Eliminating sub-optimality in Earned Value Management Scheduling

Abstract

Strategic and operational project successes rely on optimal implementation, with *time to execution* a key value driver and competitive advantage. Earned Value Management (EVM) is the most pervasive approach for schedule and cost monitoring in large scale projects. However, prior research has shown that EVM may produce sub-optimal scheduling results, specifically, we demonstrate the common conditions under which 'top-down', Earned Schedule (ES) metrics generate sub-optimal schedule assessment against the baseline. The purpose of our work is two-fold: first we articulate why sub-optimality occurs. Second, utilizing Schedule Variance Path Level metrics (SVP(t)), we resolve the ES limitation. The validity and practicality of our approach is demonstrated using three execution scenarios with simulation stress-tests. Our bottom-up approach considers schedule progress on critical and non-critical paths and utilizes total slack when necessary. Our results propose a tractable solution and improved schedule measurements, highlighting the first order importance of scheduling across all tracking periods.

Keywords

Earned schedule, Earned value management, Project monitoring, and control, Project schedule, Schedule variance, Total slack.

1. Introduction

Projects continue to fail, sometimes dramatically (Harrin, 2018), often due to scheduling and cost overruns. In this paper the authors focus on the scheduling component hence the cost component is considering beyond the scope of this paper. Diamantas et al. (2011) have previously highlighted that monitoring and controlling the project schedule is a challenge with the tools currently available to project managers. Scheduling sub-optimality is, therefore, a first order contributor to project failure and one for which we propose a methodological insight which rectifies this gap in the EVM scheduling literature.

It is estimated that around 30% of underperforming projects are terminated, while 10% of project investment costs are squandered (Project Management Institute, 2018). Among the major causes of failure are poor Project monitoring and control (PMC) systems which result in unreliable schedule and cost performance measurements and subsequent project estimate updates. Scheduling systems are intended to aid project managers in analyzing schedule progress and cost performance of their ongoing projects. Based on analytics, duration and budget deviations from the project plan are calculated, and the estimates of the expected final duration and cost are managed (Anbari, 2004;

Ballesteros-Pérez et al., 2020; Narbaev and de Marco, 2017). It follows that if scheduling systems are faulty, schedules, durations and costs are all materially affected, hence this is the focus of our contribution.

Among various PMC methods, Earned Value Management (EVM) is the most used in practice (Humphreys, 2014). It is widely applied in traditional, and to some extent, in agile and hybrid project environments. It is the recommended approach by the Project Management Institute (2011), one of the leading organizations that advance project management education, research, and practice. EVM helps to measure the duration progress and cost performance in projects, and based on such to-date measurements, the estimates of the final expected duration and cost are computed. As a part of the EVM system, the Earned Schedule (ES) metric is explicitly used to monitor and measure the project schedule progress (Lipke, 2003; Vandevoorde and Vanhoucke, 2006; Ballesteros-Pérez *et al.*, 2019)

ES is a top-down approach commonly used on the aggregate project level. However, for schedule analysis, it may produce contradictory results (Lipke, 2009, 2014; Vanhoucke, 2013). Used at the project level, the ES metric does not consider schedule progress discrepancies that may exist on the detailed project levels. These levels are analyzed at the project's work breakdown structure or schedule networks, such as a path level or an individual activity level. The inherent limitation of the ES metric is that it considers all the project paths as critical, while some project paths have total slacks. The total slack is defined as the amount of time one activity can be delayed without delaying the project's total duration (Hall, 2018). As a result, the ES-based schedule analysis, conducted on the aggregate project level, may produce inaccurate values of schedule variances, which may result in false duration forecasts.

Numerous studies investigate and acknowledge that EVM fails to accurately consider schedule progress on the path level. A few studies proposed solutions to overcome this, but, as with any approach, their models are prone to limitations. We review these studies in Section 2.4 in more detail. Overall, little research has been performed to offer an approach that is simple and deterministic, to be easily used by practitioners in the field.

In this study, we aim to achieve two objectives. The first objective is to present how schedule progress analysis by traditional EVM techniques (including ES metrics) result in the above inaccuracy and discuss why this happens. We demonstrate that such inconsistencies emerge when comparing schedule progress variances at the project level with those computed at the individual path level. To this end, the concepts of "false positive" and "false negative" are mooted in this work. By "false positive," we consider a project that is not late, but the traditional ES shows a delay. By "false negative," instead, we consider the traditional ES not showing a delay when the project is late or showing a delay with less than the actual project delay. To illustrate, when the project-level analysis suggests a schedule delay, the project may not be delayed at all, as shown by the path-level analysis ("false positive"). Detecting such false results is critical for optimization. The second objective is to propose a new approach that resolves the abovementioned limitation of EVM. Our approach considers the schedule progress variances on the individual path levels, both in critical and non-critical paths and utilizes total slack times when necessary.

The contributions of our study to the PMC body of scheduling knowledge are therefore fundamental and three-fold. First, our proposed approach considers a delay in non-critical paths only when it should be considered (i.e., when it exceeds the total slack time) for the schedule variance on the aggregate project level. Second, non-critical path activities ahead of schedule, do not mitigate the delay in the critical path. Consequently, effective in all project tracking periods, the proposed methodology produces more accurate and stable schedule variance results compared to the ones found by the traditional EVM-based ES metric. Third, our approach is simple and deterministic, which can be used in a spreadsheet. Field practitioners can use it to compare the schedule variances found on the project level with the ones found on the path level. Consequently, they will be able to spot the tracking period in the project life when the schedule progress anomaly *emerges*, thereby avoiding inaccurate or false final duration estimates.

The paper is organized as follows. Section 2 presents the fundamentals of project network analysis, schedule analysis with the ES approach, its limitations, and briefly reviews past studies that addressed these limitations. In Section 3, we propose our approach, which is based on a combination of the traditional ES and project network analysis concepts. We demonstrate the applicability of our approach on a hypothetical project network and validate it using simulation on one hundred project network scenarios. We present the results and discuss the main findings in Section 4. Section 5 concludes the paper, reports the main limitations, and highlights future research avenues.

2. Research background and problem

2.1. The project network fundamentals

For applying EVM on a project, first, the Performance measurement baseline (the project baseline) is developed during the project planning phase. The baseline development involves such actions as the decomposition of the total project scope to a manageable level (commonly, through the work breakdown structure), preparation of the project schedule with activities and resources assigned, and creation of the time-phased budget for each project activity (de Marco and Narbaev, 2013; Project Management Institute, 2017).

EVM methodology does not pose any problems for cost monitoring and control, as the cost behaviour of project activities is not directly related to the project critical path. Thus, EVM provides an enough accurate depiction of the cost progress of the undertaking. Monitoring and controlling the schedule, on the other hand, is quite distinct. Only the critical activities reflect how the duration of the activity impacts the duration of the entire project: monitoring and controlling a schedule without taking the project critical activities into consideration may be misleading (Diamantas et al., 2011).

To resolve this issue, we breakdown the project in multi paths (critical and not critical) and analyse the adherence of the progression in the paths with the baseline. Simplistically, if a delay is occurring in a non-critical path, this won't affect the project duration until the magnitude of this delay is within the path free slack. With the proposed methodology we propose, we capture data, which is ignored in the classical approach, in which any delay has the same importance, even if this delay is in non-critical activities and within the slack. Clearly this is a first order issue that cautions how EVM should be used with this important limitation.

Ideally, therefore, the baseline integrity, including the adherence to the project planned duration and the agreed budget, should be maintained throughout the project execution to finish the project on time and within budget. Furthermore, when a project starts, assuring such integrity is a core task of a project manager. The EVM approach is used during the project execution phase to achieve baseline integrity. The EVM-based project duration analysis involves objectively measuring the actual work progress, resource usage, and budget spent. Based on this analysis, the project team calculates the expected final duration of a project, reports performance problems, and, in case of substantial deviations from the baseline, takes corrective actions to bring the project back on track (Project Management Institute, 2011)

The project schedule, along with the project budget, is part of this project baseline. The Critical path method (CPM) is used to construct and manage such a schedule. This method helps to understand the project topology with an oriented graph named project network (Soroush, 1994). In this oriented graph, a project network path is defined as any possible sequence of activities from the project start to its end. Two main elements characterize the project topology: one are the critical paths, and the other is the total slack in non-critical paths. The critical paths are the longest in the project network and define the project in terms of duration (Lu and Li, 2003; Kosztyán, Pribojszki-Németh and Szalkai, 2019; Hammad *et al.*, 2020). A project is delayed if any of the tasks on the critical path (named therefore critical tasks) is delayed. Non-critical paths, on the other hand, have total slack, and such paths can be delayed for a duration less or equal to the total slack without causing a delay in the total project (Lu and Li, 2003; Vanhoucke, 2012). To this end, to control the project duration, monitoring the schedule variance in the critical path is crucial since the critical path length resembles the project duration. The probability that the critical path can change, is closely attributed to the total slack times in non-critical paths; the lower the path total slack times, the higher the probability that a non-critical path becomes critical (Hammad et al., 2020).

