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SCHEDULING SIMULATION-BASED TECHNIQUES FOR EARNED VALUE MANAGEMENT ON RESOURCE-CONSTRAINED SCHEDULES UNDER DELAYED SCENARIOS

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ABSTRACT

Earned value management (EVM) is widely utilized for project progress monitoring and cost control purposes. However, traditional EVM techniques are intended for ideal scheduling scenarios without considering the effect of activity-level and project-level delays. The EVM fails to account for dynamic changes of project status in terms of project time extension and associated cost overrun, potentially generating misleading project performance tracking indicators. This research proposes a refined EVM approach based on discrete event simulation (scheduling simulation) to tackle complicated resource-constrained scheduling. A case study is used to demonstrate its applications on a resource-constrained schedule under postulated delay scenarios. It is found that this approach is conducive to truthfully reflecting the project performance status given a resource-constrained schedule subject to complicated activity-project delay. Conclusions are drawn by recapitulating the research contributions and addressing the limitations in the end.

1 INTRODUCTION

Earned value management (EVM) is regarded as an effective time-cost integration methodology for tracking project progress and characterizing project performances in project control. EVM emerged as a financial analysis specialty in United States Defense Agencies in 1967, as part of the cost/schedule control systems criteria (C/SCSC) and the performance measurement system. The techniques have been widely applied to the manufacturing industry since 1980s. In 1996, the United States Defense Agencies formalized the C/SCSC as the earned value management system. The Project Management Institute further standardized EVM terminologies in "A guide to the Project Management Body of Knowledge" in 2000 (Project Management Institute 2005, 2008).

EVM establishes the analytical relationships between the budget cost, actual cost and the work done to allow better assessment of activity time and budget requirements (McConnell 1985). EVM techniques integrate the project scope, schedule and cost in order to indicate project performances at a particular time point.

A major construction project usually spans for years, effective time and cost tracking is important to successful project delivery. Preventive and corrective actions are required to tackle any adverse situations in time. Though previous research pointed out that EVM could be successfully applied and beneficial to the industry (Christensen 1993, 1998), its effective applications in construction have been limited. Previous research (Eldin 1989; Vargas 2003; Solomon and Young 2007; Lukes 2008; Kim and Reinschmidt 2010) found that the EVM techniques fail to obtain accurate indicators to reflect project performance status, especially when the scope, schedule and cost estimates are imprecise or subjected to changes. Thus, EVM techniques are difficult to be applied to dynamic construction projects and do not add much value to project execution, especially when (1) the construction schedule is compounded by considering the resource constraints such as: resource availability limits and multiple calendars; and (2) activity and project delays encountered during project executions.

Nevertheless, there is no standard EVM implementation methodology for coping with changing scope definitions in connection with complicated activity-project delay scenarios. Though Anbari (2003) suggested "time estimate to complete" which is defined in EVM -to a certain extent- factors in delayed project time, the extended duration is roughly predicted without any quantitative scheduling analysis. In this paper, the traditional EVM techniques are firstly reviewed, followed by introducing resource-constrained scheduling analysis based on discrete event simulation (scheduling simulation). In connection with project time extension, an improved EVM framework based on scheduling simulation is proposed. A simple case study based on a project taken from Ahuja et al. (1994) is used to demonstrate the time-cost control applications on a resource-constrained schedule under complicated activity-project delay scenarios, revealing limitations of EVM indicators.

2 EARNED VALUE MANAGEMENT TERMINOLOGY

Three parameters, planned value (PV), earned value (EV) and actual cost (AC), lay the EVM foundation (Figure 1). The PV is the planned budget cost serving as a baseline to guide project execution; the EV is the budget cost based on the work performed which is calculated by multiplying activity budget and the percentage of work completed; the AC is the actual cost of completed work.

All activities are recorded as "completed", "incomplete" or "processing" along with percentages of work completed for schedule updating on the data date. Project performance indicators such as *cost variance* (CV), *schedule variance* (SV), *cost performance index* (CPI) and *schedule performance index* (SPI) can be calculated (Table 1). These parameters indicate up-to-date cost and time performances. A negative CV value or a CPI value less than one implies the project is over-budget, while a positive SV value or a SPI value higher than one means ahead-of-schedule.

