EVM-4025

Fully Integrating Earned Value and CPM Schedule Analysis at a Causal Level – A New Analytical Approach

J. Gerard Boyle, CFCC

Abstract

Labor productivity is a major, world-wide problem in the construction industry. Not coincidentally, this productivity problem is accompanied by enormous cost and time overruns on construction projects. Moreover, a recent study found that the world has an "*annual shortfall in infrastructure spending of $ 1 trillion*". If these performance problems could be corrected, citizens and customers across the world stand to benefit.

Poor project management and execution basics has been identified as a "*root cause*" of low productivity as well as time and cost overruns. Earned Value Management ("EVM") is one of the management tools that is cited as failing to deliver performance improvements. It is clear, not only from studies, but also based on the author's experience in conceiving and implementing EVM systems for major construction programs, that existing EVM has not fulfilled its promise because of: significant and fundamental limitations and flaws in its analytics and practice; deviation from its own stated objectives, and; associated flaws in its management emphasis.

The practice of EVM requires a major overhaul and rethinking if labor productivity, as well as the project time and cost outcomes which suffer as a result, are to improve. This article introduces new EV formulas that have been practically and successfully tested on construction projects. They connect the causal productivity and resource input factors to the durations that is seen as CPM schedule output, and together, support a truly integrated and enriched analytical system which improves time and cost outcomes.

Table of Contents

TABLE OF FIGURES

TABLE OF EQUATIONS

INTRODUCTION

It is more than six years ago since a study entitled *Reinventing Construction: A Route to Higher Productivity* was released to much acclaim and interest. [1] It reported that productivity on construction projects continued to significantly trail other industries such as manufacturing. Moreover, as a consequence, projects were regularly over budget and finishing late. The "*reinvention*" it called for included the need for comprehensive, integrated, advanced performance analytics and Key Performance Indicators (KPIs). Such advanced analytics would serve as a "*source of truth*", creating performance "*transparency*". [1, p 89]

Today, one might fairly ask: What came of that study? Is productivity even on the radar? Have project controls been improved? Are there reliable project performance analytics available to improve time and budget performance on construction projects? For the reasons presented in Parts 1 and 2 of this paper, the answer is 'no'. The existing analytics are seriously flawed. In addition to the inherent problems with the analytics, CPM schedules and earned value analytics are not integrated; they reside in separate silos.

To a significant extent, performance analysis is of limited or no value. A crucial problem is that the analysis is not causal, but analysis must be causal in order to create performance transparency. And it is only with transparency that there can be accountability for poor performance to-date. Improving *future* performance also relies on a causal understanding of current problems. To improve performance on construction projects, there is need for reliable, contemporaneous, performance analytics to accurately assess schedule performance at a causal level.

Such a system is presented in these pages. CPM schedule and earned value analytics are fully integrated into a causal analysis which is helping to deliver major construction projects and programs on-time and on budget.

Part 1: CRITIQUE OF EARNED VALUE AND CPM ANALYSIS

1.1 A Brief Primer

In order to understand the limitations and flaws in existing Earned Value analytics, a brief primer and worked example of current theory and practice is provided in this section. The primary references used are: EIA-748-D[4] [15]; AACE RP 80R-13[5] [16], and AACE RP 86R-14[6] [17]. This section is a primer; it is not intended to exhaustively cover all Earned Value practices. For example, subjects such as use of the EVM information in the organization's (owner's) management processes, or the format of performance reporting, is not discussed in detail. This section is focused on aspects of EVM (and CPM scheduling) theory relevant to performance analysis.

1.1.1 Objective of EVM

According to EIA 748-D, the objective of EVM is to "*provide strong benefits for program enterprise planning and control*." [15, p.1] The means to do this is to: integrate program scope, schedule and cost objectives; establish a baseline plan for accomplishing the time and cost targets, and; make use of earned value techniques for performance measurement during the execution of the program. An EVM system should provide a sound basis for problem identification, corrective actions, and management replanning as may be required. AACE RP 86R-14 emphasizes that the "*root cause*" of variances must be investigated. [17, p 2] A major point of this paper, discussed more below[7], is that existing EVM analytics are not root causal.

[4] The Electronic Industries Alliance (EIA) 748 Earned Value Management Systems Revision 'D' (EIA-748-D). [15]
[5] AACE International Recommended Practice No. 80R-13, Estimate At Completion (EAC), Morgantown, WV: AACE International, Latest Revision. [16]
[6] AACE International Recommended Practice No. 86R-14, Variance Analysis and Reporting, Morgantown, WV: AACE International, Latest Revision. [17]
[7] See Sections 1.3.6, 2.2.4, 2.2.5, and 2.3.

1.1.2 Performance To-Date – Traditional EVM Performance Measurement Analysis

Figure 1 depicts the planned, earned and actual cumulative curves, with cost on the vertical axis, and time on the horizontal. [15, p. 20] The "*Performance Measurement Baseline*" (PMB) is the plan which, according to EVM best practice, is generated by a critical path method ("CPM") schedule loaded with dollars, labor and equipment hours, and material quantities. The PMB is the integrated scope-schedule-cost plan for the project. Schedule and cost variance are tracked against it. It is notable that in this figure, the PMB does not resemble the S-curve profile which is typical for construction projects.[8] It may be that this example does not apply to a construction project, in which case the point is that EVM *should* distinguish the unique characteristics of performance in different areas of study. On a construction project (as perhaps opposed to manufacturing and software development)[9], this PMB profile reflects an atypical performance pattern that would be properly investigated. That said, it is emphasized that the S-curve is only a heuristic; the fully developed and integrated, resource loaded CPM schedule is the optimal performance model and has primacy over any rule-of-thumb.

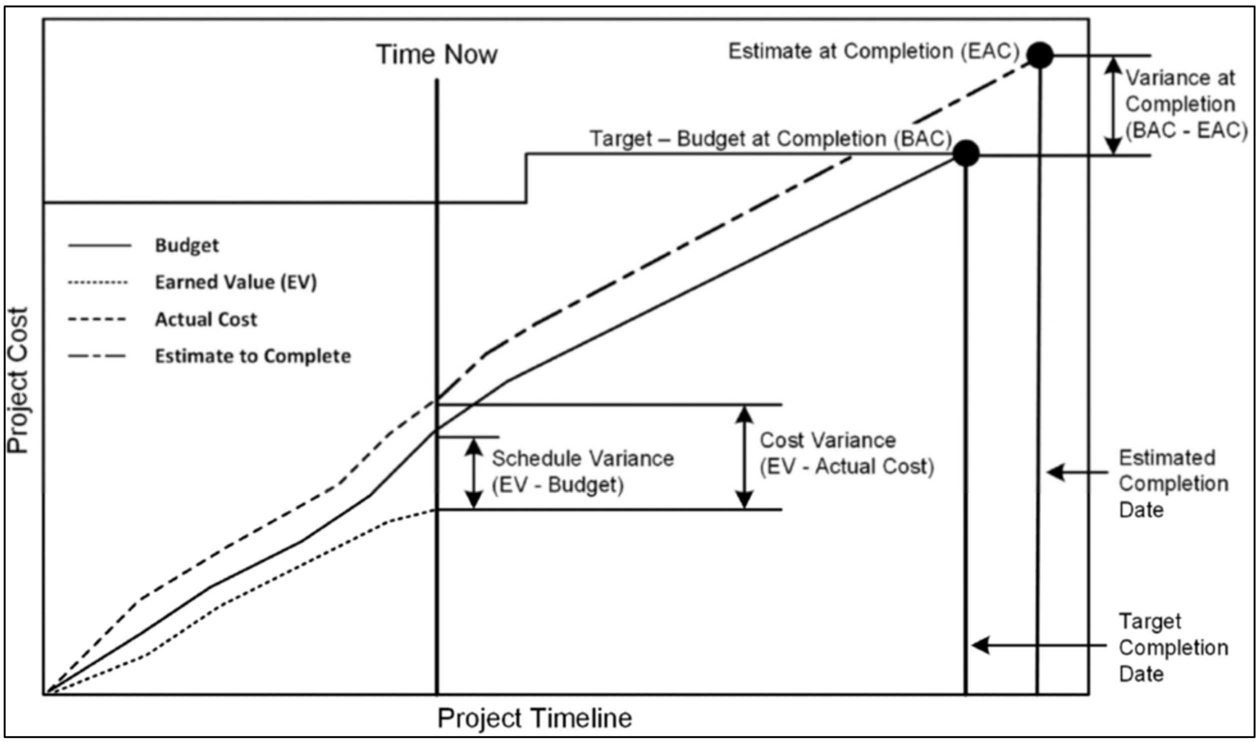


Figure 1 – EIA-748-D Performance Measurement Curve

1.1.3 Cost Variance, Cost Performance Index, Schedule Variance, & Schedule Performance Index

As indicated in Figure 1, performance to-date is analyzed by calculating the two earned value metrics: Cost Variance (and the Cost Performance Index) and Schedule Variance (and the Schedule Performance Index). These metrics both use Earned Value (EV) as the measurement of work accomplishment. Earned Value is defined as the "*value of completed work expressed in terms of the budget assigned to that work*". [15, p. 8] It is calculated by multiplying the percentage of completed work by the budget for the work (EV = Percentage Complete x Budget at Completion).

