• ABSTRACT •

Earned value management (EVM), a technique mainly used to manage project cost, was developed during the second half of the twentieth century by an agency of the USA government. It was enriched, at the beginning of the current century, with an extension named earned schedule (ES) (Lipke, 2003), which added to EVM the capability to manage the project schedule. In 2014, earned duration management (EDM), a novel, and monetary value free technique for project schedule management, was proposed by Khamooshi and Golafshani (2014). Earned duration (ED), the project schedule indicator from EDM uses only activity dates and durations from EVM, and aims at replacing ES. By not using cost as a proxy for time, ED overcomes one of the most criticized aspect of ES. This paper intends to (i) compare ED with ES to learn some fundamental lessons, (ii) propose the combination of ED and planned value (PV) from EVM to produce an EDM-based project-level earned value (EV^d), and (iii) assess the adequacy of EV^d as an alternative to earned value (EV) from EVM in project time and cost management. The comparison between the project real cost and both EVM and EDM-based independent estimates at completion, on a set of real projects, was the vehicle for assessing the adequacy of EV^d as a viable alternative to EV. Workload avoidance by replacing activities earned value calculations with the simpler and more consistent determination of the activities earned durations, and the enhanced visibility of potential schedule problems caused by lower cost/duration ratio activities, are benefits that EV_d offers to project managers.

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COMBINING EDM AND EVM

a proposed simplification for

PROJECT TIME

and COST MANAGEMENT

1.INTRODUCTION

EVM is a methodology used to measure and communicate the real physical progress of a project and to integrate the three critical elements of project management (scope, time and cost management).

The PMI survey (Pulse of the Profession, 2016) informs that 33% of surveyed organization uses EVM in their projects. Although this is a good slice of the participants, of the 33% only 12% always uses it and 21% of the respondents inform that they often use the technique. Given the time EVM exists (the reader is referred to The Measurable News edition 2017-2 to have an overview of the history of EVM), it is reasonable to expect it to have a larger presence in the project management community.

Recognized experts point to barriers to the dissemination of EVM. Among these, the most common are lack of motivation, lack of expertise and lack of top management support (Song, 2010). Another obstacle is the foreign language often spoken by EVM advocates (Fleming and Koppelman, 2004). Hurdles like lack of a proper cost data collection process, lack of tools that supports EVM, unclear cost/benefit justification, cost of implementation, etc. impose additional difficulties to EVM widespread adoption.

Executive support and motivation are the prime resources needed by project managers to properly implement EVM on their projects. To gain such support, project managers need to be experts on EVM

beforehand and sell its benefits to the organization management body. The PMs will not be able to do the selling unless they are capable of translating EVM jargon to top management language.

EVM reputation, developed during its infancy in the US Department of Defense (DoD), as a complex and sophisticated system that should be applied only to large projects, scared project managers away from the technique. This confuses and frighten the newcomers. However, EVM can be used in projects of any size that have a properly developed WBS, a schedule based on this WBS, a budget that can be distributed among the work packages of the WBS and a process to acquire actual schedule and cost information during its execution. EVM is also easy to understand should the PM receive appropriate guidance and invest time on learning it. However, EVM is a laborious endeavor and requires discipline from the project team to deliver its benefits. The proposal in this paper should help reduce EVM generated work burden while maintaining its advantages.

This paper is organized in six sections and a reference section at its end. After this Introduction, section 2 reviews some pertinent literature.

Section 3 presents an overview of the EVM and EDM techniques explaining and providing a graphical visualization of their main elements, and introducing their usage in the project management domain. The equations involved in the creation of the S curves for the EVM and EDM elements, as well as ES and ED calculations are presented. Section 3 contains a table showing the correspondences between EVM and EDM indicators and indexes, and ends with a description of the usage of EVM and EDM in project management.

Section 4 conceptualizes the proposed combination. Subsection 4.1 shows a graphical visualization of the EDM/EVM combination as well as the equation to calculate the earned value of the proposal. A brief explanation of the mean absolute percentage error (MAPE) is given. Three criteria for selecting real projects from the OR-AS database (Batselier and Vanhoucke, 2014, 2015) are shown in subsection 4.2. Four projects were selected for the assessment of the proposed EDM/EVM combination using these criteria. A table with relevant information on these four projects is provided.

Section 5 graphically compares the elements of EVM and EDM for the four selected projects and the found differences are considered. In sequence, the proposed EVM/EDM combination is practiced on the selected projects, and the resulting graphs and MAPE values are examined and commented. The ability of the proposal in providing viable independent estimate at completion for cost without the need for using the traditional earned value activity calculation is ascertained. After that, the lessons learned are summarized. Additional 10 projects, from the same database, are used to further check the validity of the proposal. An analysis of the results for the fourteen projects is conducted.

In section 6 the conclusions and recommendations are presented.

2. LITERATURE REVIEW

Earned Schedule was first described in Lipke's seminal article (2003) which was expanded and detailed in his book "Earned Schedule" (Lipke, 2009), and first analyzed, from an academic perspective, in the book "Measuring Time" (Vanhoucke, 2010a), which was awarded the IPMA Research Award. ES was a fundamental contribution to the solution of the long-standing problem of schedule management in EVM.

The paper by Vandevoorde and Vanhoucke (2006) concluded, after testing three different project duration forecast methods with three real-life projects, that "Earned Schedule was the only method which showed satisfying and reliable results during the whole project duration". A subsequent study of the same three forecasting methods by Vanhoucke and Vandevoorde (2007), with extensive simulation on a set of 4,100 computer generated artificial projects with 30 activities each, confirmed that "the ES method outperforms, on the average, all other forecasting methods".

However, critiques to ES surfaced as it is dependent on activities planned cost to produce its schedule indicators. A paper by Kamooshi, and Golafshani (2014) proposed Earned Duration Management (EDM), a novel technique that, although based on a subset of EVM data, avoids the usage of monetary values to produce its project duration indicators.

The paper by Batselier and Vanhoucke (2015b) appraised two techniques which integrate rework and activity sensitivity as extensions in EVM time forecasting along with EDM. 24 real-life projects from OR-AS database (Batselier and Vanhoucke, 2015a) were used in this study and the conclusion was that the two EVM extension techniques exhibit accuracy-enhancing power for different applications, while EDM performed very similar to the best EVM methods.

The paper by Andrade et al., (2015) used a notional project to demonstrate the dependency of EVM-ES schedule performance index [(SPI(t)] upon the activity planned cost.

The research by Khamooshi and Abdi (2016), which tested 19 projects from a spectrum of types (U.S. Armed Forces, Telecom, IT, R&D and Construction), found that EDM is a preferred option when compared to EVM-ES.

3. BACKGROUND

3.1. Project management and control with EVM

The earned value technique aims at measuring the efficiency of expenditures applied to project tasks. One of the most important planning task is creating the project schedule by establishing the dependencies among the activities, attributing a duration to every task and determining their planned start date. During the baseline schedule construction phase, the project budget is distributed among the work packages and along each task duration. The result

is summed up in each period and then accumulated over the project makespan to generate the project planned value S-Curve. The main elements of EVM are the three curves in Fig. 1: planned value (*PV*), actual cost (*AC*) and earned value (*EV*). Formally, the planned value for period t, PV_t, can be described by the following equation:

$$PV_t = \sum_{j=1}^{t} \sum_{j=1}^{n} PC_{ij} \tag{1}$$

where:

PC_{ij} represents the non-cumulative planned cost for activity *i* at period *j*;

n is the number of activities in the project; and

t represents the period for which the value of *PV* should be found. The *PV* curve results when t is varied from 1 to the project baseline planned duration (*BPD* or *PD*). For *t=PD* results:

$$PV_{PD} = \sum_{j=1}^{PD} \sum_{j=1}^{n} PC_{ij} = BAC$$

The same algebraic construction can be used to calculate AC_t (actual cost for period *t*) after proper substitution of PC_{ij} by AC_{ij} (the non-cumulative cost of activity *i* at period *j*) the equation below results:

$$AC_t = \sum_{j=1}^{t} \sum_{j=1}^{n} AC_{ij} \tag{2}$$

To determine the earned value for period *t*, EV_t, the project manager needs to find the earned value for every activity of the project up to and including period *t*, EV_{it}, resorting to any of the following methods (PMI, 2011):

1. Percent-complete (PC). Multiply the total planned value assigned to the activity by an estimated percentage of its completeness;

2. 50/50 method. Before the activity start EV is 0 (zero); EV is 50% of the total planned value of the activity; 100% upon its completion;

3. 25/75 method. Before its start the activity EV is 0 (zero); EV is 25% of the total planned value of the activity when it is started and reaches 100% of the total planned value upon completion of the activity.