EVM enables forecasting project performance at the scheduled project completion date based on the most current project performances at a data date. In Figure 1 and Table 2, the definitions of *budget at completion* (BAC), *estimate to completion* (ETC), *estimate at completion* (EAC) and *variance at completion* (VAC) are illustrated. BAC is the budget planned to be expended in completing the project (mathematically, it is the summation of PV on completion of the project). ETC is the predicted expense to complete the project (Table 3). The VAC value, which indicates the future cost performance, implies cost overrun (negative) or saving (positive) likely to occur upon project completion. The *to-complete performance index* (TCPI) indicates the project performance trend (Table 4). TCPI can be evaluated based on either EAC or BAC. Project productivity improvement is indicated if the TCPI value is greater than one, and vice versa. Based on the EVM indicators, project managers can effectively monitor and forecast project performances on a continuous basis.

In order to truly reflect project performances, the availability of a precise resource-constrained schedule is the prerequisite to implementing EVM on a construction project. To tackle the complexity in generation of an accurate resource-constrained schedule, scheduling simulation provides the cost effective solution, as introduced in the following section.

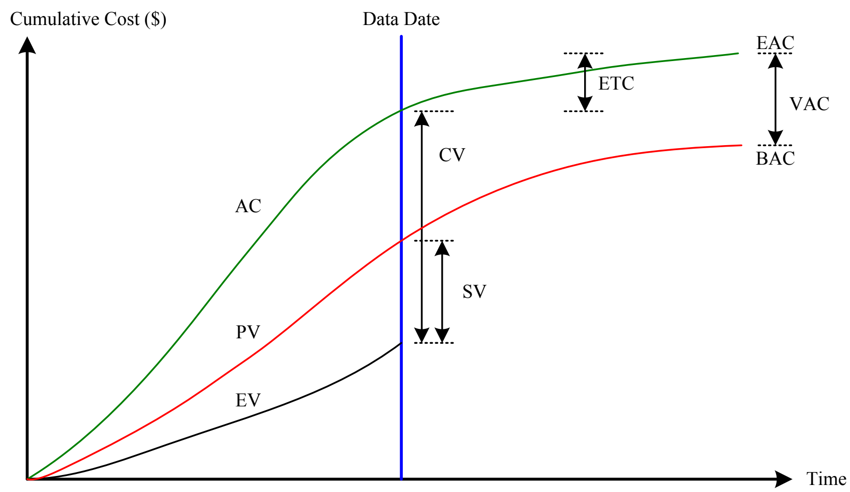

Figure 1: EVM parameters overview

Table 1: Basic Formula

Indicator	Formula
Cost Variance (CV)	EV – AC
Schedule Variance (SV)	EV – PV
Cost Performance Index (CPI)	$\frac{EV}{AC}$
Schedule Performance Index (SPI)	$\frac{EV}{PV}$

Table 2: Forecasting Formula

Forecasting Indicator	Formula
Estimate At Completion (EAC)	AC + ETC
Estimate To Completion (ETC)	EAC – AC
Variance At Completion (VAC)	BAC – EAC

Table 3: ETC Assumptions

ETC Assumption	Formula
Work performed at Budget Rate	BAC – EV
Work performed at Present CPI	$\frac{BAC - EV}{CPI}$
Work considering both CPI and SPI	$\frac{BAC - EV}{CPI \times SPI}$

Table 4: Trend Formula

Trend Indicator	Formula
To-Complete Performance Index based on EAC ($TCPI_{EAC}$)	$\frac{BAC - EV}{EAC - AC}$
To-Complete Performance Index based on BAC ($TCPI_{BAC}$)	$\frac{BAC - EV}{BAC - AC}$

3 ROLE OF SCHEDULING SIMULATIONS IN EARNED VALUE MANAGEMENT

On a construction project, driving resources including skilled laborers and equipment collaborate on a particular activity for certain time duration in order to accomplish the activity. Matching multiple driving resources during activity execution is analogous to scheduling a "meeting" on a time slot when all the resources involved are available (Lu et al. 2008). The inevitable activity interruption owing to resource matching can considerably complicate the critical path scheduling analysis and cause confusions on the resulting total float (TF) values, which may be not more valid and become misleading in controlling activity and project delays. Previous research (Fondahl 1991; Lu and Li 2003; de la Garza and Kim 2005, 2009) concurred that TF breaks down when the schedule is highly constrained by resource availability and calendars, thus compromising the application of critical path scheduling analysis.