[8] The PMI EVM Practice Standard [2, p 109]] uses a "*Bicycle Project*" as the PMB. In this case, current EVM literature does not account the differences likely to exist to between manufacturing (or other industries) and construction performance patterns.

[9] This paper is based on the use of EVM on construction projects. Performance patterns in other industries and work types are not considered.

At regular time intervals during the execution of the project, usually monthly, the EV metrics are updated and analyzed. In Figure 1, cumulative AC and EV are plotted up to the "*Time Now*" status date.

Cost Variance:

Cost variance (CV) is "*a metric for cost performance on a program*". [15, p. 8] It is the difference between what has been earned (EV) and the actually expended cost (AC), and is expressed in the formula: CV = EV – AC. Favorable performance is equal to or greater than zero. The Cost Performance Index (CPI) is a ratio which provides the relative size of EV to AC (CPI = EV ÷ AC). It is an "*indicator of the cost efficiency at which work is being performed*."[10] The CPI is favorable if it is equal to or greater than 1.00. Both of these definitions refer to "*cost*" performance and efficiency. The EIA-748-D makes a distinction between "*Efficiency Variance Calculation*" and "*Labor Rate Variance Calculation"* and provides formulas for each.[11] [15, p 19] Most of the EV literature bases its analysis on dollars instead of hours, reflecting the dollar-cost focus of current EV analysis. For reasons to be explained later, the Labour Rate Variance Calculation is the focus in this paper.

CV literature does not advance a clearly articulated position on the effect, if any, of CV or CPI variances on the duration of the work. As noted above, time duration variance is deferred to CPM schedule analysis. It is allowed that CV is an "*indicator*", but what it might indicate in terms of time is not clear. For example, in the case of a very low CPI (say 0.50, or 50% of plan), typical analysis might speculate that "*the work will likely take **twice as long**[12] to finish and most probably **cost more due to the extended duration***." [17, p 6] Another example from the literature states: "*If … late to the baseline plan tasks are determined to have a positive schedule float position (slack) and are not felt to represent high risks to the project, then **added resources should not be authorized**. The reason is that **any added resources will have a permanent negative impact on the cost efficiency rate** and will produce no positive critical path schedule results*." [19]

In Part 2, the causal determination of performance activities is proven to be deterministic, and an implication of the new deterministic formula is that a low CPI does not necessarily extend duration. Moreover, extended duration is proven to not necessarily result in increased cost.

Schedule Variance:

Schedule variance ("SV") is defined as the "*value of the work that is ahead of or behind schedule*". [15, p19] It is the difference between EV and planned value (SV = EV – PV). The Schedule Performance Index (SPI) is the ratio of EV to PV (SPI = EV ÷ PV). An SV value of zero or more, or an SPI of 1.00 or more, is considered favorable. SV and SPI measure *effectiveness* in accomplishing what was planned to be achieved by a given point in time.

EIA-748-D states that "*the schedule variance provides **early insight** into overall schedule performance and should be used in conjunction with milestone status reports [and] **critical path data***." [15, p 19] The *Project Management Institute's* (PMI) EV Practice Standard states: "*Consistent with long-standing EVM practice, the network schedule remains the **primary source** of schedule analysis*." [2, p 97] AACE RP 80R-13 cautions that "*SPI is **broad indicator** of schedule progress against the plan only. SPI requires an assessment of the network critical path …. Additionally, SPI … **always equals 1.0** when the … CA or project **is complete**. It will move in the direction of 1.0, **especially after 80 %** of the work … As a result, this equation is **not recommended beyond that poin***t." [17, p6] These different sources all agree that SV (and SPI) is of limited value in analyzing time variance, especially as the project enters the later stages. The CPM network schedule is considered the *separate* analytical tool used to evaluate time performance. Part 2 rejects these premises; it proposes that SV (and SPI) is always an essential performance metric (along with CV and a newly introduced third metric) in integrated CPM schedule time analysis.

SV is not considered a reliable metric. The CV – a metric of *cost* performance - *is* pronounced by EVM theory to be the reliable metric which is the primary focus of current EVM analysis. CPM schedule analysis is considered separate, distinct and *the* reliable analytical tool. And yet the stated objective of EVM is to ***integrate*** (which is to combine)

---

[10] Gary C. Humphreys, Humphreys Associates, "Project Management Using Earned Value, Fourth Edition", (2018). The EIA-748-D does not define CPI or SPI.

[11] Labor Rate Variance = Actual Hours x (Earned Rate – Actual Rate). Efficiency Variance Calculation = Earned Rate x (Earned Hours – Actual Hours).

[12] All emphasis is added unless otherwise stated.

cost and *time* control, so in what sense is the current EVM method truly integrated if EVM defers to CPM analysis in the case of time analysis? Part 2 provides an analytical method that fully integrates time and cost.

Current EV theory is based on the premise that CV and SV variances should not be combined in analyzing time and cost variance.[16] The metrics are thought to be independent; not interconnected. Part 2 introduces formulas which demonstrate that, in the case of labor resources performing the work (i.e. Direct cost, Discrete Effort)[17] the metrics *are i*n fact connected and determine activity duration.

1.1.4 Thresholds

Peak performance in EVM is the avoidance of negative (unfavorable) variances in CV and SV.[18] However, EVM theory does not provide clear thresholds to indicate at what point a negative variance, or off-trend, is such as to warrant immediate management action to mitigate. A five percent negative variance is sometimes used as a high risk level indication, but there is no rationale provided for this number, or any other that is used. [16, 2] In Part 2, a threshold is proposed that takes account of the deterministic connection between time and the resource inputs which determine time (in the case of labour activities) as well as fundamental CPM principles.

1.1.5 Cost Forecasting

Reflecting the primacy of the CV metric over SV in EVM theory, there are actually 3 formulas to forecast cost, but none to forecast future SV (i.e., progress) variance.[19] The cost formulas calculate earned at completion (EAC) as follows:

- "*Optimistic*" Formula: EAC = Actual Cost + (BAC – EV);
- "*Pessimistic*" Formula: EAC = BAC ÷ CPI;
- "*Worst Case*" Formula: EAC = BAC ÷ (CPI x SPI)

EVM theory does not propose that one method is more reliable than the others. Each of them are said to have advantages and disadvantages which the analyst should consider. [16, pp 4-6] In Part 2, a new deterministic formula which connects output to the efficiency (CPI) and resource supply inputs, is used to demonstrate that the "Worst Case" formula is without a sound rationale. Moreover, it is emphasized that achieving timely completion must account for forecasted CV and CPI variances as well as resource supply.

1.1.6 Productivity

CPI, where it is calculated using labor hours instead of dollars, is a measure of productivity (or efficiency) without the possible variance caused by changes in hourly labor dollar rates. However, reflecting the cost focus of EVM, standard definitions define CPI as a measure of "***cost** efficiency*".