4. Milestone method. After the activity completes EV reaches the total planned value for the activity, before completion EV value is 0 (zero).

5. Weighted milestone method. In longer duration activities, a weighted value can be assigned to the achievement of each intermediate and tangible results (interim milestone). These values can then be used as the milestone method above.

6. Physical measurement. The measurement of physical entities that can be related to the progress of the activity towards its completion. This measurement which includes all material, effort, and other involved resources, is converted to a monetary unit and used as the activity earned value.

After determining EV_{it} for every project activity up to and including *t*, EV_t is calculated as follows:

$$EV_t = \sum_{i=1}^{n} EV_{it} \tag{3}$$

EV_t measures the project physical advancement in terms of the planned value. In other words, EV_t represents the material result of the application of effort, resources and money to the project activities up to, and including, period *t*.

Equations (1), (2) and (3) were used (along with correspondent equations for EDM) to create a spreadsheet application for the calculations used to construct the curves and tables in section 5.

EVM uses the PV curve as the cornerstone for controlling the project. The project manager and his team monitors the progress of the project against the PV curve at predetermined times known as status dates (SD) at actual time (AT). At each SD, information about the activities are collected and EVM used to determine and communicate the progress of the project. Cost variation (CV), defined as the difference "EV – AC", and schedule variation (SV), as "EV – PV" are reported. Here surfaces the first critique to EVM as a technique for managing project schedules, SV, a monetary value, is used to report the project schedule status.

The second and more incisive critique to EVM schedule management ability is that, at the end of the project, SV reaches €0 (zero monetary value) indicating that the project finished as planned, irrespective of it being late (Lipke, 2003). EVM, therefore, fails to properly indicate schedule performance. Earned schedule was the result of the attempts at creating a sound schedule indicator from EVM data.

Fig. 1, which includes earned schedule (ES) concept, illustrates a set of PV, EV and AC curves as they would appear in a typical project. Examining Fig. 1, it becomes evident that ES offer a sensible solution for the second critique above.
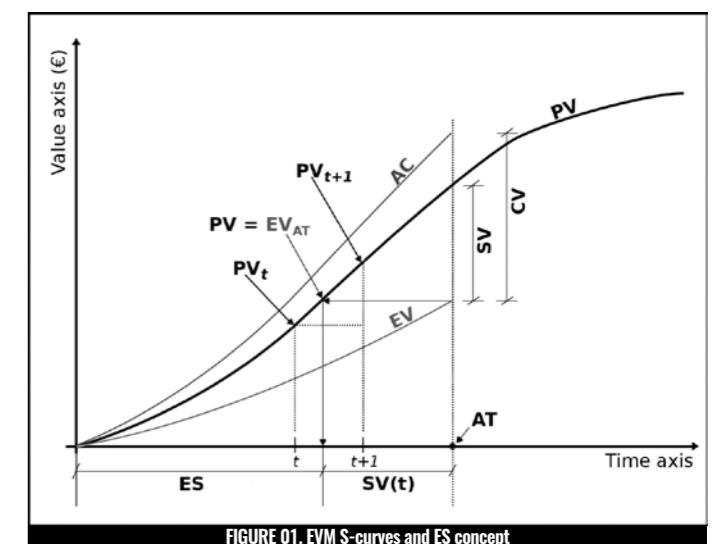

FIGURE 01. EVM S-curves and ES concept

Table 1 provides the meaning of some EVM-ES abbreviations.

BAC	Budget at completion. Also known as *baseline cost*.
PD	Planned Duration. The project planned duration (time elapsed from planned start to planned finish). Also known as Baseline Planned Duration (BPD).
SD	Status date. The calendar date when the EVM measurements were taken. Status date and actual time (AT) are used interchangeably.
AT	Actual time. The time elapsed from project start till the status date. The same as actual duration (AD) from EDM.
EV	Project Earned value at SD.
CV	Cost variation at SD.
CPI	Cost Performance Index at SD.
SV	Schedule variation at SD (Measured in monetary units).
SPI	Schedule performance index (cost based).
$SV(t)$	Schedule variation at SD. The small t between parenthesis indicates that this element is measured in time units.
$SPI(t)$	Schedule performance index (schedule based).
EAC	Estimate at completion for cost.
ETC	Estimate to complete for cost. This is a projection for how much resources (expressed as a monetary value) will be needed to complete the project from SD on.
$EAC(t)$	Estimate at completion for time.
$ETC(t)$	Estimate to complete for time. This is a projection for how much time (expressed as workdays) will be needed to complete the project from SD on.
t	Integer period t on the project makespan.
$t+1(UC)$	Next integer period after t on the project makespan. UC (the abbreviation of "project unit of calendar") indicates that the number "1" is a unit of time.
PV_t	The planned value at time t which satisfy the following relationship $EV \geq PV_t$.
$PV_{t+1(UC)}$	The planned value at time $t+1UC$ which satisfy the following relationship $EV < PV_{t+1(UC)}$.
ES	The time interval from the beginning of the project up to the projection, on the time axis, of the point on the PV curve whose ordinate is equal to EV.
PC_i	Percent complete for activity i.
EV_i	Earned value for activity i.
TABLE 01. Explanations of EVM terms	

With the explanation in Table 1 and referring to Fig. 1, the equation for ES is:

$$ES = t + \frac{EV - PV_t}{PV_{t+1(UC)} - PV_t} \times 1(UC) \qquad (4)$$

In (4) ES is the result of the sum of t periods (t is a whole number) such that $EV \geq PV_t$ and $EV < PV_{(t+1(UC)}$, with a fraction of a period represented by:

$$\frac{EV - PV_t}{PV_{t+1(UC)} - PV_t} \times 1(UC)$$

With ES constructed, SV(t) is defined as the difference "ES-AT", and SPI(t) as the ratio "ES/AT".

3.2. Schedule management and control with EDM

Like EVM, the idea behind the technique presented by Khamooshi and Golafshani (2014), Earned Duration Management (EDM), is to build the S-curve of the cumulative units of duration of the project activities. In EDM there is no consideration for the cost or effort involved in an activity. EDM only deals with the planned, estimated, earned and actual durations of project tasks. Consequently, distinct from EVM-ES, EDM avoids the use of monetary units as a proxy for time in its calculations.

Fig.2. depicts the earned duration management concept and some of its elements. The total planned duration (TPD) is the curve created by counting the planned tasks that exist in each unit of calendar (period) of the project and accumulating this over the project planned duration, in a process similar to the construction of the PV curve of EVM. The total actual duration (TAD) represents the number of tasks that were worked in each period accumulated up to the actual duration (AD), and the total earned duration (TED) is the accumulated curve, up to AD, of the effectively earned periods of the tasks worked.

Formally, the EDM equations for TPD, TAD and TED are:

$$TPD_t = \sum_{j=1}^{t} \sum_{i=1}^{n} CP_{ij} \qquad (5)$$

where:

TPD_t represents the total planned duration at period t;

CP_{ij} is a count of 0 (zero) or 1 (one) depending on the existence of planned activity i during period j;

n is the number of activities in the project; and

t is the period for which TPD should be found. The TPD curve results when t is varied from 1 to the project planned duration (PD).

The total actual duration for period t, TAD$_t$, is calculated using the equation below:

$$TAD_t = \sum_{j=1}^{t} \sum_{i=1}^{n} CA_{ij} \qquad (6)$$

where: TAD$_t$ represents the total actual duration at period t;

CA_{ij} is a count of 0 (zero) or 1 (one) depending on the existence of actual activity i during period j;

n same meaning as above;

t is the period for which TAD is sought.

The determination of the TED value for period t of the project follows a similar process as for the calculation of EV$_t$ in EVM. At period t and for every project activity i, the PM estimates the value, in units of time, of its earned duration. Next, the total earned duration up to, and including, period t is calculated using the following equation:

$$TED_t = \sum_{i=1}^{n} ED_{it} \qquad (7)$$

where: TED$_t$ represents the total earned duration at period t;

ED$_{it}$ is the value of the earned duration for activity i up to, and including, period t;

n,t same meaning as above.