Resource-constrained schedules can be generated by mathematical programming formulation or scheduling simulation which is based on heuristic rules and discrete event simulation. The scheduling simulation approaches can handle construction projects of practical size and complexity more effectively. Such approaches, including the resource-constrained critical path method (de la Garza and Kim 2005) and resource-activity critical path method (Lu and Li 2003), can generate feasible resource-constrained schedules for CPM analysis. Scheduling simulation is also employed in the present research study.

Pritsker et al. (1989) defined the simulation as "building a logical model of a system". Scheduling simulation is the ideal methodology to represent complex logical and resource constraints in analyzing the resource-constrained schedule, though the simulation is deterministic (e.g. activity times are constants). However, a valid scheduling simulation can be readily adapted to a stochastic simulation by representing activity times as statistical distributions. By simulation of logical work flows, the construction execution performances such as project completion time could be easily examined (Halpin 1977; Kartam and Ibbs 1996). Based on the simulation model, the schedule can be simulated by tracking the changes of the status of construction system at discrete time points (Pidd 1992). A resource-constrained schedule can be evaluated in a more realistic fashion, in contrast with the mathematical formulations which may not sufficiently account for all the relevant practical constraints.

To conduct scheduling simulation in this research study, two scheduling software tools, Primavera® P3™ Project Planner (*P3*) and the Simplified Simulation-empowered Scheduling (*S3*), are employed. In *P3*, the project network is defined by linking activity blocks according to activity precedence relationships. Combining resource leveling features under the settings of meeting-activity type and interruptible activity duration, *P3* is capable of accurately generating resource-constrained schedules from the forward pass scheduling simulation subject to availability limits and calendars being imposed on driving resources. Note the simulated schedule is deterministic as the activity duration can only be inputted as constants in *P3*. On the other hand, the simulation engine of *S3* runs on discrete event simulation. The activity blocks are linked by disposable and non-disposable resources. The activity times are set as constants so as to ensure both *P3* and *S3* results are compatible. Valid resource-constrained schedules can readily turn into project evaluation and review technique (PERT) simulations (or Monte Carlo simulation on CPM) in *S3*. The details of Monte Carlo simulations and transformations between CPM scheduling and PERT simulation can be referred to Pidd (1992) and Lu et al. (2008).

The project time extension (PTE, representing project delay) is largely attributed to activity time extensions (ATE, representing activity delay) which occur on multiple activities during the execution stage of a construction project. PTE and ATE are calculated as Eqs. (1) and (2), respectively. The relationships between PTE and ATE are highly non-linear which are characterized in Siu and Lu (2011). By comparing the difference between updated and original project/activity completion times, PTE/ATE can be readily evaluated. ATE can be evaluated in both *P3* and *S3* by incrementally prolonging activity duration. As a result, PTE is derived as the lengthened time for project completion as a result of imposing ATE. For cross-validation, this research firstly employs *P3* to generate activity priorities based on the heuristic rules. *S3* is then used to generate a resource-constrained schedule based on *P3*-produced activity priorities.

$$\text{PTE} = \text{Delayed Project Completion Time} - \text{Scheduled Project Completion Time} \tag{1}$$

$$\text{ATE} = \text{Delayed Activity Duration} - \text{Original Activity Duration} \tag{2}$$

Based on an accurate correlation between the project and activity time extensions, the traditional EVM framework is refined. A simple case example is used to demonstrate applications of established EVM techniques on a resource-constrained schedule under complicated activity-project delay scenarios, and EVM's limitations are addressed.

4 IMPROVED EARNED VALUE MANAGEMENT FRAMEWORK

The traditional EVM framework is only applicable to a project with a steady scope as emphasized in Section 2. The PV defines the budget with a precise scope definition (without variations or project delays), the BAC is fixed given a fixed project scope. The indicators can be ambiguous in case of delays because project and activity delays may imply scope change has taken place on the project. Thus, an improved EVM approach is proposed to address delay scenarios based on the simulated resource-constrained schedules, so as to enhancing the accuracy of EVM indicators.