Moreover, EVM assumes that optimal productivity is linear: if at any time CPI is below 1.00 it is considered unfavorable. Perhaps in support of this assumption, EVM theory frequently invokes an empirical study (by Christensen) which found that CPI is unlikely to change more than 10 percent after 20 percent of earned progress. [3][22] In Part 2, it is pointed out that on construction projects, the planned (labor) productivity in not necessarily

[16] Humphreys [18], p. 474. "*Cost Variance and schedule variance do not mix with each other or cancel each other out. A poor cost variance combined with a good schedule variance does not mean that everything is all right*."
[17] Defined in EIA-748-D, p. 8. [15].
[18] Values below plan are "unfavorable". As discussed above, though strictly true for the CV and CPI metrics, SV and SPI variances are considered less reliable. In fact, there is caution that expending resources to recover SP/SPI carries the risk of increasing the cost over-run. These positions reflects the cost-bias in existing theory as well as a flawed understanding about the connection between time and cost in the case of labour-based (performing) activities.
[19] There are formulas to calculate time delay. For example, the *Independent Estimate at Completion Date* (IECD) formula divides the remaining budget (BAC – Earned) by the average earned value per (monthly) period.
[22] AACE RP 80R-13 [16, p 22] references this paper.

linear: in fact, it may conform to a curve which varies over time. According to this characteristic pattern, there is low productivity over the early stages, which gradually builds to a positive peak, and then declines over the latter stages.[23]

The *To Complete Performance Index* (TCPI) is a calculation of the future cost performance required to complete on budget. [16, p 7] It provides a going-forward productivity performance target intended to recover the original labor cost budget. The budget dollars (or in this case hours) for the remaining work are divided by the budget available to complete the work based on the hours expended to date.

1.1.7 Earned Schedule Time Forecasting

According to the AACE RP 80R-13 [16, p 15], "*ES is a method of using readily available duration-based elements of earned value to calculate schedule performance and variances and to predict schedule duration*." It uses the ratio of the time at which the planned value was earned ("ES") over the current time ("AT") in the formula SPI(t) = ES ÷ AT. Estimated duration is calculated by dividing the original planned duration by the SPI(t) as follows: ED = Planned Duration ÷ SPI(t).

1.2 Traditional EV Model – A Worked Example

1.2.1 Contract Delivery Method

For this worked example, assume that the Owner's project manager ("PM") is required to analyze performance on a stipulated sum (Design-Bid Build) contract between the owner and the general contractor. On Design-Bid-Build contracts, actual dollar cost is not typically available. That is because, according to the base risk assumption, cost is a "contractor" risk. That being the case, it is sometimes argued by contractors, and even consultants, that EVM is not suitable for D-B-B, or alternatively, that only the SV and SPI metrics can be beneficially used. In fact, as this example shows, performance analysis based on labor hours (without cost) is not only beneficial, but essential to reliable schedule analysis. Dollar cost of labor hours is not essential to evaluate labor performance[24], but hours are always required.

1.2.2 Importance of Schedule Specification

If the schedule specification does not clearly specify the requirement for a fully resource loaded (including hours) schedule, and other terms required for EVM analysis, it is highly unlikely that the contractor will provide the same and EVM will be severely limited as a consequence. In this case, the contractor complied with a detailed schedule specification requiring the contractor to produce fully resource-loaded CPM schedules, a narrative and other required reporting, regularly updated with earned progress and actual labor (and equipment) hours. Accurate earned value and actual hours are available for the analysis.

Figure 2 provides the EVM formulas and calculations that were performed by the PM. By this point, half of the original contract time has expired. Using labor, instead of dollar hours, might be considered atypical for EVM, which is focused on dollar cost variance. However, the PM has always, and properly, placed importance on labor hours in evaluating performance. The axiom "*control the hours and control the project*" [25] [4] holds true in his estimation. As a simplifying assumption, the analysis is focused on the performance of one major subcontractor whose work is critical at the time of the update.

[23] See Section 2.2.2 which describes the standard performance model in construction.
[24] This is not to say that hourly dollar cost is unimportant. In terms
[25] Total Cost Management Framework, p. 147. [4]

Formula:	Worked Example:
Earned Value (EVM) = %age Complete ×Budget at Completion (BAC)	*EVM = 40% ×1,000 hrs. = 400 hrs.*
Cost Variance and Cost Performance Index and Forecasting Formulas:	
Cost Variance (CV) = Earned Value - Actual Value	$CV = 400\ hrs. - 600\ hrs.$ = -200 hrs.
Cost Performance Index (CPI) = (Earned Value) ÷ (Actual Value)	*Cost Performance Index (CPI) = (400 hrs.) ÷ (600 hrs.) = 0.67*
To Complete Performance Index (EAC) = (BAC-EVM) ÷ (BAC-AC)	*TCPI(EAC) = (1,000 - 400) ÷ (1,000 - 600) = 1.52*
Earned At Completion (EAC) - "Optimistic" = Actual Cost + (BAC-EVM)	*EAC = 600 hrs.+ (1,000 hrs.-400 hrs.) = 1,200 hrs.*
EAC = BAC ÷ (CPI(E)) – "Pessimistic"	*EAC = (1,000 hrs.) ÷ (0.67) = 1,493 hrs.*
EAC = BAC ÷ (CPI × SPI) – "Worst Case"	*EAC = (1,000 hrs.) ÷ (0.67 × 0.80) = 1,875*
Schedule Variance and Schedule Performance Index and Forecasting Formulas:	
Schedule Variance (SV) = Earned Value - Planned Value	*Schedule Variance (SV) = 400 hrs. - 500 hrs.= -100 hrs.*
Schedule Performance Index (SPI) = (Earned Value) ÷ (Planned Value)	*Schedule Performance Index (SPI) = (400 hrs.) ÷ (500 hrs.) = 0.80*
Schedule Variance (Months) = SVCUM ÷ EVM Monthly Average	$SV\ (Months)$ = (−100 $hrs.$) ÷ (80 $E.hrs./m$) = -1.25
Time Now Variance (TNV) = Earned PMB Time – Time Now	*Time Now Variance (TNV)= 4.3 months - 5.0 months = - 0.7 months*
Independent Estimate at Completion Date (IECD) = Time Now (months) + (BAC - Earned(cum)) ÷ (Earned (avg))	*IECD = 5 (months) + (1,000 -400) ÷ (400 ÷5) = 5 + (600 ÷ 80) = 12.5 (months)*
Earned Schedule Formulas:	
SCHEDULE VARIANCE (time) = EARNED SCHEDULE - ACTUAL TIME	*SCHEDULE VARIANCE (time) = 3.5 mnths. - 5.0 mnths. = -1.5 mnths.*
SPI(t) = EARNED SCHEDULE ÷ ACTUAL TIME	*SPI(t) = (3.5) ÷ (5.0) = 0.70*
ESTIMATED DURATION (ED) = PLANNED DURATION ÷ (SPI(t))	*ESTIMATED DURATION (ED)= (10 months) ÷ (0.70) = 14.3 months*

Figure 2 - Worked EVM Example: Formulas and Calculations

On the basis of the EVM and schedule data, the PM is tasked with creating a brief report and dashboard for senior management which assesses schedule, budget and claims risks along with recommended action to mitigate the same. The report includes a performance "*dashboard*" (not shown here) featuring an array of "*trend*", "*alert*", and "*traffic light*" icons and gauges to indicate *key performance indicators*[27] (KPI's). One of the exhibits in the Dashboard is the traditional EVM graph, which the PM has created for this project (Figure 3) using the data in Figure 2. It shows cumulative progress and actual data to-date as well as time and cost forecasting, and is the subject of the following analysis performed by the PM.