Visually Fig. 1. and Fig. 2. are very similar. In both figures, the horizontal axis (time axis) represents the same entity, the passage of time. However, while in Fig. 1 the vertical axis is a measure of project value (planned, actual or earned). In Fig. 2 the unit of the vertical axis is not related to any usual project measurement (neither money nor, as a matter of fact, any unit of effort [e.g. man.hour]
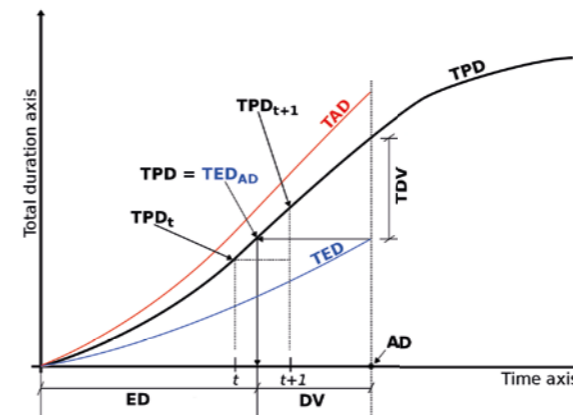

FIGURE 02. EDM S-curves and ED concept

or production [e.g. units produced] that are, sometimes, used in EVM), its unit is an accumulation of the duration of work, planned, actual or earned. This measure can be expressed in workhours, workdays or workweeks. In this paper, the unit of total duration is workdays (wds).

Like EVM, at any point of the project makespan the total duration variance (TDV) is defined as the difference "TED – TPD", and the duration variance (DV) is defined as "ED – AD".

To facilitate the adoption of EDM, Khamooshi (2014) suggested a way of using commercial project management software to handle EDM. His suggestion was to zero out or remove all resources in the project, create one resource with the cost of 1 monetary unit per day and apply it to every task. Then, using the earned value calculation capabilities of the software, one would be able to generate all EDM indicators, indexes and graphs.

Care must be exercised while using this suggestion to not confuse the activity *i percent complete index* (PC$_i$), used to calculate the activity earned value (or activity progress), with the *activity schedule progress index* (API$_i$), which measures the progress, in terms of time, of an activity towards its completion. Only in cases where the progress of an activity guards a linear relationship (in terms of scope or physical progress) with time, it can be assumed that PC$_i$ is an accurate measure of progress in schedule (Khamooshi and Golafshani, 2014). Having the API$_i$ for an activity, its earned duration, ED$_i$, is calculated by the multiplication of the activity baseline planned duration, BPD$_i$, by the API$_i$:

$$ED_i = BPD_i \times API_i \qquad (8)$$

When there is no linear relationship between the activity progress and time, an alternative method of determining the API$_i$ is by estimating the remaining duration of activity i and applying the following equation (Khamooshi and Golafshani, 2014):

$$API_i = \frac{AD_i}{AD_i + ETC(t)_i} \qquad (9)$$

where AD$_i$ is the actual duration of activity i at the status date, and ETC(t)$_i$ is the estimated duration to complete activity i at the status

date. ETC(t)$_i$ is estimated by subject matter experts (which may well be members of the project team).

Table 2 provides explanation for some Fig. 2 as well as other EDM abbreviations.

AD	Actual duration. The time elapsed from project start till SD.
TPD	Total planned duration.
TED	The total earned duration.
TAD	Total actual duration.
TDV	Total duration variation at AD: the difference between TED and TPD.
ED	Earned duration: the time interval from the beginning of the project up to the projection, on the time axis, of the point on the TPD curve whose ordinate is equal to TED.
ED_i	The earned duration for activity i at any chosen time.
DV	Duration variation at AD: the difference between ED and AD.
DPI	Duration performance index.
$EAC(t)^d$	Project estimated duration at completion (also known as EDAC).
t	Integer period t on the project makespan.
$t+1(UC)$	Next integer period after t on the project makespan.
TPD_t	The total planned duration at time t such that $TED \geq TPD_t$.
$TPD_{t+1(UC)}$	The planned value at time $t+1UC$ such that $TED < TPD_{t+1(UC)}$.
$ETC(t)_i$	Estimated duration to complete for activity i.
PD_i	Planned duration for activity i
API_i	Activity i progress index at a chosen time.
TABLE 02. Explanations of EDM terms.	

where AD$_i$ is the actual duration of activity i at the status date, and ETC(t)$_i$ is the estimated duration to complete activity i at the status date. ETC(t)$_i$ is estimated by subject matter experts (which may well be members of the project team).

Table 2 provides explanation for some Fig. 2 as well as other EDM abbreviations.

Recent papers (Khamooshi and Abdi, 2016; Andrade et al., 2015) demonstrated that EDM's independency of the activities planned values results in superior and reliable project duration prediction performance. They also clarified the effect that using cost as a proxy for time has on ES because of the impact of activities planned values on EV curve profile. The EV curve profile depends strongly on activities planned values, actual start dates and actual durations. To exemplify this, suppose that two activities, with the same planned duration and planned start date but with largely dissimilar planned values, are subject to varied delays during project execution, the resulting EV curve profiles will be distinct and dependent on which activity is delayed further. This profile variation produces incoherent ES values. ED, which is immune to activities planned values, do not present such behavior.

A comparative study of EVM-ES and EDM schedule indicators for project duration forecast performance, conducted over 19 projects from different industries, concluded that "a duration-based performance measure is a better indicator for use in predicting the duration of a project" and "The EDM model (or EDAC) outperforms the ES model [or EAC(*t*)] in duration forecasting." (Khamooshi and Abdi, 2016).

--- 3.3. Correspondent equations for EVM/EDM cost and schedule indicators and indexes ---

EDM Equations	EVM -ES Equations	Notes
$DPI = \dfrac{ED}{AD}$ (10)	$SPI(t) = \dfrac{ES}{AT}$ (11)	AD and AT are synonyms
Find t such that $TED \geq TPD_t$ and $TED < TPD_{t+1(UC)}$ $ED = t + \dfrac{TED - TPD_t}{TPD_{t+1} - TPD_t}$ (12)	Find t such that $EV \geq PV_t$ and $EV < PV_{t+1(UC)}$ $ES = t + \dfrac{EV - PV_t}{PV_{t+1} - PV_t}$ (13)	These are the earned duration and earned schedule for the project. (t may have different values for EDM and EVM).
$EAC(t)^d = AD + \dfrac{BPD - ED}{DPI}$ (14)	$EAC(t) = AT + \dfrac{BPD - ES}{SPI(t)}$ (15)	Forecast project duration at completion
$ETC(t)^d = \dfrac{BPD}{DPI} - AD$ (16)	$ETC(t) = \dfrac{BPD}{SPI(t)} - AT$ (17)	These equations may be used to calculate an independent estimate of the time to complete the project
$ETC(t)_i$	$ETC(\$)_i$	These values are estimated by subject matter experts or the PM team for every activity at SD.
$API_i = \dfrac{AD_i}{AD_i + ETC(t)_i} \times 100$ (18)	$PC_i = \dfrac{AC_i}{AC_i + ETC(\$)_i} \times 100$ (19)	API_i and PC_i may be calculated using the formulas or estimated directly by the PM team.
$ED_i = BPD_i \times API_i$ or (20) $ED_i = BPD_i \times PC_i$	$EV_i = PV_i \times PC_i$ (21)	If there is a linear relationship between the activity progress and time PC_i can be used to calculate ED_i for activity i.
N/A	$EAC(\$) = AC + \dfrac{BAC - EV}{CPI}$ (22)	Forecast project cost at completion
N/A	$CPI = \dfrac{EV}{AC}$ (23)	Cost performance index
N/A	$SPI = \dfrac{EV}{PV}$ (24)	Schedule performance index

TABLE 03. Correspondence and associated equations for EDM/EVM indices and indicators

--- 3.4. Project management and control using EDM and EVM ---

Having both techniques, it is natural to proceed using them to manage project cost and time independently. Although, in many projects this may be justifiable, a question is raised:

• Is there a way to avoid the work involved in calculating two sets of indexes (PC_i and API_i) and the complexity of running separate EDM and EVM calculations?

The duration profile of an activity is always linear, one workday is always equal to one workday independent of it being less or more productive. The value profile of an activity, however, may be non-linear as it depends on the distribution of workload and/or other values along its duration. Therefore, ascertaining an activity earned value may require a significant effort from the project manager and/or its team members. On the other hand, determining the earned duration of an activity is, normally, easier.

The combination of EDM and EVM, proposed in this paper, offers a process for calcu-

lating an alternative earned value for the project which, by replacing EV from EVM, avoids the need for determining the EV_i for every activity at each status date. Using this combination reduces complexity and eases the burden upon the project manager and his team members.