Given project and activity delays, EV may continue to increase during the delays. An unrealistic SPI value would be produced if PV remains unchanged. Thus, PV/EV/AC must be updated accordingly as a result of the delays being experienced. The refined approach modifies the EVM equations as (3) to (5). The delayed activity PV is updated, which takes into account the delayed time and the original PV per day. EV is calculated according to the updated PV for the delayed activities. The increment of PV or EV reflects scope variation in terms of time and cost. On the other hand, the cost associated with project time extension (PTE) such as liquidated damage, denoted as "cost per day", is included in the calculation of delayed activity's AC. It is noteworthy that the calculated EVM indicators are compatible with the EVM terminology, with particular emphasis on practical applications in the context of delayed scheduling scenarios. However, all the EVM indicators only reflect project performances according to the delayed schedule (updated). In bridging both EVM and CPM frameworks, PV in EVM analysis is deliberated based on the early start time (ES) and early finish time (EF) from CPM analysis based on scheduling simulations. The steps are illustrated in the case study.

$$\text{Delayed Activity PV} = (\text{PV / Day}) \times \text{Duration from Early Start to Data Date} \tag{3}$$

$$\text{Delayed Activity EV} = \text{Delayed Activity PV} \times \text{Percentage of Work Completed} \tag{4}$$

$$\text{Delayed Activity AC} = \text{AC} + (\text{PTE} \times \text{Cost / Day}) \tag{5}$$

5 CASE ILLUSTRATION

The case study project network is taken from Ahuja et al. (1994) to demonstrate the improved EVM framework. The scheduling network (Figure 3) plus activity time and resource requirements are shown (Table 5). The project consists of nine activities and two resource types. The resource availability limits are 6 laborers and 1 crane on a daily basis. Multiple calendar constraints are also imposed on driving resources. The laborers run on 6 work-day weeks, taking Sunday off; while the crane runs on 5 work-day weeks, taking both Saturday and Sunday off. The cost information is shown in Table 6, and liquidated damage per day is assumed at $5000/day.

Primavera® P3™ Project Planner (*P3*) was firstly employed for forward pass scheduling simulation. The automatic leveling by built-in heuristic rules of *P3* generates activity execution sequence with activity priorities given in Table 5. The larger the code number, the higher the priority for activity execution. *S3* was then used to simulate the resource-constrained schedule. Both *S3* and *P3* produce identical schedules with 23 days project completion time. Figure 4 shows the planned schedule simulated by *S3*. Based on this resource-constrained schedule, the associated direct cost can be budgeted with respect to activities' early start and finish times (Table 7). The cost budget for the total project without any activity and project delays is $56000.00. Two delay scenarios are postulated: (1) considering one activity delay, and (2) considering multiple activity delays.

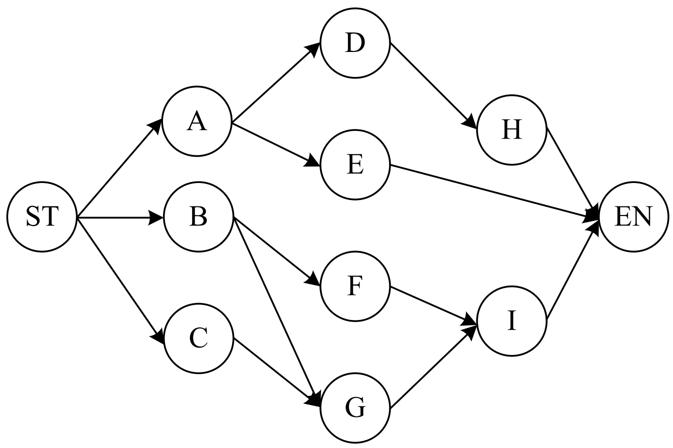

Figure 3: Scheduling network for example project

Table 5: Activity and Resource Requirements

Activity	Duration (Days)	Resource Requirement		Priority
		Labor	Crane	
A	2	4	1	7
B	3	4	0	8
C	5	4	0	9
D	4	3	0	3
E	4	1	0	4
F	3	2	1	5
G	6	2	0	6
H	2	2	1	1
I	3	2	0	2