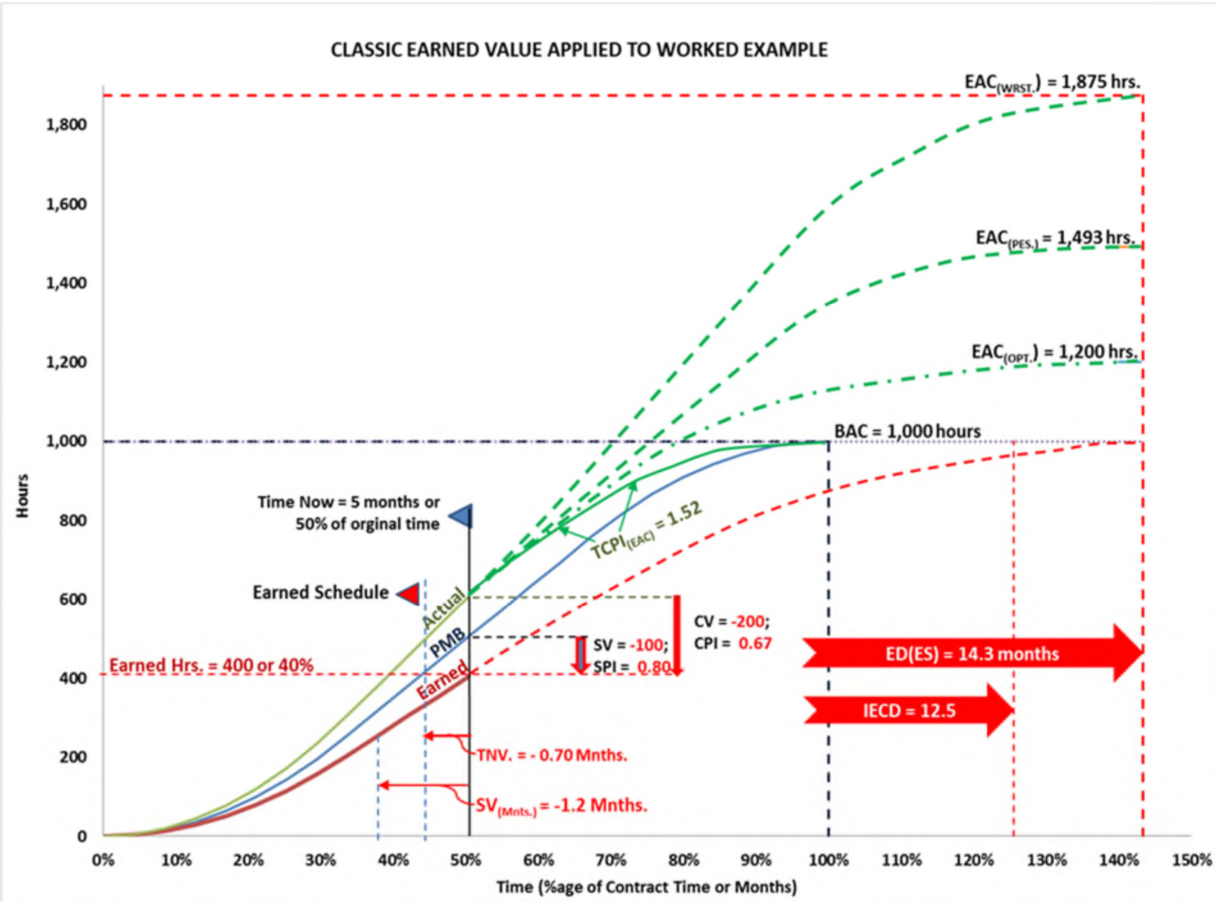


Figure 3 - Worked Example: Traditional EVM Model

<u>1.2.3 Analysis of Cost Variance and Cost Performance Index</u>

Recognizing that the CV and CPI metrics are considered the primary and most reliable performance variance metrics in EVM analysis, the PM first assesses the cost and productivity metrics. There is a negative CV (CV = -200 hours). As of this update, the subcontractor, who is performing the work, has expended 600 hours (60% of it budgeted hours), but only earned (or accomplished) 400 hours (40% of its budgeted hours). The CPI is 0.67, which is seriously unfavorable, and also stable, not having changed since the first update. The SPI indicates that for every expended labor hour, only 67 percent of an hour (or 40 minutes) is earned. CPI is a measure of efficiency; in this case, labor productivity.

If these hours are extended by an average paid hourly rate of, say, $60.00 per hour[28], the SV in dollars would be $12,000. The total labor budget is $60,000. A contractor (or subcontractor), assuming it is tracking such variances,

[27] A Key Performance Indicator is a quantifiable measure used to evaluate the success of an organization, employee, etc. in meeting objectives for performance.
[28] As noted above, as a simplifying assumption, dollar-rate variances are not considered. Performance analysis is focus. On D-B-B projects, dollar rate escalation would only be compensable according to the terms of the Contract.

which one would expect of a competitive contractor, would evaluate how much of a concern an overrun of this dollar magnitude is at this advanced point in time. It might be that the original estimate was understated through its own fault; say because it missed a scope of work or its estimated level of productivity was too low given operational constraints, or both. If so, a revised estimate (or re-baseline of the hours) should be established because measurement of EVM variances against an incorrect or unfeasible estimate results in faulty EVM analysis.

Another explanation for the overrun might be issues (changed scope of work, delayed access, etc.) that have arisen on-site over which the contractor does not have control, and for which the contractor does not have responsibility under the contract. In this case, a competent contractor would, on a well-run project, inform the owner of the problem, advise of the cause and cost implications, and recommend means and measures to mitigate. On the other hand, on many stipulated sum contracts, such information is not revealed to the owner until late in the project, by which time delay and cost over-run are a certainty, and the question becomes, instead of prevention or mitigation, who will pay for it?

These CV and CPI (productivity) deficits to-date should, the PM reasons, be a matter of serious concern to the subcontractor, if not the general contractor. Given the negative CV, the PM wonders if the subcontractor might be reluctant in the future to increase its work force, even if necessary to advance time, for fear of further cost over-runs. Some owners might consider the contractor's labor hour losses a "*contractor problem*" believing, perhaps correctly from a contractual point of view, that the contractor is at risk for this additional cost. In this case, the PM (and management) understands that such a position confuses the objective analysis of project performance with contractual risk allocation, possibly at the peril of all parties to the contract, including the owner. Even on a D-B-B contract, and under circumstances where the owner is not at risk for the contractor's labor overrun, a labor performance problem, in terms of both productivity and availability, needs to be made transparent, and subject to analysis, because the possibly consequent cost and efficiency problems may imperil the time and other objectives of the project.

The PM is mindful of EVM literature warning that low labor productivity would very likely result in longer duration and delay. And yet, according to EVM theory, CV is not connected to the (time) schedule. This means that any concern over the CV is based only on the risk to the cost objective; not on any risk to the PMB or time, even though adherence to the PMB is the primary objective of EVM. Moreover, the PM believes that labor resource levels matter significantly in determining how much work is accomplished, but there is no EVM metric to measure variance in resource supply. In fact, EVM theory warns that adding resources will add cost.[29]

1.2.4 CV and CPI Forecasting

EVM forecasting is primarily concerned with CV, as opposed to time, forecasting, and reflecting this emphasis, the PM has three alternative calculations available to estimate final labor cost. In Figure 3, each of the cost forecast curves (hatched, green lines) have been drawn to show the expected deceleration characteristic of the latter third of time.[30] All of the curves are extended to the completion date forecasted by the ES formula.[31] Figure 4 provides the total budget-hour over-runs predicted by the different formulas. All of them predict an overrun: the "*optimistic*" formula indicates a 20 percent over-run; the "*pessimistic*", 49 percent, and; the "*worst case*", 88 percent.

Escalation considerations aside, it is optimal to have a dollar value variance, in addition to labor hours, to enable a complete analysis of performance.

[29] See Section 1.1.3.

[30] As mentioned above, this S-curve characteristic is not reflected in EIA-748-D.

[31] See Section 1.1.7.

Method:	Projected EAC (hours):	Projected Over-run vs. budget (hours)	Percentage (over-run) Variance vs. Budget:	Final Forecasted CPI:	CPI for Remaining Work:	CPI at 20% Earned Progress	CPI Forecast Variance (Forecast vs. Actual @ 20%):	Amount Forecast Varies from 10% stability:
	'A'			'B'	'C'	'D'	'E'	
				= 1,000 ÷ 'A'			= 'C' - 'D'	=10% - 'E'
"Optimistic" IEAC Forecast	1,200	200	20%	0.83	1.00	0.67	0.33	-23%
"Pessimistic" IEAC Forecast	1,493	493	49%	0.67	0.67	0.67	0.00	0%
"Worst Case" IEAC Forecast	1,875	875	88%	0.53	0.53	0.67	-0.14	24%

Figure 4 - IEAC Hours Forecasts

Given the forecasted delay and the forecasted overrun in hours, the PM wonders: if actual labor hours were increased as per the "*worst case*" forecast, for example, would there be an improvement in time performance? EVM theory says this is unlikely.[32]

As mentioned above, EVM does not provide guidance as to which of the labor hour calculations is most reliable or appropriate in a given circumstance, so the practitioner is left to pick one. Absent such guidance, the PM relies on the qualitative connotation of the formula descriptions. There is no basis for "*optimism*", he reasons, because things have not noticeably changed on the project, so why would future cost performance improve? If the "*worst case*" calculation is correct, the contractor will suffer enormous losses (almost a ninety percent overrun), and there is risk that it will pull back its labor force, instead of responding to the needs of the project. Constrained by the limits of EVM theory, the PM reports these concerns to management without being able to offer much insight into mitigation or the level of risk to the time and budget objectives.

