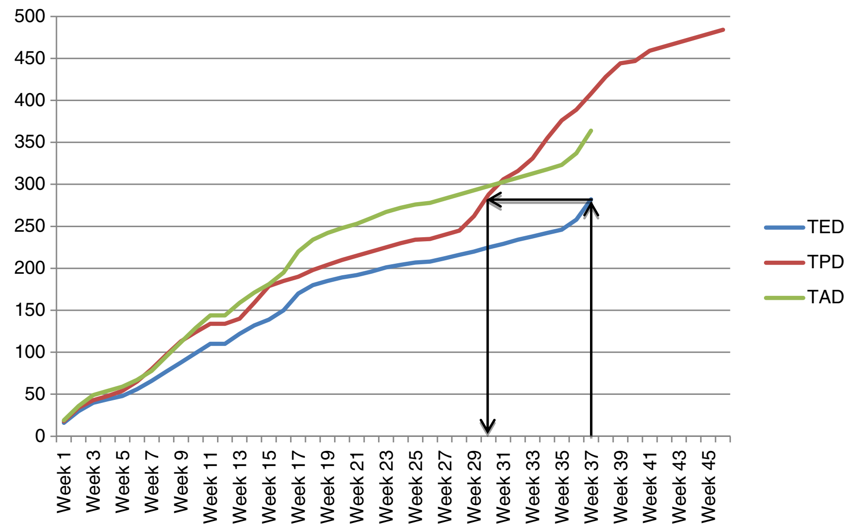

Fig. 8. EDM graph at the end of week 37, the total duration (y axis is in days) whereas the project duration/progress is in weeks.

The Project Progress Index is calculated as follows:

$$PPI = \frac{ED(t)}{BPD} = \frac{30}{46} = 0.65$$

This time around, $SPI(t)$ is much closer to the performance suggested by DPI. As explained in the previous sections, this is mainly due to cost and schedule profiles getting closer to each other at this stage of the project. And is not a sign of $SPI(t)$ being a good schedule performance measure, or that $SPI(t)$ could be used in place of DPI as a good schedule measure. Had the cost and schedule profiles not been close at this stage, similar to the results at the end of week 18, the performance suggested by $SPI(t)$ would have been different and inaccurate compared to the value suggested by DPI.

The result from both the earlier example project and the USCG project shows that EDM provides a more realistic schedule assessment. In case of USCG project $SPI(t)$ is a much better measure than SPI but as it was discussed above, the duration-based index is a more rational alternative and natural choice when dealing with duration or time.

Using the USCG project data upon completion, the calculated results for micro (activity) level measures are presented in Table 5.A, Appendix 5.

As expected, the activity progress index for each activity is at 100% showing the activity is completed. As explained earlier and can be seen in Table 5.A, upon completion of the activities, the duration performance and estimation indices will be the same.

Using this data, and the calculated DEI_i and CEI_i we can calculate Duration Estimation Index for the USCG project. DEI is given by:

$$DEI = \frac{\sum_m^1 DEI_i}{m} = 0.82$$

This means that the overall duration estimation accuracy was about 82%.

And CEI is calculated as follows:

$$CEI = \frac{\sum_m^1 CEI_i}{m} = 0.89$$

This means that the estimating team had an overall accuracy of about 89% in estimating the cost for the activities of this project.

These findings could be used for review and assessment of estimation methods and improving the accuracy of planning data for the future projects.

Considering that the USCG project was completed in week 57 as opposed to the scheduled week 46, hence, we calculate the Duration Performance Index, for project as:

$$DPI = \frac{ED(t)}{AD} = \frac{BPD}{AD} = \frac{46}{57} = 0.8$$

As mentioned earlier, EDI at the end of the project will always be equal to one. We can calculate this index as:

$$EDI = \frac{TED}{TPD} = \frac{484.5}{484.5} = 1$$

And, of course, we expect the Project Progress Index at the end of the project to be 100% or equal to one as follows:

$$PPI = \frac{ED(t)}{BPD} = \frac{BPD}{BPD} = \frac{46}{46} = 1$$

Each of these measures depicts a different aspect of the project and its activities, and combined together, provide a comprehensive understanding of the status of the project as expected from a comprehensive monitoring and control system.