Table 6: Cost Requirements

Cost Types	PV ($ / Day)	AC ($ / Day)
Labor	500.00	700.00
Crane	2000.00	1800.00

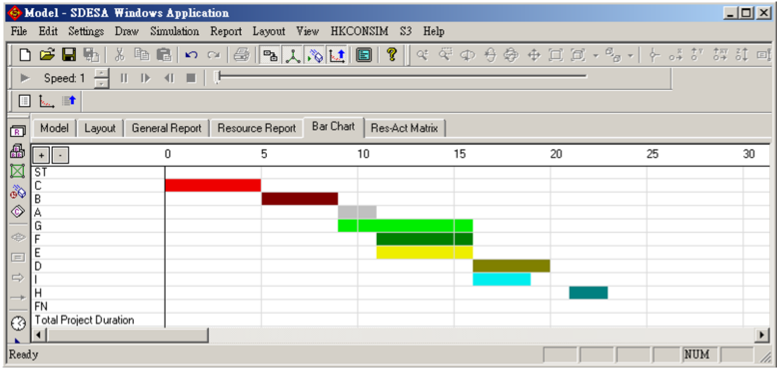

Figure 4: Originally Planned Schedule Simulated by *S3*

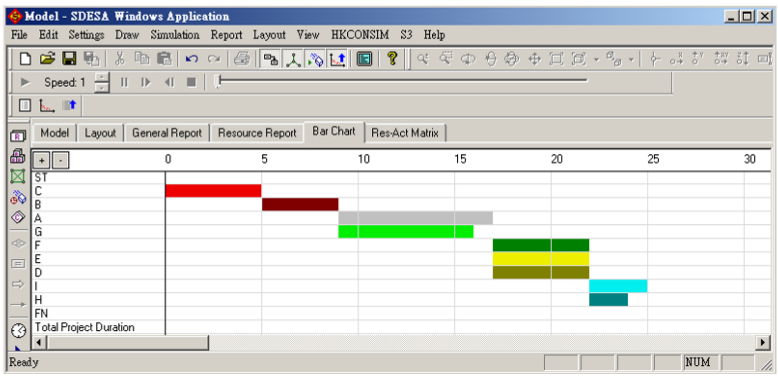

Figure 5: Delayed Schedule Simulated by *S3*

In the first delay scenario, Activity A's duration is delayed from two days to six days, which ends at one day beyond its late finish time. The resulting delayed schedule, which was also generated by *S3* based on the same activity priorities generated by *P3*, is shown in Figure 5. The project completion time increases from twenty-three days to twenty-five days. According to Eqs. (1) and (2), ATE is 4 days and PTE is 2 days. The result shows the PTE-ATE relationships exhibit highly non-linearity (Siu and Lu 2011). Table 7 tabulates the actual cost for this delayed schedule. Days 7, 14 and 21 are assumed to incur zero direct cost (as bolded) as they are non-working days. The project cost increases from \$56000.00 (according to the originally planned schedule) to \$89800.00 (according to the updated schedule) due to extra activity expenses.

Because Activity A owns 3-day TF, its completion time can be delayed from Day 12 to 15 without extending the project completion time. However, PV and EV on the delayed activity A are updated according to (3) and (4) respectively. For instance, on Day 11, PV is (4000×2) = \$8000.00; EV is $(8000 \times 2/6)$ = \$2666.67; AC is (4600×2) = \$9200.00. On Day 12, PV increases to (4000×3) = \$12000.00, EV is $(12000 \times 3/6)$ = \$6000.00, AC is (4600×3) = \$13800.00. The EVM indicators on Activity A remain unchanged in the following two non-working days. Similar procedures are taken to calculate the EVM indicators from Day 15 to Day 17. By using the formulae in Table 1, the values of SPI and CPI from Day 11 to 17 are calculated and given in Table 8.

The cost associated with time extensions such as liquidated damage should be considered on Day 17. AC is modified to $(58400+2 \times 5000)$ = \$68400.00 according to (5). The CPI immediately decreases from 0.79 to 0.67. The sudden drop reflects the cost overspend resulting from project delays (PTE). This improved EVM framework was successfully applied to this single activity delay (activity A) scenario. Next, the EVM is applied in multiple activity-delay scenario (activity A and G).