2.2. The schedule progress analysis using ES at the project level

To assess the project progress, EVM computes the amount of work completed in monetary units (Earned Value, EV) against the planned budget (Planned Value, PV) (Anbari, 2004; Vanhoucke, 2013). A graphical representation of the EVM and ES metrics is given in Figure 1. EV is equal to the percent of actual work completed multiplied by the planned value budgeted for this work. To measure the schedule progress at a particular tracking period (*t*), Schedule Variance (SV) is used (Lipke *et al.*, 2009; Narbaev and de Marco, 2017; Ballesteros-Pérez *et al.*, 2019) as per (1):

$$SV_t = EV_t - PV_t \quad (1)$$

SV is expressed in monetary (Anbari, 2004; Narbaev and de Marco, 2014; Przywara and Rak, 2021) and not in time units, which makes it difficult to interpret. The ES technique, an extension to EVM, has been proposed to overcome this unit of measure inconsistency. ES is a metric representing the time in which PV corresponds to EV (Figure 1) and found by (2) (Lipke, 2003). ES is then compared with Actual Time (AT) to determine to-date project progress (3). If SV(t) is greater than zero, the project is ahead of schedule. If SV(t) is negative, however, like in the case in Figure 1, the project is behind schedule.

$$ES_t = {PV_t}^{-1}(EV_t) \quad (2)$$

$$SV_t(t) = ES_t - AT_t \quad (3)$$

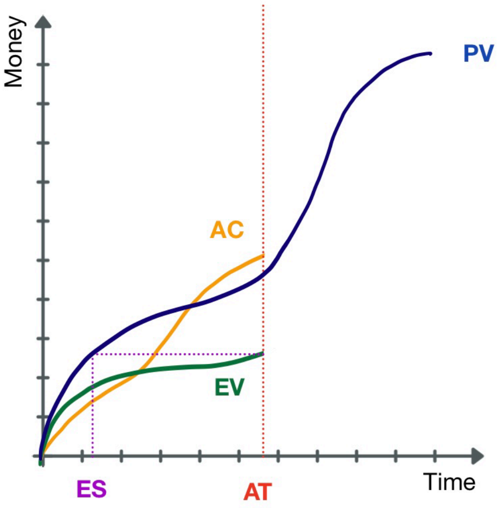


Figure 1. The EVM and ES metrics. ES is giving more reliable results compared to EVM on the schedule component.

2.3. The ES(t) limitations at the project level

Even though (3) is logical to use compared to (1), since it reports the schedule progress in time units, SV(t) by (3) does not consider the project's network topology. Namely, this project-level metric does not account for how individual activities in multiple paths progress and their respective total slack times. SV(t) ignores the distribution of activities concerning their predecessors and successors. The error becomes more significant when the project network has more parallel activities than serial ones (Barrientos-Orellana *et al.*, 2021). Consequently, it is prone to provide false schedule variances (Vanhoucke and Vandevoorde, 2009; Vanhoucke, 2010; Hussein and Moselhi, 2013; Zheng and Bi, 2014; Martens and Vanhoucke, 2018; Wood, 2018; Andrade, Martens and Vanhoucke, 2019; Chang, Yu and Cheng, 2020) and subsequent duration estimates.

We report two limitations of the SV(t) metric, computed by the traditional ES approach.

The first limitation is its inability to recognize the magnitude of an actual delay resulting from the project paths. A total delay in the project schedule is generated only by a delay in the critical activities or by a delay in non-critical activities, which exceeds the total slack. Using (3) at the project level, a delay in a non-critical activity within its total slack influences the SV(t) calculation, while it should not.

The second limitation is that any delay in the critical activities is mitigated by the schedule performance in the non-critical activities. To better understand this situation, consider a delay in the critical activity, hence, in the whole project. This delay is captured by (3) at the project level. However, if some non-critical activities are ahead of schedule, this desirable performance in the non-critical path should not offset the poor performance in the critical path. Instead, the ES metric at the project level is influenced by the performance in non-critical activities, producing unreliable results. We might have a situation where a delay in the critical activity is fully offset by the advancement (being ahead of schedule) in the non-critical activities.

2.4. A review of previous studies

Numerous studies addressed EVM's possible inaccuracy in the schedule analysis at the project level. They recognized that this traditional approach does not consider total slack times in non-critical activities.

A few studies proposed probabilistic models to address this issue. Kim and Reinschmidt (2009) recognized the importance of duration forecasting and how project managers seek reliable and simple indicators that accurately monitor the project status to enable appropriate control actions. They claimed that the limitation of EVM and CPM was their deterministic analysis. They considered the project uncertainties an alternative by developing a probabilistic scheduling methodology using the Bayesian Beta S-curves. However, powerful to use in scheduling analysis, the approach is cumbersome to implement in practice; being stochastic, it has a limited application in real case scenarios due to computation complexities. Hammad et al. (2020) propose to predict the changes in the critical path using a probability distribution. This methodology can be used with CPM to enhance project monitoring accuracy. They proposed limiting the schedule analysis to the critical and near-critical paths for more accurate results. However, their approach was limited as it depended on the probability of the critical path change, which may not be accurate enough. Also, their method was complex as assigning probabilities to each project activity was necessary, limiting its application in real case scenarios.

Other studies stated that ES inaccuracy can still be investigated at the project level, mainly due to little or unreliable schedule information from the path level. These are deterministic models but are still mainly used at the project level. So, Hussein and Moselhi (2013) used a different approach to overcome EVM inaccuracy due to the lack of path-level analysis. He introduced the Schedule Compression Index, which captured the delayed progress in non-critical activities. The rationale is that a delay in non-critical activities does not necessarily reflect a delay in the project; it depends on the amount of total slack the delayed activity has. The index considers project activities that are not completed and, on average, gives more reliable results than the ES metric by the traditional EVM approach. We note that yet powerful to use, this metric is still used at the project level and therefore does not assist project managers in differentiating between critical and non-critical activities. Later, to overcome this issue, Ballesteros-Pérez et al. (2019) proposed two new metrics, Earned Schedule Max and Earned Schedule Min. The authors measured the schedule progress in the project's most advanced and delayed paths to understand what may happen in the critical and non-critical activities. A limitation of this work is that both indicators are still calculated at the project level. Therefore, the project topology (potential schedule issues including delays and total slack times) was not fully considered. Andrade et al. (2019) and Wood (2018)also identified a possible reason for the inaccuracy of the traditional EVM and ES approaches in considering the schedule metrics in monetary units and not in time units. However, even if based on time units, the ES metric derives from the EVM-based EV metric, measured in monetary units.

For this reason, the authors tested a new approach, Earned Duration Management, that created new duration-based metrics. However, the schedule analysis with this approach works at the project level, and therefore, project network specificities (activity criticality, delay, and total slack times) are not considered. For example, it is impossible to distinguish whether a source of a delay is a critical activity or a non-critical activity.

The following authors investigated the issue by considering the project topology. Vanhoucke and Vandevoorde (2009)noted the importance of the project network topology as a crucial monitoring and forecasting parameter and indicated the activity total slack as a critical indicator. They also demonstrated that forecasting accuracy depends on project topology; the less the project is serial (i.e., the more the project has parallel activities), the less accurate metrics at the project level are. However, in this study, the criticality of ES inaccuracy was acknowledged and tested, but no mathematical model was proposed. Vanhoucke (2010) addressed the EVM and ES inaccuracy by proposing a sensitivity analysis at the activity level, identifying which non-critical activities are more likely to become critical and to influence the project duration. However, this approach is complex to be used by practitioners; it is difficult to identify the subset of such activities and the necessity to keep this subset to a number that allows a quick analysis, is also a limitation. Later, Martens and Vanhoucke (2018) considered project control as one of the three most essential activities in project management, together with baseline scheduling and risk analysis. They introduced the concept of tolerance limits to detect when the project progress was not following its schedule baseline. Also, to enhance the EVM accuracy, they suggested calculating EVM metrics in terms of work content units instead of monetary units. However, a powerful tool for schedule control, their approach could not detect whether a delayed source is from critical or non-critical activities. Recently, Capone and Narbaev (2021) conducted a comparative analysis to understand the likely differences in schedule variances calculated at the project and path levels. They also confirmed that SV(t) produces inconsistent results in schedule analysis because it does not consider the total slack times in non-critical activities when used at the project level.