4. ADDITIONAL EDM/EVM DETAILS AND CONCEPT OF THE PROPOSED COMBINATION

--- 4.1. Combining EDM and EVM ---

Using EVM for project cost management and EDM, instead of EVM-ES, for project schedule management and estimating the project duration, may impose an additional workload burden on the project manager. For projects in which no linear relationship between activity progress and time exists, it will be necessary, at each status date and for every activity i, to additionally generate the activity i schedule progress index (API_i) and calculate the activity ED_i using the equation $ED_i = API_i \times PD_i$, where PD_i is the planned duration for activity i.

The present paper proposes a process for using ED from EDM along with PV from EVM to calculate an alternative project earned value (named to EV^d distinguish from the original EV from EVM) which avoids the need for the determination of the PC_i for the project activities on each status date. This EV^d would be a substitute for EV from EVM.

The concept of the proposed combination is exhibited in Fig. 3. Its top portion shows the S curves for TPD and TED from the EDM technique. In sync with the top portion, the bottom portion displays the PV and AC curves from the EVM technique. Along with these curves the process to produce EV^d is depicted: the ED from EDM is projected down to the EVM diagram and reaches the PV curve at a point that has EV^d as its ordinate.

When ED, as is the case in Fig. 3, falls between consecutives time periods t and t+1(UC), it is necessary to perform the interpolation depicted in Fig. 4 which is an expansion of the portion of Fig. 3 enclosed in a dashed rectangle called "Section of interest".
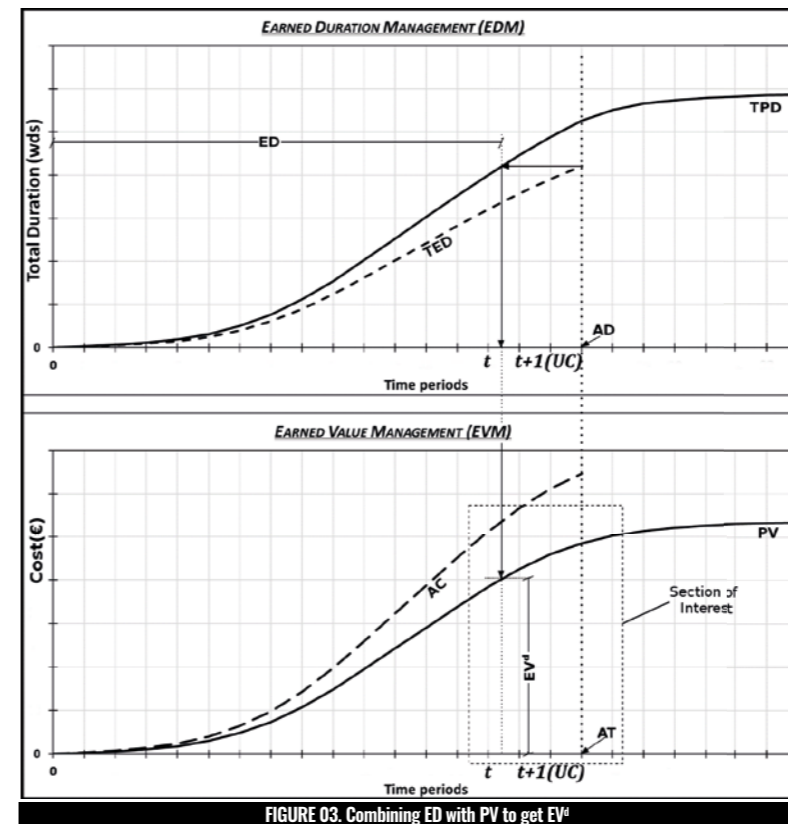

FIGURE 03. Combining ED with PV to get EV^d
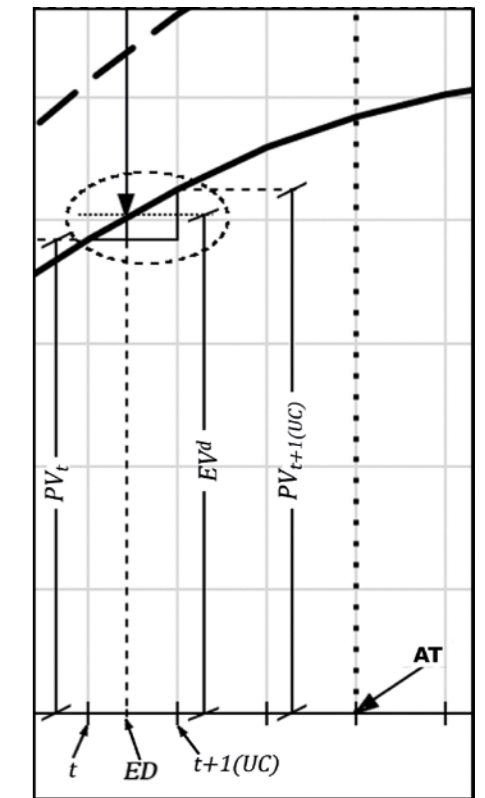

FIGURE 04. Interpolation expanded view

Inside the ellipse in Fig. 4, one can identify two triangles in solid lines. The property of similarity between these triangles is used to derive the interpolation equation.

Using t to indicate the period in project calendar units, UC as the abbreviation of "project unit of calendar" and the properties of triangle similarity the following equation results:

$$\frac{EV^d - PV_t}{PV_{t+1(UC)} - PV_t} = \frac{ED - t}{t+1(UC) - t}$$

After convenient rearrangement of terms, the equation for EV(d) emerges:

$$EV^d = \frac{PV_t + ED - t}{t+1(UC) - t} \times (PV_{t+1(UC)} - PV_t) \quad (25)$$

The elements on the right side of equation (25) are selected respecting the following constraints ED≥t and ED<t+1(UC); and PV(d)$_t$ and PV(d)$_{t+1(UC)}$ are the project PV values at time periods t and t+1(UC), respectively.

As t+1(UC)-t=1(UC) the above equation is rewritten as:

$$EV^d = PV_t \ \frac{ED - t}{1(UC)} \times (PV_{t+1(UC)} - PV_t) \quad (26)$$

In the mentioned application spreadsheet, EV^d is computed, for each workday of the project makespan.

Replacing EV with EV^d produces a set of EDM-based cost indicators alternatives to their EVM counterparts. The alternative to cost performance index

(CPI) from EVM is the EDM-based CPI^d. The alternative to estimate at completion (EAC($\$$)) from EVM is the EDM-based EAC($\$$)^d.

In section 6, EV^d will be used to produce a new estimate at completion EAC($\$$)^d for the cost of the selected projects. The equation for EAC($\$$)^d is:

$$EAC(\$)^d = AC + \frac{BAC - EV^d}{CPI^d} \quad (27)$$

$$\text{where:} \quad CPI^d = \frac{EV^d}{AC} \quad (28)$$

Like equation to estimate project duration at completion, EAC(t)^d, is:

$$EAC(t)^d = AD + \frac{PD - ED}{DPI} \quad (29)$$

The mean absolute percentage error (MAPE) will be used to compare the project real cost (RC) against EAC($\$$) and EAC($\$$)^d and real duration (RD) against EAC(t) and EAC(t)^d. The approach adopted is based on the book "Measuring time – improving project performance using earned value management" (Vanhoucke, M., 2010a). where MAPE is defined according to the following equations:

$$MAPE(Cost) = \frac{100\%}{n} \times \sum_{t=1}^{n} \left| \frac{RC - FC_t}{RC} \right| \qquad (30)$$

$$MAPE(Time) = \frac{100\%}{n} \times \sum_{t=1}^{n} \left| \frac{RD - FD_t}{RD} \right| \qquad (31)$$

where:

n is the number of time periods in the project makespan;

RC is the real cost of the project at completion;

FCt Is the forecasted cost of project in period t;

RD is the real duration of the project at completion;

FD_t is the forecasted duration of project in period t.

FCt may assume the value of EAC(\$) or EAC(\$)^d at period t. As well, FD_t may assume the value of EAC(t) or EAC(t)^d at period t.

--- 4.2. Real projects selection criteria and summary data for selected projects ---

Real projects will be the vehicle for the comparative assessment of EDM/EVM combination versus EVM in project cost management. The criteria below will be used in the selection of real projects from the OR-AS database (Batselier and Vanhoucke, 2015b) for the study:

(i) Each project uses only variable costs (by avoiding projects with fixed cost activities, this criterion allows the assumption of a linear relationship between activity progress and time, and, therefore, the identity between PC_i and API_i was used in the model spreadsheet);

(ii) All activities planned durations are expressed in days, not in hours;

(iii) No projects have holidays in the agenda.