Table 7: Activity Cost Calculations for Planned and Delayed Schedules

Planned Resource-Constrained Schedule													
	1	2	3	4	5	6	**7**	8	9	10	11	12	13
A	0	0	0	0	0	0	**0**	0	0	4000	4000	0	0
B	0	0	0	0	0	2000	**0**	2000	2000	0	0	0	0
C	2000	2000	2000	2000	2000	0	**0**	0	0	0	0	0	0
D	0	0	0	0	0	0	**0**	0	0	0	0	0	0
E	0	0	0	0	0	0	**0**	0	0	0	0	500	500
F	0	0	0	0	0	0	**0**	0	0	0	0	3000	0
G	0	0	0	0	0	0	**0**	0	0	1000	1000	1000	1000
H	0	0	0	0	0	0	**0**	0	0	0	0	0	0
I	0	0	0	0	0	0	**0**	0	0	0	0	0	0
Daily Cost	2000	2000	2000	2000	2000	2000	**0**	2000	2000	5000	5000	4500	1500
Cumulative	2000	4000	6000	8000	10000	12000	**12000**	14000	16000	21000	26000	30500	32000
	14	15	16	17	18	19	20	**21**	22	23	-	-	-
A	**0**	0	0	0	0	0	0	**0**	0	0	-	-	-
B	**0**	0	0	0	0	0	0	**0**	0	0	-	-	-
C	**0**	0	0	0	0	0	0	**0**	0	0	-	-	-
D	**0**	0	0	1500	1500	1500	1500	**0**	0	0	-	-	-
E	**0**	500	500	0	0	0	0	**0**	0	0	-	-	-
F	**0**	3000	3000	0	0	0	0	**0**	0	0	-	-	-
G	**0**	1000	1000	0	0	0	0	**0**	0	0	-	-	-
H	**0**	0	0	0	0	0	0	**0**	3000	3000	-	-	-
I	**0**	0	0	1000	1000	1000	0	**0**	0	0	-	-	-
Daily Cost	**0**	4500	4500	2500	2500	2500	1500	**0**	3000	3000	-	-	-
Cumulative	**32000**	36500	41000	43500	46000	48500	50000	**50000**	53000	56000	-	-	-

Delayed Resource-Constrained Schedule													
	1	2	3	4	5	6	**7**	8	9	10	11	12	13
A	0	0	0	0	0	0	**0**	0	0	4600	4600	4600	0
B	0	0	0	0	0	2800	**0**	2800	2800	0	0	0	0
C	2800	2800	2800	2800	2800	0	**0**	0	0	0	0	0	0
D	0	0	0	0	0	0	**0**	0	0	0	0	0	0
E	0	0	0	0	0	0	**0**	0	0	0	0	0	0
F	0	0	0	0	0	0	**0**	0	0	0	0	0	0
G	0	0	0	0	0	0	**0**	0	0	1400	1400	1400	1400
H	0	0	0	0	0	0	**0**	0	0	0	0	0	0
I	0	0	0	0	0	0	**0**	0	0	0	0	0	0
Daily Cost	2800	2800	2800	2800	2800	2800	**0**	2800	2800	6000	6000	6000	1400
Cumulative	2800	5600	8400	11200	14000	16800	**16800**	19600	22400	28400	34400	40400	41800
	14	15	16	17	18	19	20	**21**	22	23	24	25	-
A	**0**	4600	4600	4600	0	0	0	**0**	0	0	0	0	-
B	**0**	0	0	0	0	0	0	**0**	0	0	0	0	-
C	**0**	0	0	0	0	0	0	**0**	0	0	0	0	-
D	**0**	0	0	0	2100	2100	2100	**0**	2100	0	0	0	-
E	**0**	0	0	0	700	700	700	**0**	700	0	0	0	-
F	**0**	0	0	0	3200	3200	0	**0**	3200	0	0	0	-
G	**0**	1400	1400	0	0	0	0	**0**	0	0	0	0	-
H	**0**	0	0	0	0	0	0	**0**	0	3200	3200	0	-
I	**0**	0	0	0	0	0	0	**0**	0	1400	1400	1400	-
Daily Cost	**0**	6000	6000	4600	6000	6000	2800	**0**	6000	4600	4600	1400	-
Cumulative	**41800**	47800	53800	58400	64400	70400	73200	**73200**	79200	83800	88400	89800	-

Table 8: EVM Calculations from Day 11 to Day 17 in Single-Activity Delay Scenario

End of Day 11			
Activity	PV	EV	AC
A	8000.00	2666.67	9200.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	0.00	0.00	0.00
F	0.00	0.00	0.00
G	2000.00	2000.00	2800.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	26000.00	20666.67	34400.00
SPI:	0.79	CPI:	0.60

End of Day 12			
Activity	PV	EV	AC
A	12000.00	6000.00	13800.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	500.00	0.00	0.00
F	3000.00	0.00	0.00
G	3000.00	3000.00	4200.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	34500.00	25000.00	40400.00
SPI:	0.72	CPI:	0.62

End of Day 13			
Activity	PV	EV	AC
A	12000.00	6000.00	13800.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	1000.00	0.00	0.00
F	3000.00	0.00	0.00
G	4000.00	4000.00	5600.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	36000.00	26000.00	41800.00
SPI:	0.72	CPI:	0.62