5. Conclusion and recommendations

There are hundreds of projects failing to be delivered as scheduled each year. Over-emphasis on cost, lack of focus on accuracy of estimation, and using cost as a proxy for measuring duration-related performance of the project in EVM have been identified in this paper as an issue. Realizing that there is normally some correlation between time and cost, to improve duration-focused performance measurement accuracy, we provided a new approach and recommendations to decouple the schedule and cost dimensions in EVM by adding Earned Duration while maintaining the unique interaction of the three major project management elements of scope, cost, and time similar to EVM. A new model to emphasize the duration/schedule aspect of the project called Earned Duration Management or EDM is introduced. Focusing on duration from estimation to delivery not only helps to manage the schedule more effectively, it could also lead to cost saving as well. Using duration to assess schedule related performance of a project provides a number of advantages. The new estimation indices can be used for benchmarking, documenting lessons learned, and re-evaluation of the models and processes used for each part, section, department or the project as a whole in the future. The Total Planned Duration, Total Earned Duration, Total Actual Duration graph is a very powerful tool focused on duration (called EDM graph) which could play the same role as EVM graph does for cost. The newly introduced Project Progress Index (*PPI*), Duration Performance Index (*DPI*), and Earned Duration Index (*EDI*) are better duration-based performance measures to be used in control and management of project schedules. These measures overcome the deficiencies of cost-based schedule performance indices.

List of acronyms and symbols

AC	Actual Cost
ACWP	Actual Cost of Work Performed.
AD	Actual Duration
API_i	Activity Progress Index (for activity i)
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
BPD	Baseline Planned Duration
C/SCSC	Cost/Schedule Control Systems Criteria
CEI	Cost Estimation Index
CPI	Cost Performance Index
CSI	Cost-Schedule Index
CV	Cost Variance
DEI	Duration Estimation Index
DPI	Duration Performance Index
DV	Duration Variance
EDAC	Estimated Duration at Completion
EDI	Earned Duration Index
EDM	Earned Duration Management (method)
EDTC	Estimated Duration To Complete (for project)
EPC	Engineering, Procurement, Construction
ES	Earned Schedule (method)
EV	Earned Value
EVA	Earned Value Analysis
EVM	Earned Value Management (method)
EVMS	Earned Value Management System
PD	Planned Duration
PPI	Project Progress Index
PV	Planned Value
SV	Schedule Variance
SPI	Schedule Performance Index
SPI(t)	Earned Schedule, Schedule Performance Index
TAD	Total Actual Duration
TDV	Total Duration Variance
TED	Total Earned Duration
TPD	Total Planned Duration.
USCG	United States Coast Guard
UCL, LCL	Upper and Lower Control Limits
WBS	Work Breakdown Structure.

Table of formulas.

Formula	Description	Measure	Level	Equation number
$CV = EV - AC$	Earned Value, Cost Variance		Micro/macro	(1)
$SV = EV - PV$	Earned Value, Schedule Variance		Micro/macro	(2)
$CPI = \frac{EV}{AC}$	Earned Value, Cost Performance Index		Micro/macro	(3)
$SPI = \frac{EV}{PV}$	Earned Value, Schedule Performance Index		Micro/macro	(4)
Find t such that $EV \geq PV_t$ and $EV < PV_{t+1(calendar\ unit)}$ $ES(t) = t + \frac{EV - PV_t}{PV_{t+1(calendar\ unit)} - PV_t} \tilde{n}1\ (calendar\ unit)$	Earned Schedule		Micro/macro	(5)
$SPI(t) = \frac{ES(t)}{AD}$	Earned Schedule, Schedule Performance Index		Micro/macro	(6)
$CSI = SPI \times CPI$	Cost-Schedule Index		Micro/macro	(7)
$API_i = \frac{AD_i}{AD_i + EDTC_i}$	Activity Progress Index, for activity i		Micro	(8)
$ED_i = BPD_i \times API_i$	Earned Duration of scheduled activity i		Micro	(9)
$TPD = \sum_{i=1}^{n} PD_i$	Total Planned Duration		Macro	(10)

(*continued*)