The PM considers the above-mentioned empirical study (by Christensen) [3] which found that CPI is unlikely to change more than 10% after 20% of earned progress. According to the Christensen study, the "*cumulative CPI is stable from the 20 percent completion point on most contracts* … [and] "*knowing that the cumulative CPI is stable is important. The government can now conclude with some confidence that a contractor is in serious trouble when it overruns the budget beyond the 20 percent completion point. Beach, the inquiry officer who investigated the cancellation of the A-12, was justifiably critical of the optimistic estimates of both the contractor and the government*." [3]

Mindful of this study, the PM has added columns in Figure 4 to show how the forecasted total hours based on the EVM formulas compared to the CPI stability the Christensen study anticipates. Since CPI has remained steady at 0.67, the "*pessimistic*" estimate, which assumes that past performance continues into the future, is certainly supported by the study. The "*optimistic*" forecast assumes remaining productivity reaches the original plan (i.e., CPI = 1.00), which would require a thirty-three percent improvement in productivity, which is twenty-three percent more than the study considers likely. Finally, the "*worst case*" forecast seems unlikely in the opposite direction, with the contractor performing twenty-four percent worse than the expected range of the study.

Still, the PM is concerned about what he sees as the possibly adverse (time) performance implications of on-going productivity deficits. The goal of EVM analysis is to identify performance off-trends indicated by the metrics, and then take expeditious action to mitigate the same, but EVM theory provides little in the way of causal understanding about how the CV (and SV metrics) might affect the PMB and targeted time completion. Similarly, the EVM thresholds applied to the forecasting of CV do not have a clear deterministic basis.

In this case, the PM accepts the evidence from the EVM cost forecasts that full recovery of the budgeted labor hour overrun is almost certainly not possible, and opines that the CPI is unlikely to change by more than 10 percent, especially given its stability to date. The PM reasons that since the CPI has been stable from the beginning of the project, it might be that the originally budgeted hours were underestimated. On the other hand, over the same

[32] See Section 1.1.3.

period of time, the PM recalls that the contractor had been notifying the owner of various delays alleged to be adversely impacting productivity and delaying the work. What contributed to lower productivity is usually determined on the basis of a "*balance of probabilities*".

1.2.5 Analysis of Schedule Variance and Schedule Performance Index

Having completed the cost analysis, the PM now turns to the SV and SPI performance analysis section of the report. CV and SV analysis are separated consistent with EVM recommendations. As shown in Figure 3, the SV, which is a measure of (progress) variance from the PMB, is negative 100 hours. As of this date, the PMB required that 500 labor hours would have been earned, but only 400 labor hours have been earned. The SPI of 0.80 indicates that 20% less work been accomplished than planned.

The SV, translated to months, indicates that progress is behind, in terms of time, by 1.25 months (see above time axis in Figure 3), although there is no EVM threshold or other guidance to indicate how much of a risk to timely completion this deficit indicates. Similarly, the *time-now variance* is negative 0.70 months, but EVM does not propose time thresholds for this which would indicate a level of urgency.

The PM is aware that according to probabilistic (Monte Carlo) schedule analysis, the consumption of float, which is happening in this case (as can be seen by looking at activity time variances in the CPM schedule), has the effect of lowering the probability of timely completion because of float path convergence.[34] [5] Based on this effect, the PM reasons that negative SV, which is measured on the Y-axis, would indicate some amount of negative time variance (on the Y-axis), which is time float consumption, but EVM theory defers to CPM scheduling on such questions.

Logical consistency would seem to dictate that this negative SV should be a cause of significant concern because the achievement of the PMB is the stated objective of EVM. [17, p 1] Performance measurement against the (PMB) plan is the stated primary objective of earned value management. If SV never varied from the PMB, the project would finish on time, but in EVM, the metric which measures variance versus the PMB, which is the SV, is treated as unreliable with respect to any time implications, and secondary in importance to the cost (CV) metric.

1.2.6 Time Forecasting

EVM theory advises that for time forecasting, CPM analysis, not SV, is the proper analytical tool. SV is said to possibly offer some "*insights*" which are not clearly articulated.[36] The PM fully understands that the SV is a direct measure of progress variance; not of time. However, he reflects that when an activity is delayed in progress, it is not accomplishing the same amount of work as it was originally planned to do in the baseline duration. Therefore, this premise that SV has no connection to time, seems unlikely to him based on practical experience.

Neither SV nor SPI are used in the forecasting formulas for estimating the final duration of the project. To estimate delay, the PM uses the EVM "*Independent Estimate at Completion Duration*" (IECD) formula. It is based on a calculation for the remaining duration which uses an average of earned progress to date and, so calculated, forecasts a total duration of 12.5 months (see red-colored arrow in Figure 3).

1.2.7 Earned Schedule

The PM also uses the Earned Schedule (ES) formulas to forecast duration. The total project duration calculated by the ES Extended Duration (ED) formula is 14.3 months, which is almost 2 months (or ~20%) longer than the (12.5 month) forecast (above) using the IECD formula which is based on an average of actually earned progress continuing to completion. The longer duration, ED formula, has been used for the actual cost forecasts, but there is no EVM guidance on which of these formulas is more reliable or preferable.

---

[34] Merge Bias occurs whenever two or more paths converge in a network and the uncertainty about their durations is such that any of them might turn out to be critical. [5]

[36] See, for example, [15, p 19], and [2, p 58]

Traditional EVM analysis recommends deference to the time forecast generated by a bottom-up CPM schedule forecast. On the other hand, ES advocates are not at all circumspect in this regard; they confidently proclaim the superiority of ES to EVM in time forecasting, and argue it can be used for "*detailed schedule analysis*".[38] Notwithstanding the negative EVM metrics, the contractor's latest CPM schedule update, and all of those that preceded it, forecasts timely completion. The updates have not been reviewed for feasibility of the forecasts because the Owner believed this was a contractor risk. In his management report, the PM duly reports that although the EVM schedule metrics are unfavorable, and suggest delay, EVM best practice dictates deference to the CPM schedule update which shows on-time completion. CPM and EVM are not integrated; they are segregated.

1.2.8 Combining CV and SV

Although, according to EVM theory, CV and SV are not thought to be interconnected, the PM has seen EVM analysis which shows them side-by-side in the same graph, as shown in Figure 5. In the graph, CV and SV to-date is plotted against the percentage of planned time. EVM theory posits that, during the early stages, on typical projects, project resources are usually not provided as planned[39] [18, p 476], and this results in positive cost variance[40] and negative schedule variance. According to current theory, both SV and CV are expected to trend negatively in later stages.

[38] ES website: www.earnedschedule.com.
[39] This is partially supported by the "*Allen*" input curve discussed below. The Allen Curve is a cumulative empirical curve showing actual resource allocation over time.
[40] This assumes that productivity necessarily drops with increased resources. As discussed in Part 3, this is not necessarily the case.