The following fourteen projects from the real project data database fit these criteria:

• C2013-03 Brussels Finance Tower.xlsx

• C2014-04 Compressor Station Zelzate.xlsx

• C2014-08 Apartment Building (4).xlsx

• C2015-02 Railway Station (1).xlsx

• C2015-03 Industrial Complex (1).xlsx

• C2015-04 Apartment Building (5).xlsx

• C2015-05 Apartment Building (6).xlsx

• C2015-06 Family Residence (2).xlsx

• C2015-07 Industrial Complex (2).xlsx

• C2015-08 Garden Center.xlsx

• C2015-09 Railway Station (2).xlsx

• C2015-27 Railway Station Antwerp.xlsx

• C2015-35 Retirement Apartments.xlsx

• C2016-08 SCM System.xlsx

Four projects out of these fourteen have been selected for further analysis. The reason for selecting them was the fact that they allow for the fundamentally different conclusions shown in section 5.7. Some information on these four projects are provided in Table 4.

5. REAL PROJECTS CALCULATION AND GRAPHICAL PRESENTATION

Section 5.6 exhibits the graphs resulting from the calculations. Figures 5, 6, 7, and 8 are shown side by side to enhance visual comparison of the projects during their planning and execution. The top graph shows the PV curve, plotted on left vertical axis, and TPD, ES and ED curves, plotted on the right vertical axis, for each of the four selected projects.

Except for the first project, the bottom graphs show curves for the percent difference (%diff) between ED and ES.

Table 5 contains MAPEs of estimates at completion for cost [EAC(\$) and EAC(\$)^d against RC] and for duration [EAC(t) and EAC(t)^d against RD] of the four selected projects.

These graphs and table were extracted from reports generated by the above mentioned automated spreadsheet, specially developed to work with projects from the OR-AS real project data.

--- 5.1. Conventions for the graphs ---

The PV, TPD, ES and ED curves for the four projects above are shown in figures 5, 6, 7 and 8. The curves profiles are analyzed and the lessons learned summarized in Table 6 of section 5.7.

With the intent of providing a reference on the graphics to facilitate the comprehension of the conclusions the following horizontal lines are included in the figures:

• BAC (Budget At Completion) ....

• RC (Real Cost) ——————

• PD (Planned Duration) -----------------

• RD (Real Duration) -·-·-·-·-·-·-·-·

The unit of the left vertical axis of the graphs, against which the PV, BAC and RC are plotted, is euro (€), and the unit of the right vertical axis is accumulated workdays (wds), for plotting TPD, ES, ED, PD and RD. The horizontal axis shows the project timeline in working days.

--- 5.2. Project C2015-27 Railway Station Antwerp ---

The reason for choosing project C2015-27 was the fact that all its activities have the same cost/time rate value, 32.62€/hr. Such feature leads to identical curve profiles for cost (PV) and total duration (TPD), as shown in Fig. 5. In addition, the figure shows that ES and ED values are exactly equal for projects with planned identical cost/time rate for all activities.

One may be tempted to extend the above ES and ED behavior to any project in which PV and TPD curves have superposable profiles. Such an extension is not warranted and it should be easily dismissed by just observing that PV depends on activities planned cost, duration and start date, and TPD, only on activities duration and start date. Consequently, there are combinations of these elements that produce the same PV and TPD profiles with different planned cost/time rates among activities.

Table 5 shows that, because PV and TPD have the same profile and ED and ES, the same value over the project makespan, EAC(\$) and EAC(\$)^d as well as EAC(t) and EAC(t)^d exhibit a perfect match over the four percent completed stages.

--- 5.3. Project C2014-04 Compressor Station Zelzate ---

A project card for the C2014-04 project is available in OR-AS database (Batselier and Vanhoucke, 2014). It is worth noting that all activities in this project are serially arranged. This results in the TPD curve being a straight-line segment, as shown in Fig. 6 (a), up to the project planned duration.

Project C2014-04 shows that, even though the PV and TPD curves have such diverse profiles, ED and ES values are almost the same over the project makespan as displayed in Fig. 6 (a).

Fig. 6 (b) represents a percent difference comparison between ED and ES values and was created using the following equation (it is assumed that $ES_i > 0$):

$$\%diff = \frac{ED_i + ES_i}{ES_i} \times 100\% \qquad (32)$$

The differences (spikes) shown in Fig. 7 resulted from the fact that the serial feature (finish/start alignment) was not fully respected during the project execution.

This project configuration contradicts the argument against earned schedule which states that "the greater the disparity between duration and cost profiles, the more deficient the schedule performance measures/forecasts." (Khamooshi and Abdi, 2016). Therefore, discrepant PV and TPD profiles not always result in deficiency on EVM-ES schedule performance measures/forecasts. If a project planned schedule is composed of serially organized tasks and its execution respects the "finish/start" alignment between these tasks, such a configuration will always result in equal values for ED and ES, irrespective of how much disparity exists between their planned duration (TPD) and cost (PV) profiles.

The suggestion (Lipke, 2009) was made that EVM-ES can be used for analyzing the project critical path (CP). The same is applicable to EDM, and, as a CP is a serially organized section of a project, it will appear as a straight-line segment in a graph of TPD x Time. CP analysis performed using EDM will provide the same results as with EVM-ES, should the finish/start alignment be respected for all activities during project execution.

The cells for project C2014-04 in Table 5 shows very close values for all MAPEs in every PC stages.

--- 5.4. Project C2015-07 Industrial Complex (2) ---

Different from project C2014-04, Fig. 7 (a) shows that the TPD curve for project C2015-07 has a profile close to that of the PV curve. Also, both ED and ES curves seem superposed for almost all their extension.

A close similarity of PV and TPD curve profiles as in Fig. 7 (a) is not, however, an assurance for identical ED and ES values. The curve of percent difference between ED and ES in Fig. 7 (b) highlights this statement for project C2015-07.

A negative %diff informs that ED value is smaller than ES. In other words, a negative %diff indicates that the project is running slower when measured by EDM than when measured by EVM ES.

The most significant peaks in the ED/ES percent difference curve for project C2015-07 occurred before it reaches one quarter of its execution, as shown in Fig. 7 (b). Our investigation of 10 additional projects from OR-AS database (Batselier and Vanhoucke, 2014) confirmed that, for most projects, the biggest ED to ES differences occur during the projects initial stage.

It is noticeable the difference between correspondent MAPEs values of cost and duration for this project in Table 5 when compared to the two previous projects. Only the MAPEs values for cost on the full project (0% ≤PC≤100%) shows a small difference (0.2%).

--- 5.5. Project C2015-04 Apartment Building (5) ---

The profiles of PV and TPD curves in Fig. 8 (a) are very dissimilar and the TPD curve is in no way akin to a straight-line segment.

Irrespective of the difference between PV and TPD profiles, Fig. 8 (b) informs that ED and ES have the same value over a significant portion of the project beginning. The cause for this behavior is not related

Project	Number of activities	Planned duration (PD) (wds)	Total planned duration (wds)	Real duration (RD) (wds)	Baseline cost (BAC) (€)	Real cost (RC) (€)	Activities start status	% activities
C2015-27	18	68	87	81	22.7 K	25.3 K	Delayed	50.0%
							On time	44.4%
							Advanced	5.6%
C2014-04	24	522	521	844	62.4 M	65.5 M	Delayed	91.7%
							On time	8.3%
							Advanced	0%
C2015-07	138	297	1387	313	6.0 M	5.4 M	Delayed	46.4%
							On time	38.4%
							Advanced	15.2%
C2015-04	56	160	295	205	2.8 M	2.6 M	Delayed	48.2%
							On time	44.6%
							Advanced	7.1%

TABLE 04. Summary data on selected projects

to project configuration, but, rather, to the schedule management performance during the initial portion of C2015-04. The execution of activities, during the initial portion of this project, in close compliance with their planned durations and start dates, resulted in ED and ES having the same values during most of this phase.

Contrary to the previous projects, ED/ES %diff for project C2015-04 in Fig. 8 (b) does not exhibit a descending trend while advancing towards completion.

Table 5 displays, as expected, an excellent match between MAPEs for the estimates at completion for cost and duration in the initial PC stage (0% ≤ PC < 30%). For the middle and final stages, MAPE values are close enough that any of the estimates at completion, for cost or duration, could be used as a reasonable prediction for the RC or RD of the project.