Lipke (2003) introduced the ES-based SV(t) measured in time units as an alternative to the EVM-based SV measured in monetary units. However, SV(t) fails to detect a delay's origin; it does not consider that a delay from the non-critical activities impacts the project's total duration differently than a delay from the critical activities. Later, Lipke (2012) suggested utilizing (1) and (3) only on the critical path, in case the project contains parallel activities (i.e., multiple paths), since this may lead to more accurate results. This case assumes that the critical path should be constant. However, the critical path may change during project execution, especially when the total slack times are relatively small. Our proposed methodology considers the possible change in the critical path when progressing from one tracking period to another.

To conclude, all the above studies addressed the EVM-based SV limitations and proposed either deterministic or probabilistic approaches. Nevertheless, we note that, while the intrinsic issue of SV (measuring the schedule in monetary units) was well addressed by SV(t), all the metrics proposed in the literature are calculated either at the project level or at the activity level, but, de facto, do not consider the project topology. The deficiency of SV(t) to analyze the schedule progress at the path level has only been recognized (and well investigated), but an approach to solving this has not been proposed.

The current study aims to develop a mathematical approach to overcome the two limitations of SV(t). We propose a simple mathematical approach in which (3) is calculated for every project's path and compared with the path total slack. Unlike the traditional ES approach, our model can detect any delay affecting the project's total duration, even if the delay is beyond the critical path. Furthermore, with the proposed approach, the desired performance in non-critical path activities will not mitigate the delay in the critical path, making our approach more reliable and accurate across all the project tracking periods.

3. Methodology

3.1. The proposed approach to overcome the ES limitations at the project level

To overcome the SV(t) limitations introduced in Section 2.3, we propose calculating ES metrics at the path level to see the individual schedule performance at each path. This approach also allows us to see the performance in the critical activities separated from the non-critical ones. Consequently, the path level calculations give more information on what happens in the critical path. We can also see the extent to which the critical path performance can be affected by the non-critical activities' performance. Special attention is given when the delay in the non-critical path exceeds its total slack.

To take the above considerations into account, the current study proposes a new metric, Schedule Variance at Path Level (SVP(t)). SVP(t) is calculated as per (4):

$$SVP_t(t) = MIN(SV_t(t)_i + Slack_i) \quad (4)$$

Where $SV_t(t)_i$ represents (3) but is calculated at the path level for i^{th} path at the tracking period *t*. $Slack_i$ is the total slack of the i^{th} path, which is equal to 0 in the case of critical paths. MIN is a function that returns the minimum sum of SV(t) and total slacks across all the paths.

The new SVP(t) metric considers a delay in non-critical paths when it should be considered only (i.e., when it exceeds the total slack time). With this metric, total slack times of the non-critical path activities, which are ahead of schedule, do not mitigate the delay in the critical path. Differentiating critical and non-critical activities allows our proposed methodology to produce more realistic schedule variance results than the ones found by the traditional EVM-based ES metric.

3.2. Demonstration using project network data

We demonstrate the validity of our methodology using a fictional project network. Table 1 presents the project network characteristics, and, as an example, an assembly line construction is considered. The network has three paths: one critical and two non-critical, with different total slack times. The demonstration of the proposed methodology and the consequent mathematical model represented by (4) can be extended to more complex project networks, any other possible critical and non-critical paths, with any amount of total slack times.

Table 1

A fictional project network.

Activity code	Activity description	Duration (weeks)	Predecessors
A	Hardware specification and design	4	-
B	Installation of the conveyor belt's power line	2	A
C	Testing of the conveyor belt's power line	1	B
D	Plant's legal authorities' signatures	2	A
E	Prototype implementation	5	A
F	Assemble pre-production model	2	C, E
G	Assemble production model	3	D, F

Figure 2 shows the project network with the seven activities on nodes, their codes, and duration values in weeks. The project has three paths. The first non-critical path (NCP1) through the non-critical activities A, B, C, F, and G has a duration of 12 weeks. The critical path (CP1) through the critical activities A, E, F, and G has a duration of 14 weeks which constitute the project's total duration. The second non-critical path (NCP2) through the non-critical activities A, D, and G has a duration of 9 weeks. The critical activities concern the installation of a conveyor belt. In NCP1, we have non-critical activities B and C related to installing and testing the conveyor belt's power line. In NCP2, there is only one non-critical activity D related to the production plant's legal authorities' signatures. These activities in NCP1 have a total slack of 2 weeks, while the activity in NCP2 has a total slack of 5 weeks.

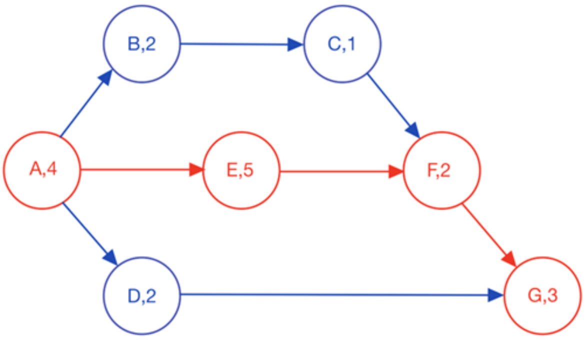
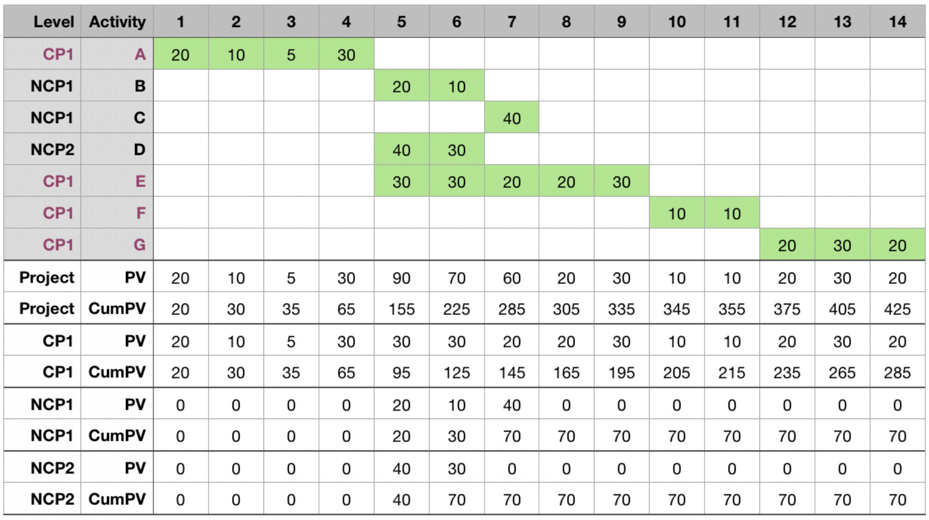


Figure 2. A hypothetical project network with one critical path and two non-critical paths.

Figure 3 shows the project baseline in case of the schedule based on activities early start, i.e., all the activities start as soon as possible. The power line installation and testing (activities B and C) cannot start before week five because activity A should be completed by that week, and activity B ends before week ten because, on that week, activity F starts. Activities B and C require only three weeks of work; therefore, they have two weeks of total slack before activity F starts. Activity D requires two weeks of work and starts no earlier than week five since activity A is completed before it starts. Activity D ends before week 12 because activity G starts that week; therefore, activity D has a total slack of five weeks.

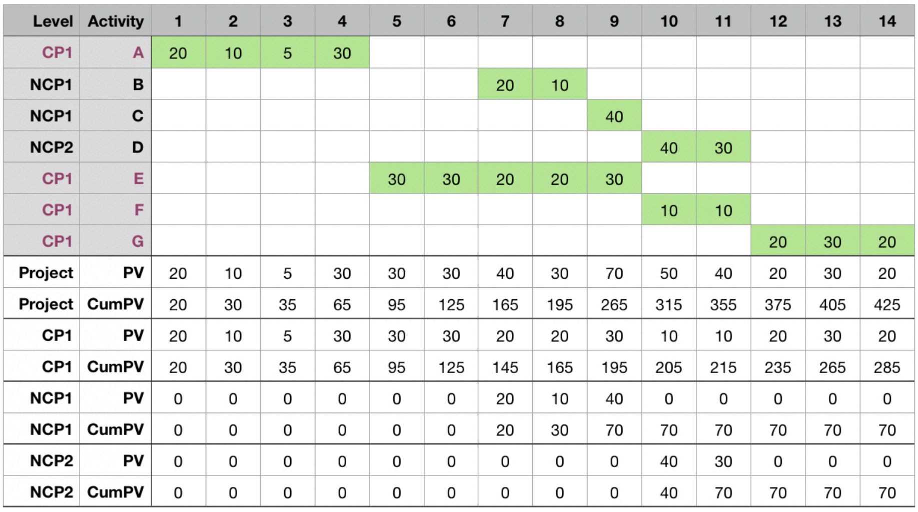


Level	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CP1	A	20	10	5	30										
NCP1	B					20	10								
NCP1	C							40							
NCP2	D					40	30								
CP1	E					30	30	20	20	30					
CP1	F										10	10			
CP1	G												20	30	20
Project	PV	20	10	5	30	90	70	60	20	30	10	10	20	30	20
Project	CumPV	20	30	35	65	155	225	285	305	335	345	355	375	405	425
CP1	PV	20	10	5	30	30	30	20	20	30	10	10	20	30	20
CP1	CumPV	20	30	35	65	95	125	145	165	195	205	215	235	265	285
NCP1	PV	0	0	0	0	20	10	40	0	0	0	0	0	0	0
NCP1	CumPV	0	0	0	0	20	30	70	70	70	70	70	70	70	70
NCP2	PV	0	0	0	0	40	30	0	0	0	0	0	0	0	0
NCP2	CumPV	0	0	0	0	40	70	70	70	70	70	70	70	70	70

Figure 3. The EVM and network data on the early start baseline.