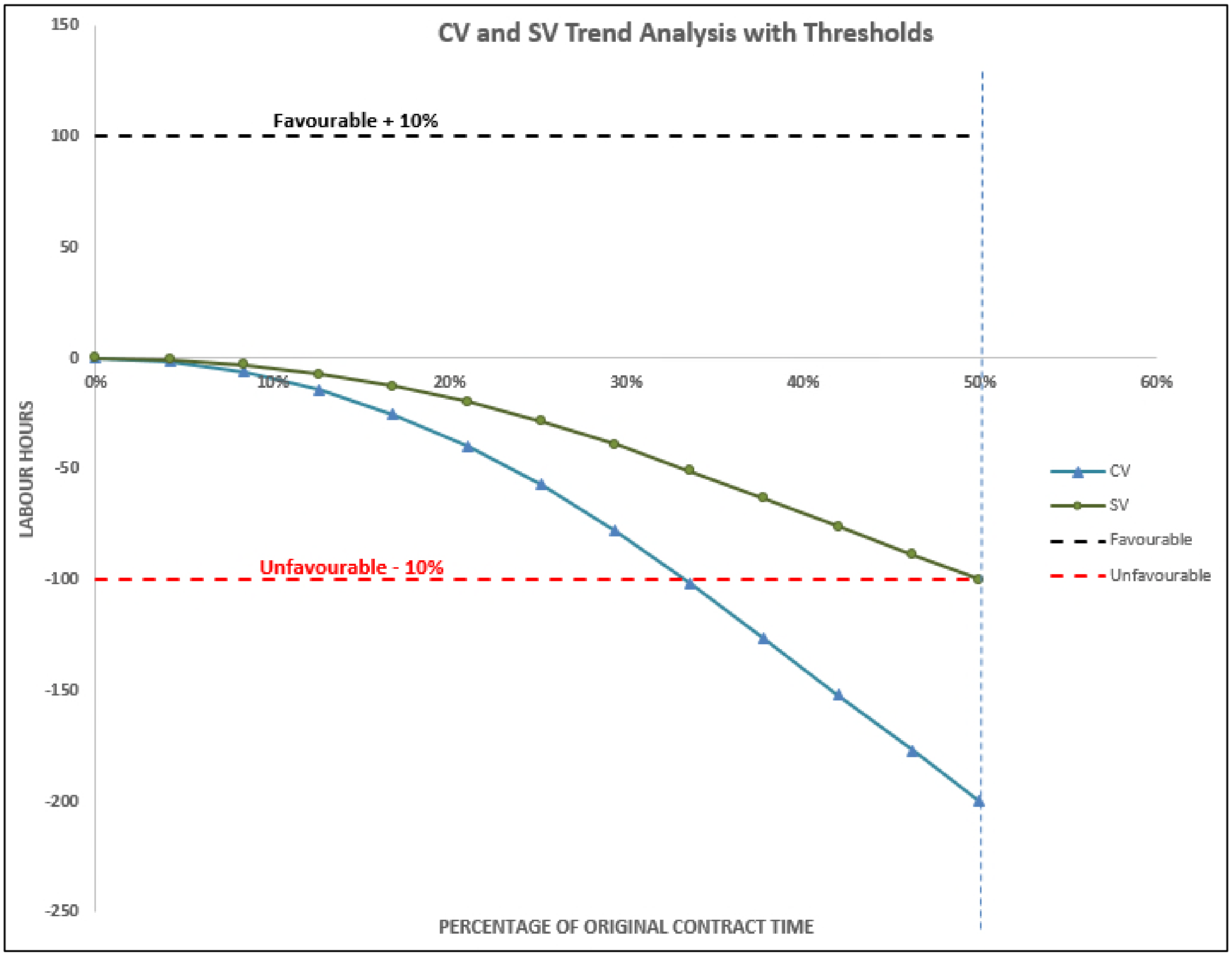


Figure 5 - CV and SV Trend Analysis

Based on the above-described typical CV and SV patterns, the behavior of both CV and SV on this project is atypical. The CV begins to trend negatively from the very beginning, and both CV and SV are worsening at an increasing rate. By fifty percent of the time, SV has reached the 10 percent threshold. The negative SV is therefore a matter of concern, but how much of a concern, and the rationale for the threshold is unknown. The ten percent threshold really only a heuristic, or rule of thumb, and as such, would have broad application that is not intended to be strictly accurate or reliable for every situation. But since, per EVM theory, SV is not reliable as to time anyway, there appears to be little or no actionable intelligence to be gleaned from this indicator.

Still, the question remains, why is negative cost variance more severe and growing compared to the negative SV. The PM wonders if the actual labor hours (the actual cost curve is the solid green line in Figure 3), which have been supplied at higher levels than planned, explain the relatively better SV performance compared to the CV. As mentioned above, there is no formula connecting these factors because, according to EVM, there is no analytical connection between the metrics.

1.2.9 Project Manager's Performance Post-Mortem

Much to the PM's disappointment, this project was ultimately an unmitigated failure in terms of performance. It finished many months after the contract completion date, and the contemporaneous schedules were of no use in correctly forecasting, or analyzing, the delay to completion, or even near-term performance. Shortly before the originally planned substantial performance date, the contractor (and several of its subcontractors) claimed for delay and disruption costs.

Relations between the contractor and the owner (and its consultant) were already acrimonious, and as litigation seemed ever-more likely, each side retreated to its advocacy corner. Since construction projects require collaboration in order to perform well, this hostile climate exacerbated existing performance problems.

Attempts at resolution using the contractually specified dispute resolution process failed – a major problem was the absence of mutual agreement on basic facts around cost and schedule performance, and reliable knowledge about the underlying root causes and effects that may have contributed to the delay and disruption.

1.3 The Failed Promise of Earned Value & CPM Project Analysis

It should be emphasized that in the above case, the PM had *more* performance data available for analysis than is typically the case. Fully resource-loaded CPM schedules were required and provided, and planned, earned, and actual hours were also provided. Despite this fact, EV analytics failed to offer timely, actionable intelligence which might have been used to improve performance. The PM was essentially an ineffectual observer, watching the project fail, without control over how events unfolded and why. There was no transparency about why the project was falling behind, and without transparency, there cannot be accountability for past, present and future performance.

1.3.1 Failure to Integrate with CPM, Primacy of $CV, and Separate Silos for CV and SV

The above example reveals major problems with EVM analysis. A major problem is the failure to consider how EVM metrics might be combined with CPM schedule analysis in order to provide a fully integrated time and cost performance analysis for the project. This is a stated objective of EVM that has not been realized, but current theory is content to accept, and even recommend, a separation. A new way to fully integrate CPM and EVM analytics is presented in Part 2.

Another problem is the primacy given to Cost Variance even though accomplishing the (time target of the) PMB is the alleged objective. Schedule Variance *does* measure variance from the PMB, but EV theory refers to SV as a secondary, less reliable, metric of limited value in time performance analysis. The deterministic formulas in Part 2 reveal that SV, along with CV, is always an essential metric in time analysis.

Moreover, CV and SV are thought to have no interconnection; that is, one has no effect on the other. As the worked example revealed, current CV and SV analysis says very little about past performance and even less about the schedule time forecast. In fact, these metrics are connected as demonstrated in Part 2.

1.3.2 Arbitrary Thresholds and Forecasts

Even with respect to CV, which is the primary EV metric, there is very little guidance as to when and how much of a negative variance should be a serious concern. EV thresholds are arbitrary: Why 10 percent? Why not 5 or 20 percent? At least with CV, EVM adopts a firm and consistent position that negative CV is unfavorable. EV seems not to know what to make of a negative SV. SV is a measure of variance from the PMB, which is the stated EV objective, but EV does not analyze the relevance of a negative SV to PMB performance. Schedule variance is nebulously described as being "*just an indicator*" of whether the schedule for the job is ahead or behind.

With respect to predicting future cost performance, the EV formulas don't have a clear rationale to support the use of one or the other. This leaves the analyst to select one on the basis of optimism, pessimism, or severe pessimism.

1.3.3 EVM Theory is Statistical & Probabilistic[41]

EVM interprets CPI (and SPI) in a *statistical*, rather than a deterministic, way. For example, forecasting analysis offers a range of outcomes - "*optimistic*", "*pessimistic*" and "*worst case*" - instead of first using project-specific data integrated with the CPM schedule. A key performance question is: what level and rate of supply of labor resources,

[41] For the purpose of this paper, probability means using known data to predict the likelihood of future events. Statistics uses data from a sample to draw inferences about a larger population.

based on the currently estimated productivity, is required to meet the time target? Yet these forecasting formulas are divorced from this central question. Likewise, the thresholds – such as the ten percent thresholds for CV and SV – are heuristics, based on experience on other projects. And when the Christensen study is applied to a particular project, this is statistical by definition - findings from a large sampling of other projects are compared to measurement on a particular project. The forecasts do not take account of the dynamic nature of a construction project over time, as in, how contemporaneous or future decision-making, based on project-specific data, might alter the forecasts.

A potential problem with a statistical perspective being prioritized at the expense of deterministic methods, is reflected in this comment from a statistician: "*… the problem [with statistical analysis] is our obsession with setting a* ***threshold*** *… the problem comes when you try to learn something about us* ***as individuals*** *from how we behave as a* ***collective****, i.e., making individual predictions from our collective characteristics*." [6, p 77]

Although statistical analysis certainly has its place in performance analysis, projects, like people, are not always well represented by statistical approaches. Each project is in many respects unique, and often to a very significant degree. Should the risk of an unfavorable CPI of 0.80 be analyzed without regard to the project-specific performance assumptions on a particular construction project? Is the ten percent threshold for CPI and SPI always an appropriate alarm level on every project? Should it be assumed that the SPI and CPI are not connected in unique ways that may determine future performance? Such *deterministic* questions are not much considered in EVM. The EVM statistical emphasis is at the expense of project-specific deterministic analysis, and that is no small matter if one is interested in a system truly dedicated to improved project performance. In fact, the reliance on a statistical, as opposed to a project-specific, deterministic, and causal analytical approach, is a major problem with EVM that requires the corrective offered in Part 2.