Formula	Description	Measure	Level	Equation number
$TED = \sum_{i=1}^{n} ED_i$	Total Earned Duration		Macro	(11)
Find t such that $TED \geq TPD_t$ and $TED < TPD_{t+1(calendar\ unit)}$ $ED(t) = t + \frac{TED - TPD_t}{TPD_{t+1(calendar\ unit)} - TPD_t} \times 1\ (calendar\ unit)$	Earned Duration		Macro	(12)
$TAD = \sum_{i=1}^{n} AD_i$	Total Actual Duration		Macro	(13)
$PV = \sum_{i=1}^{n} PV_i$	Planned Value (an EVM terminology)		Macro	(14)
$EV = \sum_{i=1}^{n} EV_i$	Earned Value (an EVM terminology)		Macro	(15)
$AC = \sum_{i=1}^{n} AC_i$	Actual Cost (an EVM terminology)		Macro	(16)
$DPI_i = \frac{ED_i}{AD_i}$	Duration Performance Index, for activity i	Progress and performance measures	Micro	(17)
$EDI_i = \frac{ED_i}{PD_i}$	Earned Duration Index, for activity i	Progress and performance measures	Micro	(18)
$SPI_i = \frac{EV_i}{PV_i}$	Schedule Performance Index, for activity i Cost (an EVM terminology)	Progress and performance measures	Micro	(19)
$CPI_i = \frac{EV_i}{AC_i}$	Cost Performance Index, for activity i Cost (an EVM terminology)	Progress and performance measures	Micro	(20)
$PPI = \frac{ED(t)}{BPD}$	Project Progress Index	Progress and performance measures	Macro	(21)
$DPI = \frac{ED(t)}{AD}$	Duration Performance Index, for project	Progress and performance measures	Macro	(22)
$EDI = \frac{TED}{TPD}$	Earned Duration Index, for project	Progress and performance measures	Macro	(23)
$CPI = \frac{EV}{AC}$	Cost Performance Index, for project (an EVM terminology)	Progress and performance measures	Macro	(24)
$EDAC = \frac{BPD}{DPI_p}$	Estimated Duration at Completion	Progress and performance measures	Macro	(25)
$EDAC = \frac{AD}{PPI}$	Estimated Duration at Completion	Progress and performance measures	Macro	(26)
$EDTC = \frac{BPD}{DPI_p} - AD = \frac{AD\tilde{n}(1-PPI)}{PPI}$	Estimated Duration To Complete, for project	Progress and performance measures	Macro	(27)
$DV_i = ED_i - PD_i$	Duration Variance for activity i	Progress and performance measures	Micro	(28)
$TDV = TED - TPD$	Total Duration Variance for Project	Progress and performance measures	Macro	(29)
$DV = ED(t) - AD$	Duration Variance for Project	Progress and performance measures	Macro	(30)
$CV_i = EV_i - PV_i$	Cost Variance for activity i	Progress and performance measures	Micro	(31)
$CV = EV - PV$	Cost Variance for project	Progress and performance measures	Macro	(32)
$DEI_i = \frac{BPD_i}{AD_i}$	Duration Estimation Index of activity i	Duration and cost estimation performance measures	Micro	(33)
$CEI_i = \frac{BPV_i}{AC_i}$	Cost Estimation Index of activity i	Duration and cost estimation performance measures	Micro	(34)
$DEI = \frac{\sum_{i=1}^{m} DEI_i}{m}$	Duration Estimation Index for project	Duration and cost estimation performance measures	Macro	(35)
$DEI = \frac{\sum_{i=1}^{m} (w_i \tilde{n} DEI_i)}{m}$	Duration Estimation Index for project (weighted)	Duration and cost estimation performance measures	Macro	(36)
$CEI = \frac{\sum_{i=1}^{m} CEI_i}{m}$	Cost Estimation Index for project	Duration and cost estimation performance measures	Macro	(37)
$CEI = \frac{\sum_{i=1}^{m} (y_i \tilde{n} CEI_i)}{m}$	Cost Estimation Index for project (weighted)	Duration and cost estimation performance measures	Macro	(38)

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Appendix 1

Table 1.A below presents EVM/ES results for the USCG project at the end of week 18.

Table 1.A
EVM results, USCG project, at the end of week 18.