Figure 4 shows the project baseline in case of a schedule based on activities late start, i.e., all the activities start as late as possible, but maintaining the project duration of 14 weeks. The power line installation starts on week seven and ends on week nine with no total slack. Activity D requires two weeks of work, starting on week ten and ending on week 11, with no total slack. In case of a late start, all the activities are critical since any delay in any activity impacts the project duration.

Figure 3 and Figure 4 also show the critical paths in red colors, which resemble CP1, the weekly project planned budget (PV) and cumulative (CumPV) planned values for the total project (column Level with the value of the project) and all paths (column Level with the values of CP1, NCP1, and NCP2). The PV values for each activity for each week are given in the green background.



Level	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CP1	A	20	10	5	30										
NCP1	B							20	10						
NCP1	C									40					
NCP2	D										40	30			
CP1	E					30	30	20	20	30					
CP1	F										10	10			
CP1	G												20	30	20
Project	PV	20	10	5	30	30	30	40	30	70	50	40	20	30	20
Project	CumPV	20	30	35	65	95	125	165	195	265	315	355	375	405	425
CP1	PV	20	10	5	30	30	30	20	20	30	10	10	20	30	20
CP1	CumPV	20	30	35	65	95	125	145	165	195	205	215	235	265	285
NCP1	PV	0	0	0	0	0	0	20	10	40	0	0	0	0	0
NCP1	CumPV	0	0	0	0	0	0	20	30	70	70	70	70	70	70
NCP2	PV	0	0	0	0	0	0	0	0	0	40	30	0	0	0
NCP2	CumPV	0	0	0	0	0	0	0	0	0	40	70	70	70	70

Figure 4. The EVM and network data on the late start baseline.

In the next section, we discuss the results of the SVP(t) applications on three project execution scenarios: two scenarios in the early start baseline and one in the late start baseline. Total slack plays a fundamental role in deciding if an activity is critical or non-critical. Moreover, critical activities play a fundamental role in determining the project's duration. By selecting the three different project executions, the authors analyze the schedule progress under two opposite conditions: the activities' maximum total slack possible (early start) and zero total slack for all the activities (late start). The ES metrics will be calculated using both the classical EVM approach (at the project level) and our proposed approach (at the path level).

3.3. Validation using project network simulations

In addition, we validate our approach using a simulation of different possible executions of the sample project network presented in Figure 2. The simulator uses a probability distribution of the path's duration, following the Program Evaluation Review Technique (PERT) approach. PERT assumes that the duration of a project activity follows the beta probability distribution (Adlakha and Kulkarni, 1989). PERT was initially designed by US Navy in 1958 to better control the project scheduling of weapon development systems. For each activity, PERT considers a three-point estimate, namely, most likely duration, pessimistic duration, and optimistic duration, to define the beta distribution (Pérez *et al.*, 2016). From these three values, the beta probability distribution is constructed (Andiyan *et al.*, 2021). According to the bottom-up project estimation approach (Project Management Institute, 2017), the estimation accuracy is typically between -10% and +30% of the most likely duration and based on this assumption, +30% of the duration value was used as pessimistic duration, and -10% of the duration value was used as optimistic duration. The authors will use Python language to design a software to simulate 100 different project executions following the PERT probability distribution and compare (4) with (3) on each of the 100 simulated executions.

Overall, in each project execution scenario, we will demonstrate that our proposed approach using SVP(t) (4) generates more realistic and accurate schedule variances than the ones computed by the traditional SV(t) model (3). In the simulations, for each project execution scenario taken randomly following the beta distribution, the new metric values are calculated and compared with the values found by the traditional metric.

4. Results and discussion

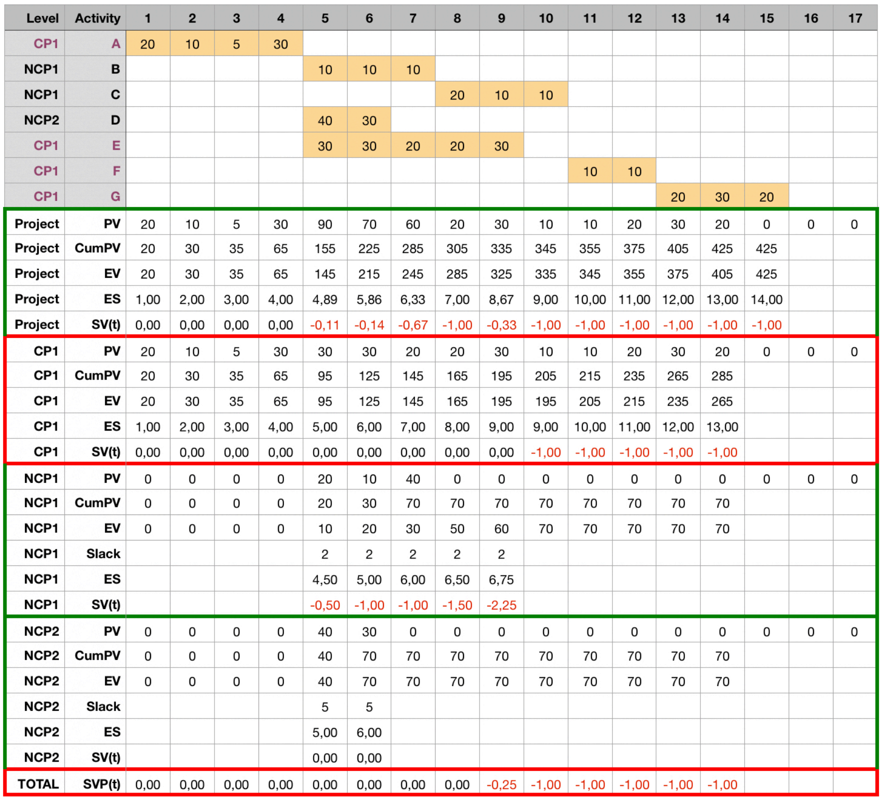
Figure 5, Figure 7, and Figure 9 present the results of three different execution scenarios of the sample project schedule. The SV(t) values by the traditional ES approach using (3) and the SVP(t) values by the proposed approach using (4) are calculated for each scenario. For the presented scenarios, the study analyzes the circumstance in which the traditional SV(t) detects the project delay when in fact, it progresses as scheduled ("false positive") or suggests the project delay which is less than the actual delay ("false negative").

4.1. Scenario 1: The early start case – the delay in NCP is more than its total slack

Figure 5 shows the project and path levels' EV, ES, and SV(t) when CP1 is delayed (the project's actual duration does not coincide with the planned duration). There is also a delay in non-critical activities (activities B and C), on NCP1, for more than the path total slack (the total slack is two weeks, and the delay in NCP1 is three weeks). The baseline considered is in Figure 3 (the early start schedule).

The project level SV(t) values show that the project has a delay starting from week five shown, SV(t)=-0.11. However, the project level results mislead since the project is not late until week 8, i.e., when the delay in NCP1 impacts CP1. Thus, we have a "false positive" suggested by SV(t) at the project level.

Contrary to this, the SVP(t) values, calculated as per (4), capture the correct project schedule status (no delay until week eight and delay from week 9). Hence, in this case, project managers should not take corrective measures till week 8, even though (3) at the project level falsely suggests this.