1.3.4 Earned Schedule: Deficient Forecasting and Mistaken Criticisms of SV

ES is touted by advocates as both the solution to the alleged deficiencies of SV and the fulfillment of the EVM promise to provide a fully integrated time and cost analytical and management method. It has gained sufficient credibility that it is referenced in EVM theory. [16, p 15] ES proponents refer to the fact that SV returns to a zero value, even on projects that finish late, as a "*quirk*" of SV that requires a solution. ES theory confidently proclaims that ES resolves the "*long-standing dilemma*" of the EVM schedule indicators providing "*false*" information for late performing projects. ES is seen by adherents as a breakthrough analytical technique that resolves these alleged problems. ES theory asserts that the performance of the time-based indicators from ES are superior to the schedule indicators from EVM. [45]

However, a major problem with ES is that it ignores fundamental CPM principles related to criticality and total float. The ED formula assumes that all of the "time now" variance is critical delay (that is, causing delay to the project finish), but on a project with any amount of total float, this is not correct. What is missing from the ED calculation is any accounting for float. Such time float is the difference between the "early curve" and the "late curve", both of which are generated by a resource-loaded CPM schedule. The Late curve is a deterministic time and progress *threshold*, after which critical delay is likely, if not certain. Once project progress reaches the Late curve, float is exhausted. ES's failure to account for the late curve is also a notable flaw in the traditional EVM analysis model. A further problem with ES is that it does not consider typical performance patterns on well performed construction projects. There is an urgent need for performance analysis combining EVM metrics with the CPM schedule, but ES is not it. Its criticisms of the EV SV are misinformed and simply add to confusion about this metric.[46] What is absent

---

[45] ES website: www.earnedschedule.com.

[46] ES criticism of SV is based on a misunderstanding of the definition and purpose of SV. It is not a "*quirk*" of SV that it returns to zero; this necessarily follows from its definition. And it is not a "*flaw*" that SV equals zero on a project which completes late. This simply reflects ES's literal interpretation of the term "*favorable*". Obviously, in the unique, and only case, where the project is completed, as opposed to being in progress, a zero SV value is not an indicator of favorability or unfavourability: it indicates completion of the required scope. SV does not currently reference the time at which it is measured, but it should, such that, for example, SV(50%) would indicate SV measurement at 50% of time.

in current EVM theory and practice (including ES) is a focus on project-specific performance factors, and how they dynamically interact and influence future cost and time outcomes.

1.3.5 Deficient CPM Schedules Create Performance Fog

Absence of Meaningful, Resource-Loaded, CPM Schedules:

Feasible and reliable CPM schedules are the foundation of an integrated scope, time and cost performance analysis system. In 2003, four leading schedule experts were interviewed in the Engineering News-Record (ENR) to discuss the state of critical path method (CPM) schedules. [7] A major concern they shared at the time was the sub-standard quality of CPM schedules. They observed that what was presented as a CPM schedule frequently "*wasn't one at all*", and criticized the "*widespread abuses of powerful software to produce badly flawed or deliberately deceptive schedules that look good but lack mathematical coherence or common sense*". The experts concluded that as a result of the prevailing poor practice, there was "*confusion, delayed projects and lawsuits*", and that instead of being an important planning and control instrument, schedules were being used as "*tools for claims*". Two decades later, there is no sign of improvement in schedules or project performance.[48]

There is scant evidence that EVM analysts, contractors, or the industry at large, appreciate how important an effective schedule regime is, not only as the basis for useful performance analysis, but also to the success of construction projects. An essential corrective to the current problems with EVM is a performance-based approach using schedule as the centerpiece, to plan, monitor and control the work. However, this well-known, highly reliable and effective project management best practice has been observed more in the breach than the observance. Instead of the non-project-specific ("statistical") approach predominating EVM practice, what is required is a system of analytics not only connected to, but actually an integral part of, a reliable CPM schedule, created for the project.

Assuming a fully defined scope of work is provided, a fully resource loaded schedule, properly prepared, is a highly reliable and precise predictor of time performance. The AACE RP *Cost Estimate Classification for Building Construction* suggests that for a Class 1 Cost Estimate, expected accuracy range in the low range is between -3% and -5%, and the high range is between +3% and +10%. [9] A Class 1 Schedule [10], which is a bottom-up, detailed plan accounting for resources and project-specific requirements based on a Class 1 cost estimate, would be expected to have a similar range of accuracy.[51] A Class 1 Cost and Schedule Estimate is considered by Contractors on D-B-B projects to a reliable-enough forecasting tool to commit to a stipulate price and time.

Scheduling is Output-Based:

In the context of productivity, "*output*" is what is produced, and "*input*" is the labor hours required to produce the output. It was noted above that EVM theory, though it has a productivity metric (the CPI), does not analytically connect the productivity input to the PMB (which is output). Similarly, CPM schedule analysis focusses on activity time variances (i.e., changes versus plan to the start, finish, or duration), which are time *outputs*. Even where schedules are resource loaded, there is not an established analytical approach to evaluate how the productivity and resource inputs may influence time. It will be shown in Part 2 that they are direct root causes which determine time performance.

The activity duration formula below is output-based and frequently used to analyze time performance. It divides the quantity of the operation by a "*daily production rate*", or *output* per day.

$$\boldsymbol{Activity\ Duration\ (w.d.) = \frac{Quantity\ (s.f.)}{Daily\ Production\ Rate\ \left(\frac{s.f.}{w.d.}\right)}}$$

[48] For a detailed discussion of best practices in CPM scheduling, see paper AACE PS.2324 [8].
[51] The cost estimate relies on the schedule for the duration used to estimate site indirect costs, which are time-based costs.

Using this output formula, a worked example for a formwork labor activity is provided below. The 10-working-day (w.d.) activity duration is calculated by dividing an assumed daily output of 1,000 square feet per working day into a total quantity for the entire formwork activity of 10,000 square feet. This formula is certainly useful in analyzing baseline feasibility, and tracking performance. If fewer units are being produced per day than planned, delay is likely and action needs to be taken. However, its limitation is that it does not provide causal insight into *why* there is less output than planned.

$$\boldsymbol{Activity\ Duration = \frac{Quantity}{Output\ per\ day} = \frac{10,000}{1,000} = 10\ w.d.}$$

Even *scheduling* software, which is designed for resource loading, is output-based. The underlying productivity assumptions, if they have been considered at all, are buried in the daily resource units.[52]

1.3.6 Output Analysis is not Root Causal – Worked Example of Footing Activity Delay

By and large, CPM delay analysis is not input based, and therefore does not identify root, direct, deterministic causes in its analysis. By definition, causation is the *act or agency* which ***produces the effect***. Therefore, if delay analysis does not consider the productivity and resource inputs that determine the "*effect*", it is not *root causal*. At an activity level, time variances are, for the most part, analyzed in terms of what are really conditions, or "*proximate*" causes, which are alleged to explain them. For example, the delay causes listed in the text boxes in Figure 6 are cited in the AACE's Forensic Schedule Analysis recommended practice. [11, p 33] Productivity *is* mentioned, but in a list along with other "*causes*".[53] Is productivity really of the same causal nature as these other delays? An example will be provided below to illustrate the risks in this type of output-based analysis.

[52] For example, in Oracle's P6 scheduling software, the labor hours are entered per day as "*Budget Units per Time*". The number of hours should based on a quantity, and account for the productivity of those hours, but there is no data field for productivity.

[53] AACE 29R-03 Forensic Schedule Analysis: "*Activity Level Variances*" are said to be "*caused*" by "delays" such as "waiting, performance, etc.. Later, at p. 108: "*Another philosophical dichotomy that complicates the evaluation of concurrency is the difference between the **proximate** (immediate) cause of the delay and effect of the delay."* What appears to be excluded from this distinction is what is called here "*direct*" causes, which are the productivity and resource supply inputs.