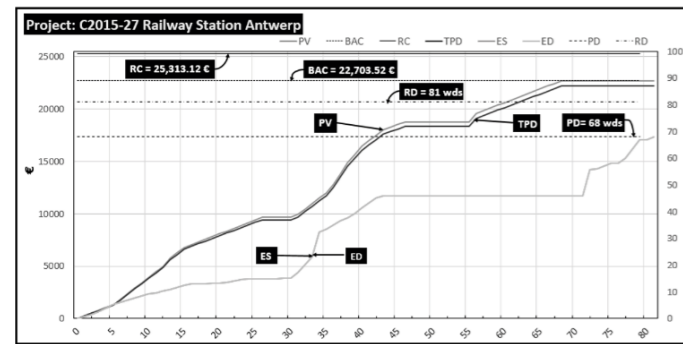### --- 5.6. Graphs and MAPE table for the four selected projects ---

FIGURE 05. PV and TPD S-curves and ED and ES curves for C2015-27 project

FIGURE 06. PV and TPD S-curves and ED and ES curves for C2014-04 project

FIGURE 07. PV and TPD S-curves and ED and ES curves for C2015-07 project
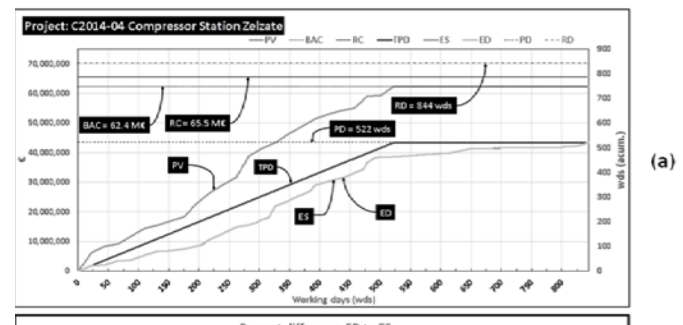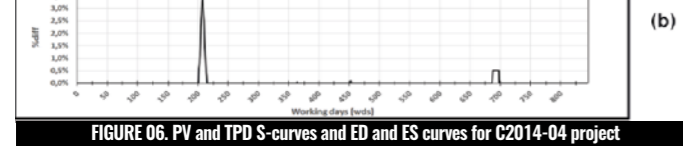

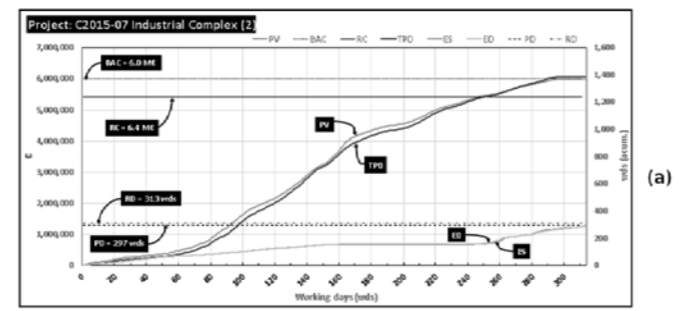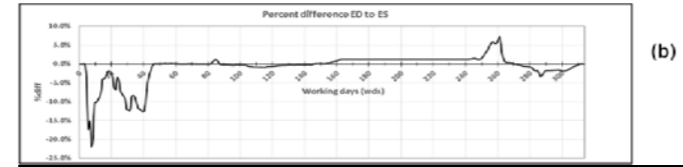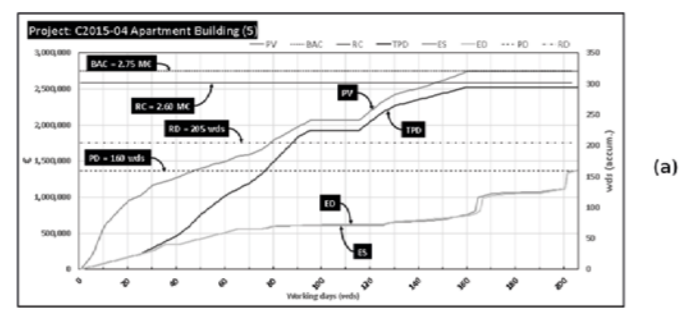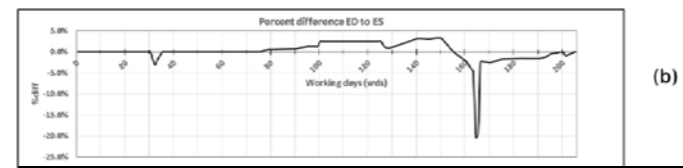**FIGURE 08. PV and TPD S-curves and ED and ES curves for C2015-04 project**

The graphs and table above were used, during the individual project analysis, to produce the Table 6 of lessons learned in next section.

--- 5.7 Lessons learned on subsections 5.2 to 5.5 ---

EDM and EVM-ES offer a similar structure for managing project schedule, but in some cases, they deliver schedule measures, ED and ES, with largely different values. There are situations where the EDM indicator informs that the project is behind schedule and EVM-ES informs it is on schedule or even ahead and vice-versa. EVM-ES schedule performance indicators, which are based on PV and EV, seem more susceptible to distortion because of their dependency on project activities planned values. EDM, which uses only time-based values to produce its sched-

Project	Criteria	Lesson	Observation
C2015-27	Identical planned time/cost rate for all activities	Projects with the same planned cost/time rate, for all its activities always have the same profiles for cost (PV) and total duration (TPD). They will also have the same values for ED and ES during their execution	PV and TPD curves are always the same. This will result in identical ED and ES curves during the project execution
C2014-04	Serial network during planning phase	Projects whose planned schedule is composed of serially organized tasks and that its execution respects the planned "finish/start" alignment between its tasks, will have equal values for ED and ES, irrespective of how much disparity exists between their planned cost (PV) and total duration (TPD) profiles. As the Critical Path is composed of serially organized tasks, EDM can be used for doing CP analysis.	PV and TPD curves profiles are not necessarily the same, but ED and ES curves are always congruent. Note that this only holds if the real project execution strictly follows the seriality. When violations in the serial structure occurs, ED and ES curves might differ.
C2015-07	PV and TPD curves have a very similar (or even identical) shape	Similarity, or even congruency, of PV and TPD profiles cannot guarantee close values for ED and ES.	Only in special cases, the closeness of ES and ED values are determined by PV and TPD profiles.
C2015-04	PV and TPD curves have a very different shape	ED and ES values will be identical when the project is executed in conformity with its baseline planned schedule.	The common trend on closer ED and ES values during the final portion of projects makespan cannot be taken for granted

TABLE 06. Lessons learned per project

ule performance indicators, has less sources of errors and this technique is expected to provide more reliable schedule indicators.

The comparisons of MAPE evaluations of the EAC($) and EAC($)^d against RC for these four selected projects, indicate that the proposed $⟦EV⟧^d$ from the EDM/EVM combination have merit as an alternative to the EV from EVM. There is a need to expand the universe of test projects and better understand possible variations. In subsection 5.8, MAPEs for additional 10 projects, from the OR-AS database (Batselier and Vanhoucke, 2014), are analyzed.

--- 5.8. Analysis of cost and time estimates at completion for additional ten projects ---

Table 7 below exhibits the MAPEs cost and time analysis for the remaining ten projects fitting the criteria in section 4.2.

Projects C2015 02 and C2015-09 shows abnormal differences between EAC($) and EAC($)^d, and between EAC(t) and EAC(t)^d in stage 0%≤PC<30%.

Examination of these projects revealed some oddities:

• Project C2015-02 has 216 activities (excluding hammocks), 124 of them have planned duration of one workday, 0.08€ of planned cost and start date planned as Oct 01, 2011 (same as the project start date). None of these 124 activities started as planned, only 6 had 1 workday of actual duration and 44 had actual duration of 10 or more workdays. Ten activities, planned to start before the late stage, with planned duration in the range of 13 to 193 workdays and planned cost between 1,655.68€ and 49,099.20€, were started and finished in the project last day.

• Project C2015-09 has 348 activities (excluding hammocks) and 134 of them have planned duration of one workday, of these, 133 have 0.08€ of planned cost and start date of Nov. 05, 2012 (same as project start date). None of the 134 activities started as planned, only 3 had one workday of actual duration and 92 had an actual duration of 10 or more workdays. 50 activities, planned to start before the late stage, with planned duration in the range of 1 to 77 workdays and planned cost between 0.08€ and 143,183.04€, were started and finished in the project last day.

The cause for the large differences between the early stage MAPEs of these two projects was the delay of the planned one workday and very low-cost activities. Because of the low cost of the activities, these delays had little effect on the projects earned values. But, as EDM concerns only with duration, delaying a high number of one day activities had a large impact on the projects earned durations. This resulted in a much lower ED as compared to ES. Referring to Fig. 1 and Fig. 3, and understanding that, in both figures, the PV curve are the same, ED< ES implies EV(d) <EV. Also, EV(d) <EV per equations (23) and (28) produces CPI(d) <CPI.