Level	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CP1	A	20	10	5	30													
NCP1	B					10	10	10										
NCP1	C								20	10	10							
NCP2	D					40	30											
CP1	E					30	30	20	20	30								
CP1	F											10	10					
CP1	G													20	30	20		
Project	PV	20	10	5	30	90	70	60	20	30	10	10	20	30	20	0	0	0
Project	CumPV	20	30	35	65	155	225	285	305	335	345	355	375	405	425	425		
Project	EV	20	30	35	65	145	215	245	285	325	335	345	355	375	405	425		
Project	ES	1,00	2,00	3,00	4,00	4,89	5,86	6,33	7,00	8,67	9,00	10,00	11,00	12,00	13,00	14,00		
Project	SV(t)	0,00	0,00	0,00	0,00	-0,11	-0,14	-0,67	-1,00	-0,33	-1,00	-1,00	-1,00	-1,00	-1,00	-1,00		
CP1	PV	20	10	5	30	30	30	20	20	30	10	10	20	30	20	0	0	0
CP1	CumPV	20	30	35	65	95	125	145	165	195	205	215	235	265	285			
CP1	EV	20	30	35	65	95	125	145	165	195	195	205	215	235	265			
CP1	ES	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	9,00	10,00	11,00	12,00	13,00			
CP1	SV(t)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-1,00	-1,00	-1,00	-1,00	-1,00			
NCP1	PV	0	0	0	0	20	10	40	0	0	0	0	0	0	0	0	0	0
NCP1	CumPV	0	0	0	0	20	30	70	70	70	70	70	70	70	70			
NCP1	EV	0	0	0	0	10	20	30	50	60	70	70	70	70	70			
NCP1	Slack					2	2	2	2	2								
NCP1	ES					4,50	5,00	6,00	6,50	6,75								
NCP1	SV(t)					-0,50	-1,00	-1,00	-1,50	-2,25								
NCP2	PV	0	0	0	0	40	30	0	0	0	0	0	0	0	0	0	0	0
NCP2	CumPV	0	0	0	0	40	70	70	70	70	70	70	70	70	70			
NCP2	EV	0	0	0	0	40	70	70	70	70	70	70	70	70	70			
NCP2	Slack					5	5											
NCP2	ES					5,00	6,00											
NCP2	SV(t)					0,00	0,00											
TOTAL	SVP(t)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,25	-1,00	-1,00	-1,00	-1,00	-1,00			

Figure 5. The results of Scenario 1: The delay in NCP is more than its total slack, thus impacting the project duration.

Note: The execution of activities B and C in NCP1 are behind schedule by more than the total path total slack. Thus, there is an impact on CP1.

The progression behavior of SV(t) on the project level and SVP(t) on the path level is graphically shown in Figure 6. We note that SVP(t) has a more regular behavior than SV(t), granting a more stable project schedule assessment, which is realistic.

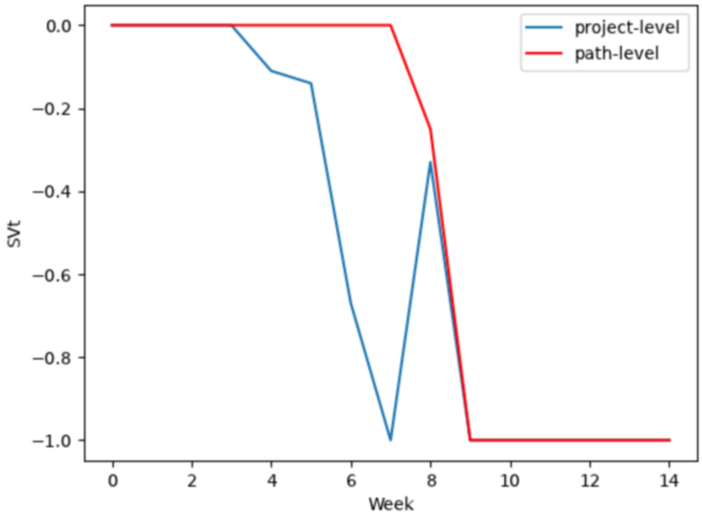
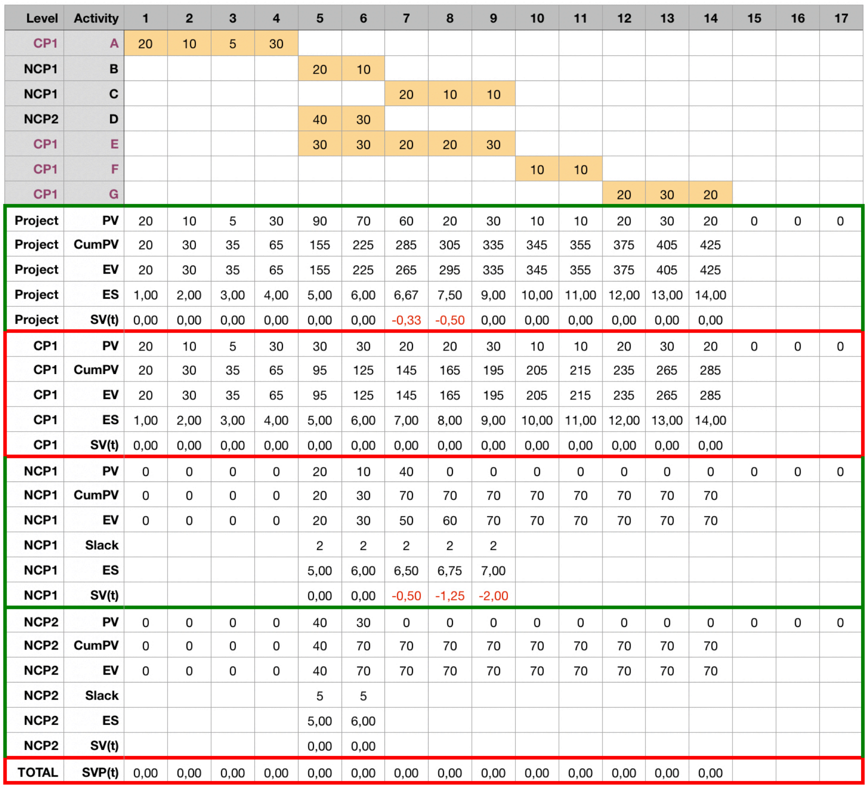


Figure 6. Scenario 1: The SV(t) progression at the path level is more stable than the progression at project level.

4.2. Scenario 2: The early start case – the delay in NCP1 is less than its total slack

Figure 7 shows the project's EV, ES, and SV(t) when it experiences a delay in non-critical activities B and C, on NCP1, for the amount equal to path total slack (the total path slack is two weeks, the delay of activities B and C is two weeks). The baseline considered is in Figure 3 (the early start schedule).

The project level ES values show that the project has a delay in weeks 7 and 8, with the corresponding negative values of SV(t), -0.33, and -0.50. However, in this case, the project level results mislead and generate a "false positive." The project does not experience any delay in weeks 7 and 8 since the delay is only due to NCP1, and it does not impact CP1. Therefore, project managers are suggested by SV(t) at the project level to activate countermeasures to bring the project back on track from week seven while it is not needed. Contrary, the SVP(t) values capture the correct project schedule status.



Level	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CP1	A	20	10	5	30													
NCP1	B					20	10											
NCP1	C							20	10	10								
NCP2	D					40	30											
CP1	E					30	30	20	20	30								
CP1	F										10	10						
CP1	G												20	30	20			
Project	PV	20	10	5	30	90	70	60	20	30	10	10	20	30	20	0	0	0
Project	CumPV	20	30	35	65	155	225	285	305	335	345	355	375	405	425			
Project	EV	20	30	35	65	155	225	265	295	335	345	355	375	405	425			
Project	ES	1,00	2,00	3,00	4,00	5,00	6,00	6,67	7,50	9,00	10,00	11,00	12,00	13,00	14,00			
Project	SV(t)	0,00	0,00	0,00	0,00	0,00	0,00	-0,33	-0,50	0,00	0,00	0,00	0,00	0,00	0,00			
CP1	PV	20	10	5	30	30	30	20	20	30	10	10	20	30	20	0	0	0
CP1	CumPV	20	30	35	65	95	125	145	165	195	205	215	235	265	285			
CP1	EV	20	30	35	65	95	125	145	165	195	205	215	235	265	285			
CP1	ES	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00	11,00	12,00	13,00	14,00			
CP1	SV(t)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			
NCP1	PV	0	0	0	0	20	10	40	0	0	0	0	0	0	0	0	0	0
NCP1	CumPV	0	0	0	0	20	30	70	70	70	70	70	70	70	70			
NCP1	EV	0	0	0	0	20	30	50	60	70	70	70	70	70	70			
NCP1	Slack					2	2	2	2	2								
NCP1	ES					5,00	6,00	6,50	6,75	7,00								
NCP1	SV(t)					0,00	0,00	-0,50	-1,25	-2,00								
NCP2	PV	0	0	0	0	40	30	0	0	0	0	0	0	0	0	0	0	0
NCP2	CumPV	0	0	0	0	40	70	70	70	70	70	70	70	70	70			
NCP2	EV	0	0	0	0	40	70	70	70	70	70	70	70	70	70			
NCP2	Slack					5	5											
NCP2	ES					5,00	6,00											
NCP2	SV(t)					0,00	0,00											
TOTAL	SVP(t)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			

Figure 7. The results of Scenario 2: The delay in non-critical activity within its total slack is not impacting the project duration.

Note: The execution of activities B and C is behind schedule within the path total slack. In this case, there is no impact on CP1 and, therefore, no impact on the project schedule.