	EV	PV	AC
Week 1	$ 9,242	$ 48,039	$ 47,110
Week 2	$ 21,590	$ 87,517	$ 88,121
Week 3	$ 33,940	$ 113,825	$ 122,100
Week 4	$ 46,290	$ 126,475	$ 133,100
Week 5	$ 58,640	$ 136,125	$ 144,100
Week 6	$ 72,964	$ 153,486	$ 157,914
Week 7	$ 90,890	$ 251,356	$ 173,905
Week 8	$ 134,982	$ 347,390	$ 311,951
Week 9	$ 207,505	$ 395,524	$ 409,452
Week 10	$ 288,317	$ 433,986	$ 429,816
Week 11	$ 380,362	$ 484,075	$ 473,683
Week 12	$ 380,362	$ 484,075	$ 473,683
Week 13	$ 384,601	$ 502,425	$ 509,511
Week 14	$ 392,878	$ 547,141	$ 551,244
Week 15	$ 404,124	$ 595,305	$ 588,585
Week 16	$ 418,309	$ 614,281	$ 625,624
Week 17	$ 440,288	$ 659,653	$ 674,570
Week 18	$ 467,789	$ 685,890	$ 703,086
Week 19		$ 739,214	
Week 20		$ 751,874	
Week 21		$ 766,624	
Week 22		$ 781,374	
Week 23		$ 804,772	
Week 24		$ 828,171	
Week 25		$ 846,890	
Week 26		$ 851,570	
Week 27		$ 858,943	
Week 28		$ 863,279	
Week 29		$ 887,813	
Week 30		$ 938,247	
Week 31		$ 984,069	
Week 32		$ 1,034,490	
Week 33		$ 1,079,281	
Week 34		$ 1,179,563	
Week 35		$ 1,261,157	
Week 36		$ 1,315,759	
Week 37		$ 1,390,280	
Week 38		$ 1,474,670	
Week 39		$ 1,531,854	
Week 40		$ 1,541,429	
Week 41		$ 1,580,029	
Week 42		$ 1,601,389	
Week43		$ 1,622,749	
Week 44		$ 1,646,911	
Week 45		$ 1,671,671	
Week 46		$ 1,696,431	

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Appendix 2

Table 2.A below presents EDM results for the USCG project at the end of week 18.

Table 2.A
EDM results, USCG project, at the end of week 18.

Week	Total earned duration (TED)	Total planned duration (TPD)	Total actual duration (TAD)
Week 1	16	18	19
Week 2	30	34	36
Week 3	40	43	49
Week 4	44	48	54
Week 5	48	54	59
Week 6	56	65	67
Week 7	66	80	78
Week 8	77	97	95
Week 9	88	113	112
Week 10	99	124	129
Week 11	110	134	144
Week 12	110	134	144
Week 13	122	140	159
Week 14	132	159	171
Week 15	139	179	181
Week 16	150	185	195
Week 17	170	190	220
Week 18	180	198	234
Week 19		204	
Week 20		210	
Week 21		215	
Week 22		220	
Week 23		225	
Week 24		230	
Week 25		234	
Week 26		235	
Week 27		240	
Week 28		245	
Week 29		262	
Week 30		288	
Week 31		306	
Week 32		316	
Week 33		331	
Week 34		355	
Week 35		376	
Week 36		389	
Week 37		408	
Week 38		428	
Week 39		444	
Week 40		447	
Week 41		459	
Week 42		464	
Week 43		469	
W eek 44		474	
Week 45		479	
Week 46		484	

Appendix 3

Table 3.A below presents EVM/ES results for the USCG project at the end of week 37.

Table 3.A
EVM results, USCG project, at the end of week 37.