End of Day 15			
Activity	PV	EV	AC
A	16000.00	10666.67	18400.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	1500.00	0.00	0.00
F	6000.00	0.00	0.00
G	5000.00	5000.00	7000.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	44500.00	31666.67	47800.00
SPI:	0.71	CPI:	0.66

End of Day 16			
Activity	PV	EV	AC
A	20000.00	16666.67	23000.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	2000.00	0.00	0.00
F	9000.00	0.00	0.00
G	6000.00	6000.00	8400.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	53000.00	38666.67	53800.00
SPI:	0.73	CPI:	0.72

End of Day 17			
Activity	PV	EV	AC
A	24000.00	24000.00	27600.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	1500.00	0.00	0.00
E	2000.00	0.00	0.00
F	9000.00	0.00	0.00
G	6000.00	6000.00	8400.00
H	0.00	0.00	0.00
I	1000.00	0.00	0.00
Total	59500.00	46000.00	68400.00
SPI:	0.77	CPI:	0.67

In a multiple-activity-delay scenario, delays on Activities A and G are considered. ATE on Activity A are 4 days, which is identical to the previous scenario, additionally, 1-day ATE occurs on Activity G. After imposing the delays to the resource-constrained project schedule, the project completion time is lengthened for two days (2-day PTE), showing ATE and PTE are related in a highly non-linear fashion subject to multiple activity delays (Siu and Lu 2011; Lu et al. 2011). Similarly, the EVM indicators on Activity A and G are updated according to Eqs. (3) to (5) to consider activity delays. Table 9 gives EVM calculations on Day 17, where the underlined values are updated costs on the two delayed activities.

The SPI and CPI values, which are smaller than one, imply underperformances in project time and cost control. Considering both current cost and schedule performances (see formulas given in Tables 2 and 3), EAC is calculated as \$99356.71 by Eq. (6), and therefore VAC is –\$33356.71. $TCPI_{EAC}$ is calculated as 0.46 by Eq. (7), indicating productivity loss on the project in the remainder of the project execution.

The improved EVM approach, which is capable to generate accurate project performance indicators for single and multiple activity delay scenarios, is demonstrated in the case study. The refined EVM techniques can be readily applied to complex construction projects under practical constraints. The proposed EVM framework can be further enhanced so as to (1) quantitatively assess the project performance by tracking scope change, work done and actual expenses on a continuous basis; (2) seamlessly connect EVM indicators with TF determined from CPM. Those limitations present further research opportunities.

$$\text{EAC} = 79800.00 + \frac{56000.00 - 47000.00}{0.78 \times 0.59} \tag{6}$$

$$\text{TCPI}_{\text{EAC}} = \frac{56000.00 - 47000.00}{99356.71 - 79800.00} \tag{7}$$

Table 9: EVM Calculations in Multiple-Activity Delay Scenario

End of Day 17			
Activity	PV	EV	AC
A	<u>24000.00</u>	<u>24000.00</u>	<u>27600.00</u>
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	1500.00	0.00	0.00
E	2000.00	0.00	0.00
F	9000.00	0.00	0.00
G	<u>7000.00</u>	<u>7000.00</u>	<u>9800.00</u>
H	0.00	0.00	0.00
I	1000.00	0.00	0.00
Total	60500.00	47000.00	79800.00
SPI:	0.78	CPI:	0.59

6 CONCLUSION

The traditional EVM approach is mainly intended for ideal scheduling scenarios without practical resource constraints or time delays. The EVM indicators fail to accurately quantify project time and cost performances, given resource constraints and delays are imposed on a planned schedule. This research has addressed the cost implications in connection with activity and project time extensions by improving the earned value management (EVM) framework, based on precise resource-constrained schedules produced by scheduling simulation. A simple project example, which is taken from Ahuja et al. (1994), is used for concept proving and illustrations in a case study. Both single and multiple activity delay scenarios are investigated. In-depth discussions on how to simulate resource-constrained schedules by Primavera® P3™ Project Planner (*P3*) and Simplified Simulation-empowered Scheduling (*S3*) and the steps in implementing the new approach under delay scenarios are included. The proposed EVM framework can be further enhanced in terms of (1) quantitatively assessing the project performance by tracking scope change, work done and actual expenses on a continuous basis, and (2) seamlessly connecting the EVM indicators with total float (TF) determined from critical path method (CPM). In short, the refined EVM approach provides a cost-effective project control methodology to track project time and cost performances on resource-constrained schedules under complicated activity-project delay scenarios.

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