The different progression of SV(t) and SVP(t) is shown in Figure 8. Also, in this case, we note a misleading behavior on SV(t) while SVP(t) is aligned with the actual project schedule status (no delay in all the weeks).

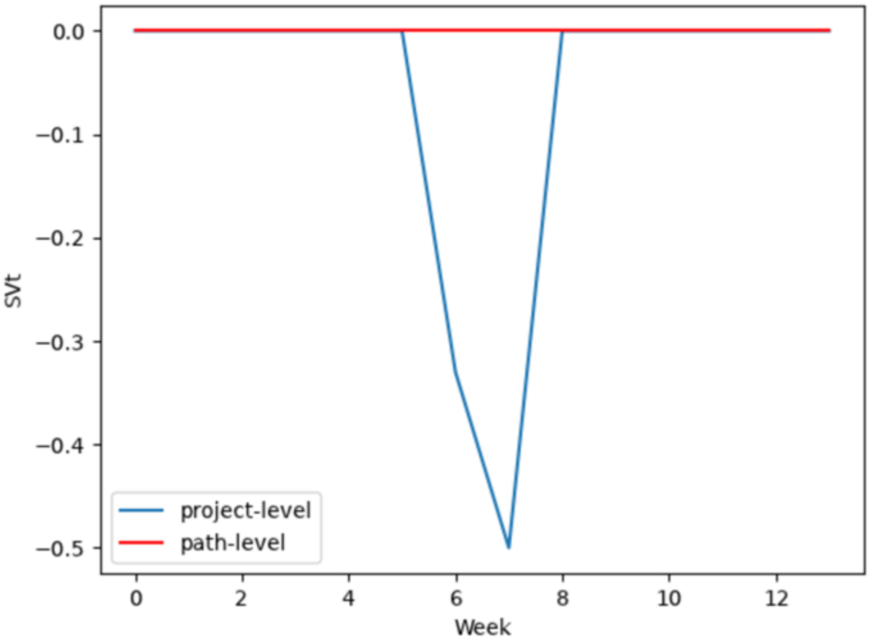
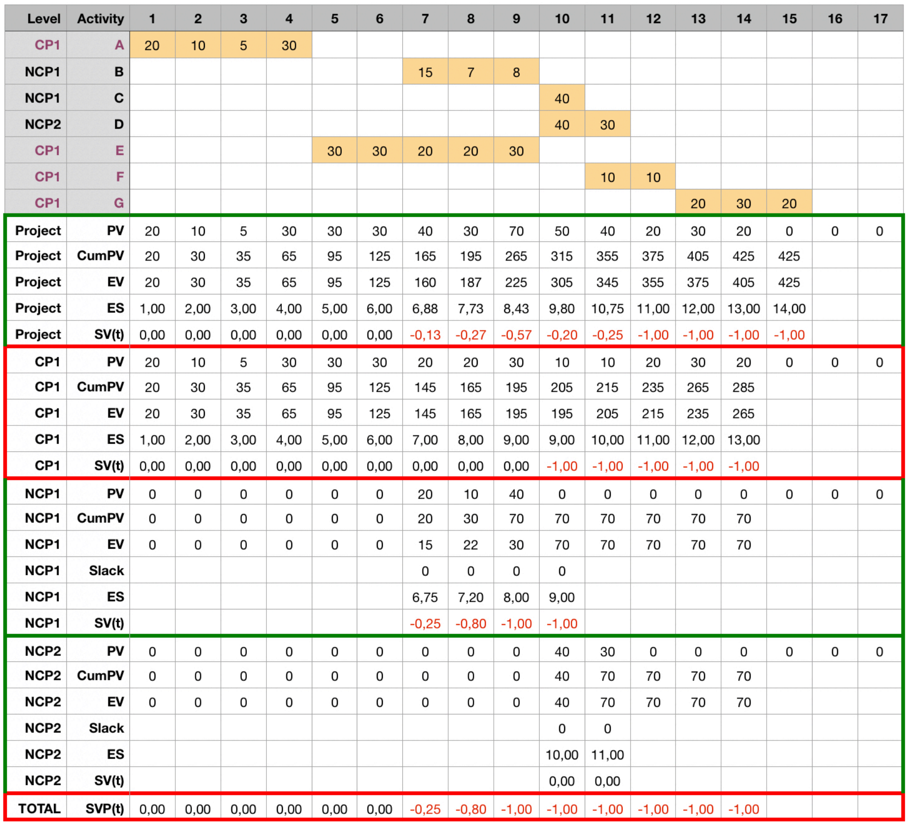


Figure 8. Scenario 2: The SV(t) progression at the path level is more stable than the progression at project level.

4.3. Scenario 3: The late start case – the delay in the non-critical path

Figure 9 shows the project and path levels' EV, ES, and SV(t) when we have a delay in NCP1 but under the condition of a late start and with no total slack. The baseline considered is in Figure 4 (the late start schedule).

The project level SV(t)=-0.13 shows that the project starts to be late on week 7, but with the corresponding SV(t) values being negative with the wrong magnitude. Indeed, the delay observed is greater than the delay calculated with SV(t) since this metric is mitigated by the total slacks of other paths that are not late. Again, the project-level results mislead and generate a "false negative." Therefore, project managers are suggested by SV(t) at the project level to activate countermeasures to bring the project back on track from week 7, but with an incorrect magnitude. The correct schedule variance is detected by an SVP(t) value of -0.25 from week 7.



Level	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CP1	A	20	10	5	30													
NCP1	B							15	7	8								
NCP1	C										40							
NCP2	D										40	30						
CP1	E					30	30	20	20	30								
CP1	F											10	10					
CP1	G													20	30	20		
Project	PV	20	10	5	30	30	30	40	30	70	50	40	20	30	20	0	0	0
Project	CumPV	20	30	35	65	95	125	165	195	265	315	355	375	405	425	425		
Project	EV	20	30	35	65	95	125	160	187	225	305	345	355	375	405	425		
Project	ES	1,00	2,00	3,00	4,00	5,00	6,00	6,88	7,73	8,43	9,80	10,75	11,00	12,00	13,00	14,00		
Project	SV(t)	0,00	0,00	0,00	0,00	0,00	0,00	-0,13	-0,27	-0,57	-0,20	-0,25	-1,00	-1,00	-1,00	-1,00		
CP1	PV	20	10	5	30	30	30	20	20	30	10	10	20	30	20	0	0	0
CP1	CumPV	20	30	35	65	95	125	145	165	195	205	215	235	265	285			
CP1	EV	20	30	35	65	95	125	145	165	195	195	205	215	235	265			
CP1	ES	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	9,00	10,00	11,00	12,00	13,00			
CP1	SV(t)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-1,00	-1,00	-1,00	-1,00	-1,00			
NCP1	PV	0	0	0	0	0	0	20	10	40	0	0	0	0	0	0	0	0
NCP1	CumPV	0	0	0	0	0	0	20	30	70	70	70	70	70	70			
NCP1	EV	0	0	0	0	0	0	15	22	30	70	70	70	70	70			
NCP1	Slack							0	0	0	0							
NCP1	ES							6,75	7,20	8,00	9,00							
NCP1	SV(t)							-0,25	-0,80	-1,00	-1,00							
NCP2	PV	0	0	0	0	0	0	0	0	0	40	30	0	0	0	0	0	0
NCP2	CumPV	0	0	0	0	0	0	0	0	0	40	70	70	70	70			
NCP2	EV	0	0	0	0	0	0	0	0	0	40	70	70	70	70			
NCP2	Slack										0	0						
NCP2	ES										10,00	11,00						
NCP2	SV(t)										0,00	0,00						
TOTAL	SVP(t)	0,00	0,00	0,00	0,00	0,00	0,00	-0,25	-0,80	-1,00	-1,00	-1,00	-1,00	-1,00	-1,00			

Figure 9. The results of Scenario 3: Non-critical activities B and C, which belong to NCP1, are behind the schedule and impact CP1. EVM is not detecting the correct magnitude of the delay.

The different progression of SV(t) and SVP(t) is shown in Figure 10. Also, in this case, we note a misleading behavior of SV(t) while SVP(t) is aligned with the actual project schedule delay magnitude.