	EV	PV	AC
Week 1	$ 9,242	$ 48,039	$ 47,110
Week 2	$ 21,590	$ 87,517	$ 88,121
Week 3	$ 33,940	$ 113,825	$ 122,100
Week 4	$ 46,290	$ 126,475	$ 133,100
Week 5	$ 58,640	$ 136,125	$ 144,100
Week 6	$ 72,964	$ 153,486	$ 157,914
Week 7	$ 90,890	$ 251,356	$ 173,905
Week 8	$ 134,982	$ 347,390	$ 311,951
Week 9	$ 207,505	$ 395,524	$ 409,452
Week 10	$ 288,317	$ 433,986	$ 429,816
Week 11	$ 380,362	$ 484,075	$ 473,683
Week 12	$ 380,362	$ 484,075	$ 473,683
Week 13	$ 384,601	$ 502,425	$ 509,511
Week 14	$ 392,878	$ 547,141	$ 551,244
Week 15	$ 404,124	$ 595,305	$ 588,585
Week 16	$ 418,309	$ 614,281	$ 625,624
Week 17	$ 440,288	$ 659,653	$ 674,570
Week 18	$ 467,789	$ 685,890	$ 703,086
Week 19	$ 497,234	$ 739,214	$ 722,107
Week 20	$ 542,217	$ 751,874	$ 798,774
Week 21	$ 592,112	$ 766,624	$ 821,274
Week 22	$ 651,281	$ 781,374	$ 834,638
Week 23	$ 695,663	$ 804,772	$ 858,145
Week 24	$ 699,208	$ 828,171	$ 884,262
Week 25	$ 703,129	$ 846,890	$ 897,561
Week 26	$ 704,175	$ 851,570	$ 899,633
Week 27	$ 713,433	$ 858,943	$ 910,375
Week 28	$ 723,137	$ 863,279	$ 922,175
Week 29	$ 732,844	$ 887,813	$ 933,975
Week 30	$ 755,441	$ 938,247	$ 954,898
Week 31	$ 779,473	$ 984,069	$ 976,834
Week 32	$ 803,503	$ 1,034,490	$ 998,770
Week 33	$ 829,857	$ 1,079,281	$ 1,010,285
Week 34	$ 859,377	$ 1,179,563	$ 1,013,992
Week 35	$ 859,968	$ 1,261,157	$ 1,017,328
Week 36	$ 862,292	$ 1,315,759	$ 1,036,114
Week 37	$ 870,915	$ 1,390,280	$ 1,089,307
Week 38		$ 1,474,670	
Week 39		$ 1,531,854	
Week 40		$ 1,541,429	
Week 41		$ 1,580,029	
Week 42		$ 1,601,389	
Week 43		$ 1,622,749	
Week 44		$ 1,646,911	
Week 45		$ 1,671,671	
Week 46		$ 1,696,431	

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Appendix 4

Table 4.A below presents EDM results for the USCG project at the end of week 37.

Table 4.A
EDM results, USCG project, at the end of week 37.

Week	Total earned duration (TED)	Total planned duration (TPD)	Total actual duration (TAD)
Week 1	16	18	19
Week 2	30	34	36
Week 3	40	43	49
Week 4	44	48	54
Week 5	48	54	59
Week 6	56	65	67
Week 7	66	80	78
Week 8	77	97	95
Week 9	88	113	112
Week 10	99	124	129
Week 11	110	134	144
Week 12	110	134	144
Week 13	122	140	159
Week 14	132	159	171
Week 15	139	179	181
Week 16	150	185	195
Week 17	170	190	220
Week 18	180	198	234
Week 19	185	204	242
Week 20	189	210	248
Week 21	192	215	253
Week 22	196	220	260
Week 23	201	225	267
Week 24	204	230	272
Week 25	207	234	276
Week 26	208	235	278
Week 27	212	240	283
Week 28	216	245	288
Week 29	220	262	293
Week 30	225	288	298
Week 31	229	306	303
Week 32	234	316	308
Week 33	238	331	313
Week 34	242	355	318
Week 35	246	376	323
Week 36	258	389	337
Week 37	282	408	364
Week 38		428	
Week 39		444	
Week 40		447	
Week 41		459	
Week 42		464	
Week 43		469	
W eek 44		474	
Week 45		479	
Week 46		484	

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Appendix 5

Table 5.A below presents activity actual duration and cost upon completion of the USCG project along with the performance measures for each activity.

Table 5.A
Activity actual duration and cost along with performance measures for the USCG project, upon completion of the project.