Due to the unreasonable large size of the MAPEs for their EAC($)^{ds} and EAC(t)^{ds}, projects C2015 02 and C2015-09 were deemed outliers and removed from the analysis that follows.

Table 8. contains the percent difference between MAPEs for cost and

Initial four project	Percent complete brackets															
	0% ≤ PC ≤ 100%				0% ≤ PC < 30%				30% ≤ PC ≤ 70%				70% < PC ≤ 100%			
	Equation (30)		Equation (31)		Equation (30)		Equation (31)		Equation (30)		Equation (31)		Equation (30)		Equation (31)	
	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d
C2015-27	17.6%	17.6%	16.1%	16.1%	30.0%	30.0%	12.2%	12.2%	18.7%	18.7%	21.5%	21.5%	3.5%	3.5%	11.6%	11.6%
C2014-04	2.8%	2.9%	16.8%	16.8%	4.8%	4.8%	12.9%	12.7%	3.0%	3.0%	24.2%	24.2%	0.7%	0.7%	10.8%	10.9%
C2015-07	18.2%	18.4%	17.3%	15.8%	33.8%	37.1%	18.6%	15.5%	15.3%	14.2%	11.5%	10.8%	6.6%	5.4%	23.9%	23.0%
C2015-04	8.0%	7.9%	21.4%	21.2%	6.2%	6.2%	22.9%	22.8%	8.5%	7.3%	20.5%	18.9%	9.2%	10.6%	21.2%	23.0%

TABLE 05. MAPEs for cost [EAC($)/EAC($)^d versus RC] and time [EAC(t)/EAC(t)^d versus RD]

Additional ten projects	Percent complete brackets															
	0% ≤ PC ≤ 100%				0% ≤ PC < 30%				30% ≤ PC ≤ 70%				70% < PC ≤ 100%			
	Equation (30)		Equation (31)		Equation (30)		Equation (31)		Equation (30)		Equation (31)		Equation (30)		Equation (31)	
	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d	EAC($)	EAC($)^d	EAC(t)	EAC(t)^d
C2013-03	4.5%	12.9%	9.8%	17.1%	6.1%	35.2%	17.9%	38.8%	5.8%	4.6%	4.6%	7.7%	1.0%	2.0%	8.9%	8.2%
C2014-08	4.2%	4.0%	10.1%	9.8%	6.8%	6.8%	23.2%	23.2%	4.8%	4.3%	6.0%	5.0%	0.6%	0.6%	2.8%	2.9%
C2015-02	46.5%	2172.0%	61.0%	253.5%	41.6%	7199.9%	30.5%	672.4%	58.3%	64.1%	80.9%	88.6%	35.2%	30.3%	64.3%	60.5%
C2015-03	10.6%	12.6%	9.1%	6.9%	8.8%	9.7%	12.5%	12.3%	18.6%	22.3%	10.6%	7.0%	1.4%	2.1%	3.5%	1.4%
C2015-05	1.5%	2.1%	4.7%	3.0%	1.6%	1.2%	6.6%	6.4%	2.2%	2.8%	3.5%	2.0%	0.3%	2.0%	4.6%	0.9%
C2015-06	5.9%	8.0%	7.7%	3.8%	11.7%	20.8%	14.7%	4.4%	5.5%	3.6%	4.7%	4.0%	0.5%	1.2%	4.9%	2.8%
C2015-08	2.6%	4.8%	18.3%	21.0%	1.2%	9.0%	40.8%	53.0%	3.7%	3.5%	12.2%	10.3%	2.5%	2.6%	4.4%	4.4%
C2015-09	17.2%	734.4%	12.2%	351.4%	25.5%	2404.3%	13.8%	1133.2%	14.1%	8.9%	13.2%	19.1%	13.3%	46.2%	9.4%	19.2%
C2015-35	17.8%	18.5%	10.1%	9.7%	31.7%	31.7%	26.8%	26.8%	18.0%	19.4%	3.1%	3.1%	3.5%	4.0%	2.6%	1.6%
C2016-08	12.8%	11.8%	45.6%	42.7%	17.5%	12.7%	63.3%	51.1%	17.0%	18.0%	62.4%	64.6%	2.6%	2.4%	5.1%	4.6%

TABLE 07. Cost and time MAPE analysis for the additional ten projects

duration estimates at completion against RC and RD, respectively, for the twelve projects, according to the following equations:

$$\%diff[MAPE(Cost)] = \frac{MAPE[EAC(\$)^d,RC] - MAPE[EAC(\$),RC]}{MAPE[EAC(\$),RC]} \times 100\% \tag{33}$$

and

$$\%diff[MAPE(Duration)] = \frac{MAPE[EAC(t)^d,RC] - MAPE[EAC(t),RC]}{MAPE[EAC(t),RC]} \times 100\% \tag{34}$$

All twelve projects	Percent complete brackets							
	0% ≤ PC ≤ 100%		0% ≤ PC < 30%		30% ≤ PC ≤ 70%		70% < PC ≤ 100%	
	Cost	Duration	Cost	Duration	Cost	Duration	Cost	Duration
	Eq. 33	Eq. 34	Eq. 33	Eq. 34	Eq. 33	Eq. 34	Eq. 33	Eq. 34
C2015-27	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
C2014-04	3.6%	0.0%	0.0%	-1.6%	0.0%	0.0%	0.0%	0.9%
C2015-07	1.1%	-8.7%	9.8%	-16.7%	-7.2%	-6.1%	-18.2%	-3.8%
C2015-04	-1.3%	-0.9%	0.0%	-0.4%	-14.1%	-7.8%	15.2%	8.5%
C2013-03	186.7%	74.5%	477.0%	116.8%	-20.7%	67.4%	100.0%	-7.9%
C2014-08	-4.8%	-3.0%	0.0%	0.0%	-10.4%	-16.7%	0.0%	3.6%
C2015-03	18.9%	-24.2%	10.2%	-1.6%	19.9%	-34.0%	50.0%	-60.0%
C2015-05	40.0%	-36.2%	-25.0%	-3.0%	27.3%	-42.9%	566.7%	-80.4%
C2015-06	35.6%	-50.6%	77.8%	-70.1%	-34.5%	-14.9%	140.0%	-42.9%
C2015-08	84.6%	14.8%	650.0%	29.9%	-5.4%	-15.6%	4.0%	0.0%
C2015-35	3.9%	-4.0%	0.0%	0.0%	7.8%	0.0%	14.3%	-38.5%
C2016-08	-7.8%	-6.4%	-27.4%	-19.3%	5.9%	3.5%	-7.7%	-9.8%

TABLE 08. Percent differences of MAPEs of EAC($)ᵈ to EAC($) and of EAC(t)ᵈ to EAC(t)

In Table 8, a positive number means that the MAPE for the duration based value, $EAC(\$)^d$ or $EAC(t)^d$, is larger than the corresponding MAPE for the base value, $EAC(\$)$ or $EAC(t)$. The smaller MAPE value is closer to the real value and, therefore, a better approximation. A value of 0.0% represents that both MAPEs are equal, and, therefore, any of them is as good an approximation of the real value as the other. Obviously, he negative values represents that the duration based values are a closer approximation to the real value than the corresponding base value.

An analysis for the results in Table 8. Is provided in Table 9.

	0% ≤ PC ≤ 100%	0% ≤ PC < 30%	30% ≤ PC ≤ 70%	70% < PC ≤ 100%	Total
EAC($)ᵈ > EAC($)	8	5	4	7	24
EAC($)ᵈ = EAC($)	1	5	2	3	11
EAC($)ᵈ < EAC($)	3	2	6	2	13
EAC(t)ᵈ > EAC(t)		2	2	2	3	9
EAC(t)ᵈ = EAC(t)		2	3	3	2	10
EAC(t)ᵈ < EAC(t)	8	7	7	7	29

TABLE 09. Counting of number of occurrences of each MAPE relation on the leftmost column

The rightmost column ("Total") of Table 9 enables a comparison of the percent differences for cost and duration instances of MAPEs in Table 8. For the twelve projects under consideration, the following can be stated based in Table 9:

1. $EAC(\$)^d$ is a cost estimate at completion as good or better than $EAC(\$)$ in 24 {11 equal MAPE[EAC($)ᵈ,RC] and MAPE[EAC($),RC] value + 13 smaller MAPE[EAC($)ᵈ,RC] than MAPE[EAC($),RC]} out of 48 comparisons of MAPE values for these estimates;

2. $EAC(t)^d$ is a duration estimate at completion as good or better than $EAC(t)$ in 39 (10 + 29) out of 48 comparisons of MAPE values for these estimates.