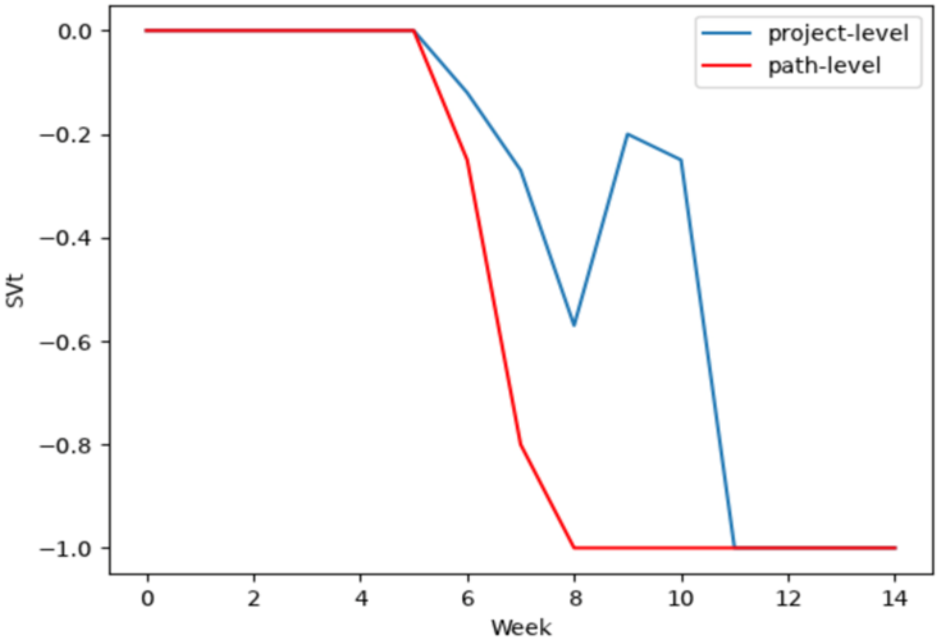


Figure 10. Scenario 3: The SV(t) progression at path level more stable than the progression at project level.

4.4. The simulation results

Figure 11 shows the SV(t) and SVP(t) progression on one hundred possible project executions, randomly selected using PERT distribution which is calculated using a three-point estimation (most likely duration, pessimistic duration, and optimistic duration). For simplicity in the calculation, but without compromising the generalization, the project network is constant, and only the project executions are variable. Figure 11 shows a more stable and robust progression on SVP(t) compared to SV(t). The latter looks more sensitive to what happens in any part of the project, even on non-critical activities that should cause a minor impact – or in some cases, no impact at all, depending on their total slack and delay – on the overall project duration. Therefore, any variation at any part of the project, at any time, impacts (3), causing a fluctuation of (3) even when there are no consequences for the project duration. Suppose we represent the schedule variance using SV(t) (3) labeled "project-level" in Figure 11. We see that the curve slope changes very often. In contrast, SVP(t) (4) is labeled "path-level," and its curve lines (in bold green) are more stable than the "project-level" curve lines (in dashed red).

From the simulation results, the schedule variance analysis with SVP(t) generates only six different projects' progress. This implies that simulated one hundred scenario executions impact the critical path and the total project duration only in six cases. This is because, in most cases, variability in activity duration impacts the non-critical paths NCP1 and NCP2 within their total slack; therefore, the total project duration does not change. Moreover, this is well detected by the proposed metric SVP(t), which works on the path level considering the total slack times. On the other hand, if we consider SV(t), we have one hundred schedules in progress, one for each simulated scenario. This implies that each simulated project execution impacts the project's total duration. However, this is unrealistic, demonstrating the inaccuracy of the SV(t) metric used on the project level.

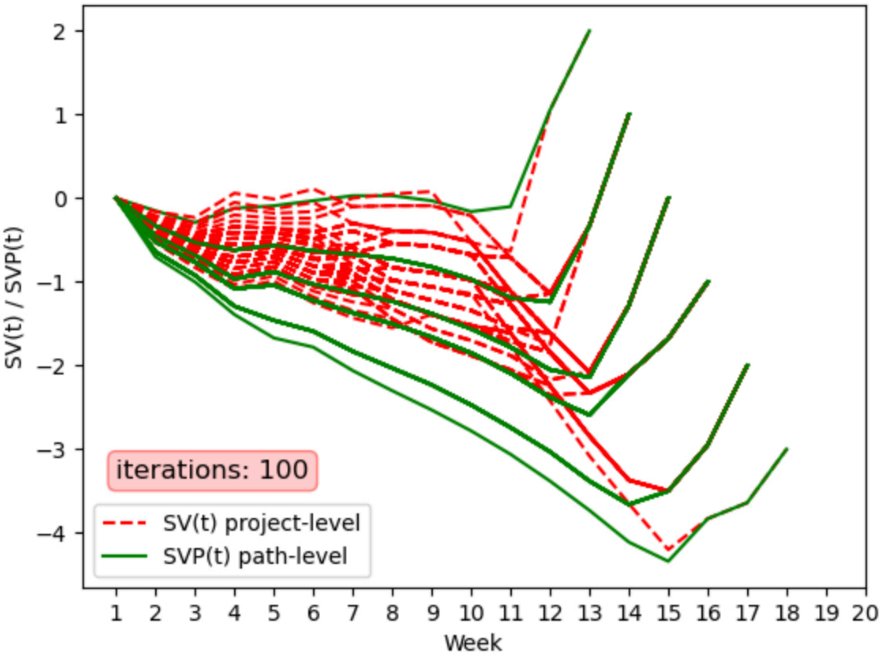


Figure 11. The comparison of the traditional SV(t) project-level and proposed SVP(t) path-level values. SVP(t) is having a more stable and robust progression compared to SV(t).

4.5. Discussion

The findings from applying our approach to the project network show that the traditional ES-based SV(t) metric provides less accurate schedule progress variances. This approach generates false (contradictory) results compared to the proposed approach using the SVP(t) metric. The main difference between the two approaches is that the SV(t) metric is used on the project level, while the SVP(t) metric is on the path level. Our study demonstrated this on three project network executions (on both early start and late start cases), and this finding was confirmed by the simulation test on 100 project networks.

We reported the main reason for the schedule inaccuracy with SV(t). This metric considers the progress in the critical path but does not consider the progress in the non-critical paths with their total slacks and aggregates the path progresses to the project level. As a result, the conventional ES technique provides the schedule progress values, which are unreliable in many scenarios. This occurs in two directions. First, when the project is not late, this is detected as late (false positive) (the scenarios in Sections 4.1 and 4.2, with their results in Figure 5 and Figure 7, respectively). Second, when the project is late, but this is not detected (false negative) or detected with a wrong magnitude (the scenarios in Sections 4.3, with its results in Figure 9). The consequences in both cases have potential negative impacts on the project performance. In the first case, expensive, unnecessary corrective actions can be placed, risking the project budget or profitability. In the second case, no sufficient corrective actions can be placed by the project manager when needed, compromising the project's success. Moreover, not realistic schedule variance may lead to poor project monitoring and, consequently, poor project control, increasing the risk of project failure.

Our approach significantly improves the accuracy of the traditional approach used at the project level. As an expected result of our methodology, we noticed that our SVP(t) metric on the path level is more reliable than the traditional SV(t) metric on the project level since it generates more accurate or true schedule variance results.

Project managers can use the proposed approach to improve the accuracy of schedule monitoring and duration forecasting. An improvement in this area directly reflects project risk reduction and therefore increases the chances of project success. The major strength of our suggested approach is that we do not introduce a new set of formulas but only calculate SV(t) metric at the path level (namely, by a new SVP(t) metric) and then aggregate its values from multiple paths to the project level.

5. Conclusion

Projects pose unique challenges for project managers in monitoring and controlling schedules and duration forecasting. The ES approach, used as a standard methodology, is top-down and does not consider schedule progress discrepancies on individual path levels. This results in inaccurate or false schedule variances, leading to poor duration forecasts and project decision-making. We identified the inability to provide realistic schedule results in the project topology. To address this issue, the authors propose two approaches: introducing a path-level study and constructing a new metric, SVP(t), which considers schedule progress variances on individual path levels, both in critical and non-critical paths. This approach is more stable across all tracking periods and is more stable across all tracking periods.

The proposed method addresses a shortfall previously highlighted in this journal by Diamantas et al. (2011) and is recommended for practitioners in the industry to use for more reliable schedule analysis and duration forecasting on ongoing projects. The project schedule should be examined not only at the overall project level but also on the path levels, and the findings should be compared before appropriate remedial actions for better schedule management are implemented.

Future research could investigate the impact of path level schedule analysis on empirical projects and their final duration. EVM data from a more extensive set of real-life projects could offer empirical path analytics, and management metrics that drastically reduce calculation load can be developed to address this limitation.

Conflict of interest statement

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus;

membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

References

Adlakha, V.G. and Kulkarni, V.G. (1989) ‘A Classified Bibliography Of Research On Stochastic Pert Networks: 1966-1987’, *INFOR: Information Systems and Operational Research*, 27(3), pp. 272–296. Available at: https://doi.org/10.1080/03155986.1989.11732098.

Anbari, F.T. (2004) ‘Earned value project management method and extensions’, *IEEE Engineering Management Review*, 32(3), pp. 97–97. Available at: https://doi.org/10.1109/EMR.2004.25113.