ID	Baseline Planned Duration (BPD_i)	Actual Duration (AD_i)	Baseline Cost	Actual Cost	API_i	DPI_i	DEI_i	CEI_i
5	5 days	7 days	$39,262.00	$40,000.00	100%	71%	71%	98%
6	2 days	4 days	$15,920.00	$20,000.00	100%	50%	50%	80%
7	3 days	3 days	$11,796.00	$13,000.00	100%	100%	100%	91%
9	4 days	6 days	$43,856.00	$70,000.00	100%	67%	67%	63%
10	3 days	7 days	$4548.00	$10,000.00	100%	43%	43%	45%
11	5 days	8 days	$30,610.00	$30,610.00	100%	63%	63%	100%
13	3 days	4 days	$4839.20	$7,000.00	100%	75%	75%	69%
14	3 days	5 days	$29,112.00	$29,112.00	100%	60%	60%	100%
15	3 days	3.5 days	$6391.20	$6,391.20	100%	86%	86%	100%
18	2 days	3 days	$69,480.00	$90,000.00	100%	67%	67%	77%
19	1 day	2 days	$60,870.00	$90,000.00	100%	50%	50%	68%
20	1 day	1.5 days	$368.00	$368.00	100%	67%	67%	100%
22	12 days	15 days	$35,400.00	$35,400.00	100%	80%	80%	100%
23	15 days	16 days	$70,196.00	$70,196.00	100%	94%	94%	100%
24	3 days	4 days	$5639.20	$5,639.20	100%	75%	75%	100%
25	10 days	13 days	$8672.00	$8,672.00	100%	77%	77%	100%
29	4 days	4 days	$8544.00	$10,000.00	100%	100%	100%	85%
30	5 days	9 days	$30,610.00	$36,000.00	100%	56%	56%	85%
31	6 days	8 days	$6504.00	$7,600.00	100%	75%	75%	86%
33	2 days	4 days	$1800.00	$1,850.00	100%	50%	50%	97%
34	2 days	2 days	$1936.00	$2,500.00	100%	100%	100%	77%
35	5 days	8 days	$23,980.00	$23,980.00	100%	63%	63%	100%
37	3 days	5 days	$5832.00	$6,300.00	100%	60%	60%	93%
38	4 days	4 days	$18,432.00	$24,000.00	100%	100%	100%	77%
39	3 days	3 days	$13,081.20	$15,000.00	100%	100%	100%	87%
41	2 days	2 days	$1728.00	$2,000.00	100%	100%	100%	86%
42	10 days	11 days	$21,440.00	$25,000.00	100%	91%	91%	86%
43	7 days	9 days	$14,546.00	$19,000.00	100%	78%	78%	77%
46	2 days	3 days	$9784.00	$12,000.00	100%	67%	67%	82%
47	3 days	4 days	$16,928.00	$16,000.00	100%	75%	75%	106%
49	2 days	2 days	$6832.00	$7,500.00	100%	100%	100%	91%
50	4 days	4 days	$6128.00	$6,000.00	100%	100%	100%	102%
52	4 days	6 days	$7724.00	$9,000.00	100%	67%	67%	86%
53	3 days	3 days	$12,776.00	$12,800.00	100%	100%	100%	100%
54	2 days	5 days	$4312.00	$7,000.00	100%	40%	40%	62%
56	2 days	2 days	$3776.00	$7,000.00	100%	100%	100%	54%
57	5 days	6 days	$6860.00	$7,000.00	100%	83%	83%	98%
58	5 days	8 days	$12,560.00	$15,000.00	100%	63%	63%	84%
61	1 day	1 day	$3248.00	$3,500.00	100%	100%	100%	93%
62	2 days	2 days	$4992.00	$5,000.00	100%	100%	100%	100%
63	2 days	2 days	$16,536.00	$20,000.00	100%	100%	100%	83%
65	1 day	1 day	$1888.00	$1,888.00	100%	100%	100%	100%
66	2 days	2 days	$2136.00	$2,500.00	100%	100%	100%	85%
67	3 days	3 days	$12,954.00	$13,000.00	100%	100%	100%	100%
69	1 day	1.5 days	$512.00	$1,000.00	100%	67%	67%	51%
70	2 days	2 days	$2736.00	$3,200.00	100%	100%	100%	86%
71	3 days	3 days	$17,904.00	$18,000.00	100%	100%	100%	99%
73	2 days	2 days	$4016.00	$5,000.00	100%	100%	100%	80%
74	2 days	2 days	$13,716.00	$14,600.00	100%	100%	100%	94%
75	3 days	3 days	$32,304.00	$35,000.00	100%	100%	100%	92%
79	0.5 days	0.5 days	$1872.00	$2,000.00	100%	100%	100%	94%
80	20 days	25 days	$50,600.00	$55,000.00	100%	80%	80%	92%
81	5 days	6 days	$5502.00	$6,000.00	100%	83%	83%	92%
83	4 days	5 days	$16,339.20	$20,000.00	100%	80%	80%	82%
84	20 days	30 days	$26,824.00	$26,824.00	100%	67%	67%	100%
87	3 days	4 days	$3186.00	$4,200.0	100%	75%	75%	76%