Should a 10% tolerance be allowed the results change:

1. $EAC(\$)^d$ is an acceptable cost estimate at completion in 30 out of 48 situations;

2. $EAC(t)^d$ is an acceptable duration estimate at completion for 43 out of 48 situations.

Accepting some tolerance for an estimate is the modus operandi for project managers. A PM should be able to establish the acceptable tolerance for estimates at completion of cost and duration for his projects.

For the 12 projects considered (Tables 5 and 7) the following are verified:

1. The maximum MAPE value in early stage for EAC($) is 33.8% for project C2015-07. Two projects have higher MAPEs values in early stage for EAC($)ᵈ: 37.1% for project C2015-07 and 35.2% for project C2013-03.

2. In middle stage, the maximum value of MAPE for EAC($) is 18.7% for project C2015-27. Two projects presented higher MAPEs for EAC($)ᵈ in middle stage: 22.3% for project C2015-03 and 19.4% for project C2015-35.

3. In the late stage, the maximum MAPE for the EAC($) of the 12 projects is 9.2% for project C2015-04, and the MAPE for EAC($)ᵈ was higher (10.6%) for this same project.

4. The maximum MAPE for EAC(t) in early stage is 63.3% for project C2016-08. None of the 12 considered projects have a larger MAPE for EAC(t)ᵈ.

5. In middle stage, the maximum MAPE value of EAC(t) is 62.4% for project C2016-08. Only project C2016-08, the same project, presents a larger MAPE, 64.6%, for EAC(t)ᵈ in this stage.

6. The project C2015-07 presents the highest value, 23.9%, of MAPE for EAC(t) in the late stage. None of the 12 considered projects has a larger MAPE for EAC(t)ᵈ.

The six considerations above indicate that, for the twelve projects analyzed, $EAC(\$)^d$ and $EAC(t)^d$ present comparable maximum values of MAPE when compared to their EVM base cost and duration estimates at completion.

Table 9 and points 1, 2 and 3 above confirm that EVᵈ is, under normal circumstances, an acceptable substitute for EV from EVM. It can also be hypothesized that a very large difference between EAC($)ᵈ and BAC could serve as a warning for the PM about possible problems on the execution of planned low cost/short duration activities (the case of projects C2015 02 and C2015-09).

Table 9 and points 4, 5 and 6 confirm that ED is a better measurement of the project duration at a status date than ES in the vast majority of projects.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the projects studied, a conclusion emerged: EVᵈ, of the proposed combination, is a viable substitute for EV from EVM.

Also, ED is a better way to measure project progress in time and is better suited to usage for estimating the duration of a project at its completion.

However, the authors recognize that EV is a better measure of project progress in value than EVᵈ, although, not by a large margin. The authors suggest that ED should be the preferred technique for measuring project progress in duration.

There are cases in which determining the earned duration status of an activity is easier than establishing its earned value. In such situations, the PM can resort to using just the EDM technique and calculate EVᵈ as per the proposed combination. The PM would avoid sizeable workload by first calculating the project earned duration (ED), next EVᵈ, CPIᵈ and then EAC($)ᵈ at the status date, and undertaking the calculation of the EVM based earned value (EV) only when justified by project characteristics or environment.

The study confirms that EAC(t)ᵈ is the preferred estimate at completion for the project duration, and, also, claims that EAC($)ᵈ is a viable estimate at completion for the project cost of the 12 projects assessed. The extension of this later finding to projects in general, and the conditions for its applicability, requires additional research on a larger set and greater variety of projects, which is beyond the scope of this paper. Should such research validate the extension of this conclusion to a wider set of projects, it may result in a significant simplification of project value and duration management and reporting.

Criterion (i) used in the selection of the 14 projects for this research, disregarded projects with fixed cost and mixed fixed and variable cost in favor of projects with pure variable cost. Having activities with fixed or fixed and variable cost would require deeper analysis and a more complex model for the determination of the EVⁱ for such activities. As EDM deals only with duration, it avoids such complexities, and the process to determine the activities schedule progress index (APIⁱˢ) is consistent, simpler and less prone to errors than the process to reach the activities percent complete (PCⁱˢ) for this kind of projects.

The large differences between EAC($) and EAC($)ᵈ and between EAC(t) and EAC(t)ᵈ in the early stage of projects C2015 02 and C2015-09, suggest the usage of EAC($)ᵈ and EAC(t)ᵈ as indicators of execution problems in activities for which cost/time rate are much lower than other activities in the project. When comparisons between EAC($)ᵈ and BAC and/or between EAC(t)ᵈ and PD reveals abnormal differences, the project manager should investigate for its root causes.

EDM also facilitates the communication between customer and contractor organizations, engaged in a project, as it involves no exchanging of sensitive cost/profit information, which is the case with EVM ES. ◆

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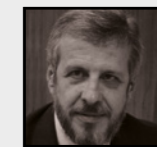
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• REFERENCES •

Andrade, P., Batselier, J., Salvaterra, F., and Vanhoucke, M., 2015. Introduction to Earned Duration. The Measurable News, 2:15-27

Batselier, J., and Vanhoucke, M., 2014. Real project data. http://www.projectmanagement.ugent.be/research/data/realdata.

Batselier, J., Vanhoucke, M., 2015a. Construction and evaluation framework for a real-life project database. Int. J. Proj. Manag. 33, 697–710.

Batselier, J., and Vanhoucke, M., 2015b. Evaluation of deterministic state-of-the-art forecasting approaches for project duration based on earned value management. International Journal of Project Management, 33:1588–1596.

Colin, J., and Vanhoucke, M., 2015. Comparison of the performance of various project control methods using earned value management systems. Expert Systems with Applications, 42:3159–3175.

Fleming, Q. W., & Koppelman, J. M., 2004. If EVM is so good, why isn't it used on all projects? The Measurable News, 2004.

Khamooshi, H., 2014. EDM: Earned Duration Management a Novel Approach - Webinar. https://www.project-management.com/videos/289128/EDM--Earned-Duration-Management-a-Novel-Approach.

Khamooshi, H., and Golafshani, H., 2014. EDM: Earned Duration Management, a new approach to schedule performance management and measurement. International Journal of Project Management, 32:1019–1041.

Khamooshi, H., and Abdi, A., 2016. Project Duration Forecasting Using Earned Duration Management with Exponential Smoothing Techniques. J. Manage. Eng., 04016032.

Lipke, W., 2003. Schedule is Different. The Measurable News, March, pp. 10-15.

Lipke, W. H., 2009. Earned schedule: an extension to earned value management for managing schedule performance. 1st ed. [e-book] Retrieved from: http://www.amazon.com.

Lipke, W., 2012. Speculations on project duration forecasting. The Measurable News, 3:3–7.

Lipke, W., Zwikael, O., Henderson, K., and Anbari, F., 2009. Prediction of project outcome: The application of statistical methods to earned value management and earned schedule performance indexes. International Journal of Project Management, 27:400–407.

Lukas, J., 2008. Earned Value Analysis – Why it Doesn't Work, AACE International Transactions, EVM.01. 2. http://www.icoste.org/LukasPaper.pdf.

PMI, 2011. Practice Standard for Earned Value Management (2nd ed.). Newtown Square: Project Management Institute, Inc.

Vandevoorde, S. and Vanhoucke, M., 2006. A comparison of different project duration forecasting methods using earned value metrics. International Journal of Project Management, 24:289–302.

Vanhoucke, M. and Vandevoorde, S., 2007. A simulation and evaluation of earned value metrics to forecast the project duration. Journal of the Operational Research Society, 58:1361–1374.

Vanhoucke, M., 2010a. Measuring time – improving project performance using earned value management. International series in operations research and management science (Vol. 136). Springer.

Vanhoucke, M., 2010b. Using activity sensitivity and network topology information to monitor project time performance. Omega The International Journal of Management Science, 38:359–370.

Vanhoucke, M., 2011. On the dynamic use of project performance and schedule risk information during project tracking. Omega The International Journal of Management Science, 39:416–426.

Vanhoucke, M., 2012. Measuring the efficiency of project control using fictitious and empirical project data. International Journal of Project Management, 30:252–263.

Vanhoucke, M. 2014. Integrated project management and control: First come the theory, then the practice. In Management for professionals. Springer.