Andiyan, A. *et al.* (2021) ‘Construction Project Evaluation Using CPM-Crashing, CPM-PERT and CCPM for Minimize Project Delays’, *Journal of Physics: Conference Series*, 1933(1), p. 012096. Available at: https://doi.org/10.1088/1742-6596/1933/1/012096.

Andrade, P.A. de, Martens, A. and Vanhoucke, M. (2019) ‘Using real project schedule data to compare earned schedule and earned duration management project time forecasting capabilities’, *Automation in Construction*, 99, pp. 68–78. Available at: https://doi.org/10.1016/j.autcon.2018.11.030.

Ballesteros-Pérez, P. *et al.* (2019) ‘Earned Schedule min-max: Two new EVM metrics for monitoring and controlling projects’, *Automation in Construction*, 103, pp. 279–290. Available at: https://doi.org/10.1016/j.autcon.2019.03.016.

Ballesteros-Pérez, P. *et al.* (2020) ‘Forecasting Accuracy of In-Progress Activity Duration and Cost Estimates’, *Journal of Construction Engineering and Management*, 146(9). Available at: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001900.

Barrientos-Orellana, A. *et al.* (2021) ‘Stability and accuracy of deterministic project duration forecasting methods in earned value management’, *Engineering, Construction and Architectural Management* [Preprint]. Available at: https://doi.org/10.1108/ECAM-12-2020-1045.

Capone, C. and Narbaev, T. (2021) ‘Understanding Schedule Progress Using Earned Value and Earned Schedule Techniques at Path-Level’, *IFIP Advances in Information and Communication Technology*, 634 IFIP, pp. 244–251. Available at: https://doi.org/10.1007/978-3-030-85914-5_26/FIGURES/3.

Chang, H.-K., Yu, W.-D. and Cheng, T.-M. (2020) 'A Quantity-Based Method to Predict More Accurate Project Completion Time', *KSCE Journal of Civil Engineering*, 24(10), pp. 2861–2875. Available at: https://doi.org/10.1007/s12205-020-1924-y.

Diamantas, V.K., Kirytopoulos, K.A. and Leopoulos, V.N. (2011) 'Earned value management under risk', *International Journal of Project Organisation and Management*, 3(3/4), p. 335. Available at: https://doi.org/10.1504/IJPOM.2011.042037.

Hall, G. (2018) 'A Realistic Look at Float Consumption'. AACE® International Technical Paper.

Hammad, M. *et al.* (2020) 'Predicting the critical path changes using sensitivity analysis: a delay analysis approach', *International Journal of Managing Projects in Business*, 13(5), pp. 1097–1119. Available at: https://doi.org/10.1108/IJMPB-07-2019-0184.

Harrin, E. (2018) 'Why Do Some Projects Fail? (And Some Succeed?)', *ITNOW*, 60(4), pp. 54–55. Available at: https://doi.org/10.1093/itnow/bwy107.

Humphreys, G. (2014) 'Project Management Using Earned Value'.

Hussein, B. and Moselhi, O. (2013) 'Performance reporting using schedule compression index', *ISARC 2013 - 30th International Symposium on Automation and Robotics in Construction and Mining, Held in Conjunction with the 23rd World Mining Congress*, pp. 783–792. Available at: https://doi.org/10.22260/ISARC2013/0085.

Kim, B. and Reinschmidt, K.F. (2009) 'Probabilistic Forecasting of Project Duration Using Bayesian Inference and the Beta Distribution', *Journal of Construction Engineering and Management*, 135(3), pp. 178–186. Available at: https://doi.org/10.1061/(ASCE)0733-9364(2009)135:3(178).

Kosztyán, Z.T., Pribojszki-Németh, A. and Szalkai, I. (2019) 'Hybrid multimode resource-constrained maintenance project scheduling problem', *Operations Research Perspectives*, 6, p. 100129. Available at: https://doi.org/10.1016/j.orp.2019.100129.

Lipke, W. (2003) 'Schedule is Different', *The Measurable News*, pp. 31–34.

Lipke, W. *et al.* (2009) 'Prediction of project outcome', *International Journal of Project Management*, 27(4), pp. 400–407. Available at: https://doi.org/10.1016/j.ijproman.2008.02.009.

Lipke, W. (2009) 'Project Duration Forecasting. A Comparison of Earned Value Management Methods to Earned Schedule', *The Measurable News*, 21.

Lipke, W. (2012) 'Speculations on Project Duration Forecasting', *The Measurable News*, (3), pp. 4–7.

Lipke, W. (2014) ‘Examining Project Duration Forecasting Reliability’, *PM World Journal Examining Project Duration Forecasting Reliability*, III. Available at: www.pmworldlibrary.net (Accessed: 9 February 2023).

Lu, M. and Li, H. (2003) ‘Resource-Activity Critical-Path Method for Construction Planning’, *Journal of Construction Engineering and Management*, 129(4), pp. 412–420. Available at: https://doi.org/10.1061/(ASCE)0733-9364(2003)129:4(412).

de Marco, A. and Narbaev, T. (2013) ‘Earned value-based performance monitoring of facility construction projects’, *Journal of Facilities Management*, 11(1), pp. 69–80. Available at: https://doi.org/10.1108/14725961311301475.

Martens, A. and Vanhoucke, M. (2018) ‘An empirical validation of the performance of project control tolerance limits’, *Automation in Construction*, 89, pp. 71–85. Available at: https://doi.org/10.1016/j.autcon.2018.01.002.

Narbaev, T. and de Marco, A. (2014) ‘An Earned Schedule-based regression model to improve cost estimate at completion’, *International Journal of Project Management*, 32(6), pp. 1007–1018. Available at: https://doi.org/10.1016/j.ijproman.2013.12.005.

Narbaev, T. and de Marco, A. (2017) ‘Earned value and cost contingency management: A framework model for risk adjusted cost forecasting’, *Journal of Modern Project Management*, 4, pp. 12–19. Available at: https://doi.org/10.19225/JMPM01202.

Pérez, J.G. *et al.* (2016) ‘Project management under uncertainty beyond beta: The generalized bicubic distribution’, *Operations Research Perspectives*, 3, pp. 67–76. Available at: https://doi.org/10.1016/j.orp.2016.09.001.

Project Management Institute (2011) ‘Practice Standard for Earned Value Management - Second Edition’, *Project Management Institute*. Available at: https://www.pmi.org/pmbok-guide-standards/framework/earned-value-management-2nd (Accessed: 9 February 2023).

Project Management Institute (2017) *A guide to the Project Management Body of Knowledge (PMBOK guide) (6th ed.)*. 6th edn, *Project Management Institute*. 6th edn.

Project Management Institute (2018) ‘Pulse of the Profession 2018’, *Project Management Institute*. Available at: https://www.pmi.org/learning/thought-leadership/pulse/pulse-of-the-profession-2018 (Accessed: 9 February 2023).

Przywara, D. and Rak, A. (2021) ‘Monitoring of Time and Cost Variances of Schedule Using Simple Earned Value Method Indicators’, *Applied Sciences*, 11(4), p. 1357. Available at: https://doi.org/10.3390/app11041357.

Soroush, H.M. (1994) ‘The Most Critical Path in a PERT Network’, *The Journal of the Operational Research Society*, 45(3), p. 287. Available at: https://doi.org/10.2307/2584163.

Vandevoorde, S. and Vanhoucke, M. (2006) ‘A comparison of different project duration forecasting methods using earned value metrics’, *International Journal of Project Management*, 24(4), pp. 289–302. Available at: https://doi.org/10.1016/j.ijproman.2005.10.004.

Vanhoucke, M. (2010) ‘Using activity sensitivity and network topology information to monitor project time performance’, *Omega*, 38(5), pp. 359–370. Available at: https://doi.org/10.1016/j.omega.2009.10.001.

Vanhoucke, M. (2012) *Project Management with Dynamic Scheduling*. Berlin, Heidelberg: Springer Berlin Heidelberg. Available at: https://doi.org/10.1007/978-3-642-25175-7.

Vanhoucke, M. (2013) ‘Measuring Schedule Adherence’, *Measurable News*, pp. 21–26.

Vanhoucke, M. and Vandevoorde, S. (2009) ‘The Measurable News Forecasting a Project’s Duration under Various Topological Structures’, *Measurable News*, pp. 26–30.

Wood, D.A. (2018) ‘A critical-path focus for earned duration increases its sensitivity for project-duration monitoring and forecasting in deterministic, fuzzy and stochastic network analysis’, *Journal of Computational Methods in Sciences and Engineering*, 18(2), pp. 359–386. Available at: https://doi.org/10.3233/JCM-180795.

Zheng, Q. and Bi, X. (2014) ‘Optimization on Earned Value Method Combined with Critical Path’, in *Proceedings of 2013 4th International Asia Conference on Industrial Engineering and Management Innovation (IEMI2013)*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 707–715. Available at: https://doi.org/10.1007/978-3-642-40060-5_68.