(continued on next page)

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Table 5.A (*continued*)

ID	Baseline Planned Duration (BPD_i)	Actual Duration (AD_i)	Baseline Cost	Actual Cost	API_i	DPI_i	DEI_i	CEI_i
88	5 days	5 days	$10,020.00	$10,020.00	100%	100%	100%	100%
90	8 days	10 days	$8224.00	$8,500.00	100%	80%	80%	97%
92	10 days	12 days	$6068.00	$6,200.00	100%	83%	83%	98%
96	12 days	13 days	$44,564.40	$56,000.00	100%	92%	92%	80%
97	4 days	5 days	$20,604.80	$21,000.00	100%	80%	80%	98%
99	2 days	2 days	$3040.00	$3,040.00	100%	100%	100%	100%
100	4 days	5 days	$11,515.20	$12,000.00	100%	80%	80%	96%
101	15 days	16 days	$33,156.00	$34,000.00	100%	94%	94%	98%
102	2 days	3 days	$4560.00	$5,000.00	100%	67%	67%	91%
104	3 days	4 days	$8485.60	$8,600.00	100%	75%	75%	99%
105	4 days	5 days	$17,985.60	$18,000.00	100%	80%	80%	100%
106	14 days	14 days	$92,488.00	$92,488.00	100%	100%	100%	100%
107	4 days	5 days	$19,521.60	$20,000.00	100%	80%	80%	98%
109	15 days	15 days	$81,696.00	$100,000.00	100%	100%	100%	82%
110	12 days	14 days	$52,204.80	$60,000.00	100%	86%	86%	87%
111	5 days	5 days	$25,652.00	$26,000.00	100%	100%	100%	99%
112	5 days	6 days	$24,800.00	$24,800.00	100%	83%	83%	100%
115	1 day	1.5 days	$11,968.00	$22,000.00	100%	67%	67%	54%
116	3 days	4 days	$2894.40	$3,000.00	100%	75%	75%	96%
117	2 days	3 days	$3240.00	$3,500.00	100%	67%	67%	93%
119	4 days	5 days	$6822.00	$7,000.00	100%	80%	80%	97%
120	2 days	2 days	$1024.00	$1,000.00	100%	100%	100%	102%
122	9 days	10 days	$16,416.00	$17,000.00	100%	90%	90%	97%
123	2 days	2 days	$3424.00	$3,500.00	100%	100%	100%	98%
125	20 days	20 days	$17,601.00	$19,000.00	100%	100%	100%	93%
126	3 days	4 days	$2700.00	$2,700.00	100%	75%	75%	100%
127	10 days	12 days	$13,274.00	$13,274.00	100%	83%	83%	100%
130	5 days	5 days	$16,440.00	$16,600.00	100%	100%	100%	99%
131	5 days	5 days	$16,440.00	$16,800.00	100%	100%	100%	98%
132	2 days	4 days	$3238.40	$4,000.00	100%	50%	50%	81%
133	3 days	3 days	$23,450.00	$25,000.00	100%	100%	100%	94%
135	3 days	4 days	$5628.00	$6,000.00	100%	75%	75%	94%
136	2 days	3 days	$1641.60	$1,900.00	100%	67%	67%	86%
137	5 days	6 days	$8184.00	$9,000.00	100%	83%	83%	91%
139	4 days	5 days	$14,432.00	$15,000.00	100%	80%	80%	96%
140	2 days	5 days	$6384.00	$7,000.00	100%	40%	40%	91%
141	2 days	3 days	$3504.00	$5,000.00	100%	67%	67%	70%
143	10 days	10 days	$46,400.00	$50,000.00	100%	100%	100%	93%
144	12 days	14 days	$51,264.00	$55,000.00	100%	86%	86%	93%
146	1 day	2 days	$3976.00	$6,000.00	100%	50%	50%	66%
147	1 day	2 days	$2429.60	$3,000.00	100%	50%	50%	81%
148	1 day	1 day	$9212.00	$15,000.00	100%	100%	100%	61%
149	10 days	11 days	$49,520.00	$55,000.00	100%	91%	91%	90%

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