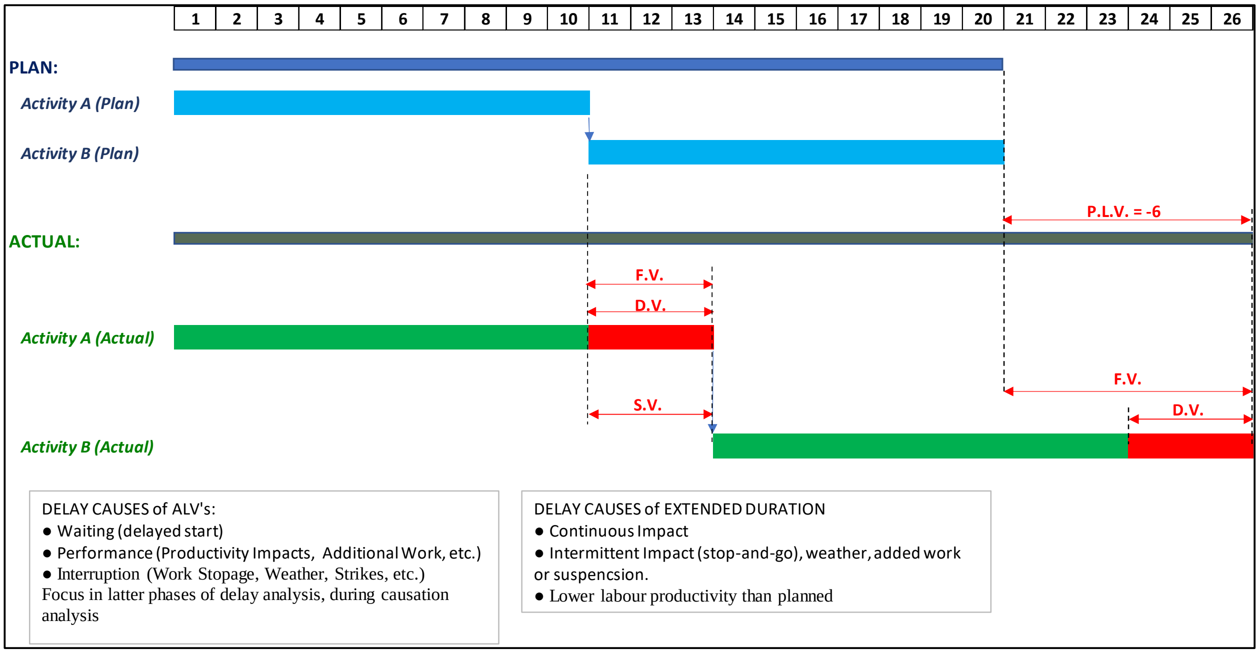


Figure 6 - Current Causal analysis of Activity Level Variances

An output-based delay analysis is shown in Figure 7. A schedule update at the time demonstrates, according to the contractor, that a contract change, which added embedded conduit around which the concrete trades would have to work, caused 3 days of critical delay. The "*cause-effect matrix*", often used by forensic analysts, indicates that the conduit change was a "*primary cause*" of delay, along with delayed access to a footing and a delay in clarifying wall penetration locations. Following from these "*primary*" causes, delayed RFI response and Change Order (CO) preparation resulted in further delay. This created unexpected conditions such as trade stacking, overtime, and the like, which, according to the contractor, have been proven by empirical studies to cause productivity loss. In an effort to mitigate delay, the contractor asserts, it increased crew size, resulting in further productivity losses.

In response, the PM asserts that the delay was caused by contractor performance problems such as missed deliveries, and contractually non-compensable causes such as adverse weather.

After much back-and-forth, no agreement is reached on the time and productivity claims, and the executed CO includes only the direct[54] cost of the work. The contractor reserves its right to claim later for the excluded delay and productivity costs. In Part 2, it will be shown that neither the contractor nor the owner correctly identified the direct, root cause of the delay.

[54] Time-based costs, such as "*site indirect*" costs, are not included.

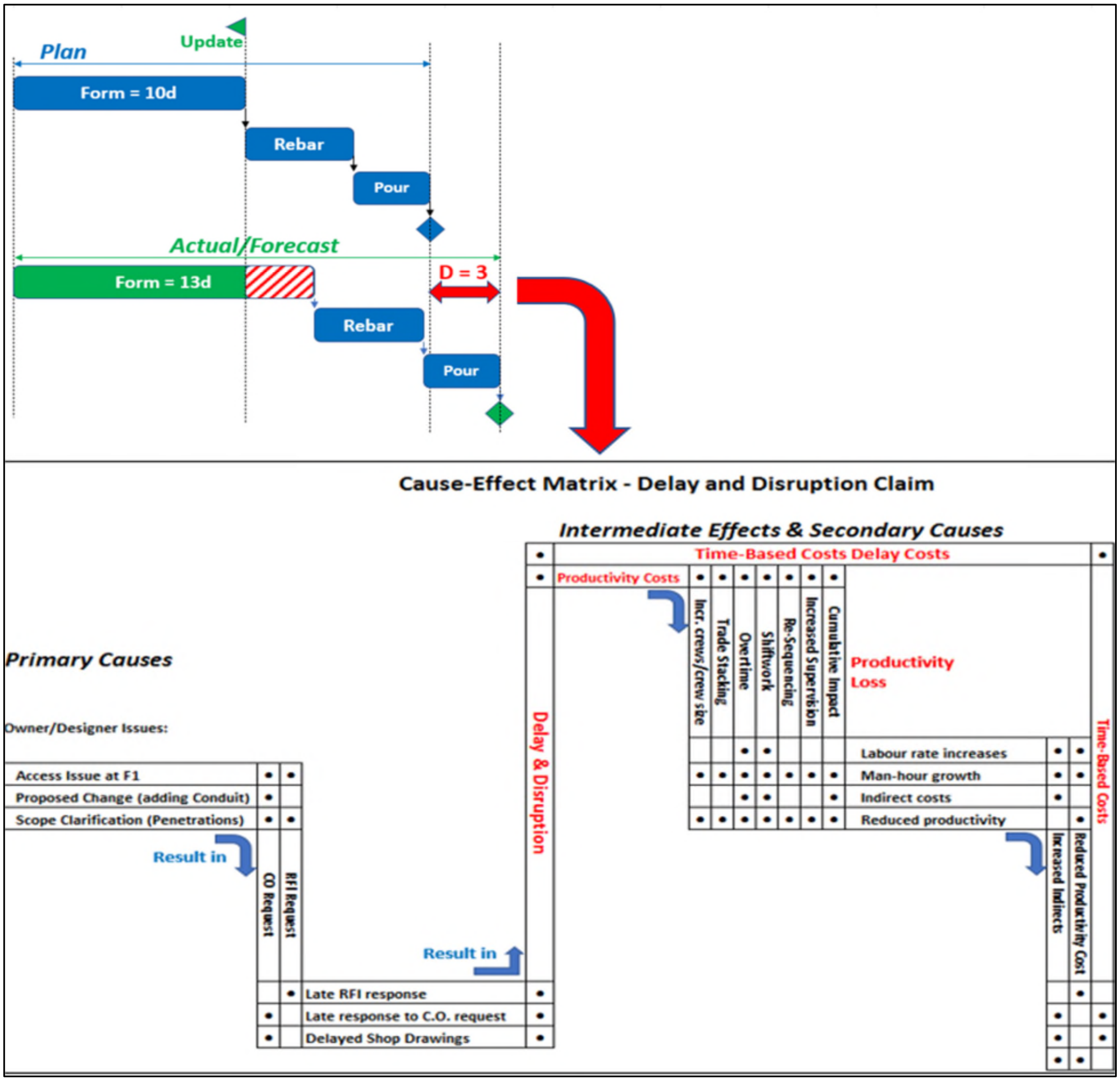


Figure 7 - Is Output-Based Analysis Causally Correct?

1.4 Part 1 Summary: Unanswered Questions

The discussion in Part 1 compels the following questions:

1. In a system dedicated to achieving the PMB, is the current EVM prioritization of CV, as opposed to SV, analytically sound?
2. In a system dedicated to achieving the PMB, why does EVM not offer analytics that are integrated with time performance analysis?
3. Is EVM theory correct in separating CV and SV as separate and independent metrics? Do the CV and SV metrics have a connection to the CPM schedule which would aid in time performance analysis?
4. Is the EVM assumption correct that linear productivity at a favorable level is indicative of optimal performance? Put another way, is it possible that even on well performing projects, negative productivity should be expected at certain stages as an accepted performance pattern?

5. Are the normally cited reasons for negative activity start or duration variances, such as deficient drawings, disruptive contract change orders, equipment delivery delays, and so on, really root causes?
6. Why is EVM and CPM analysis output based? Might there be a deterministic formula to connect duration to the productivity and resource inputs? If so, could this be used in causal, input-based schedule analysis?
7. Why is there not an EVM metric to measure variance in resources, even though there are metrics to measure variance in earned progress (i.e., SV and SPI) and productivity (CV and CPI)?
8. Should EVM analysis take account of typical PMB performance characteristics exhibited over time that would be expected on well-performing construction projects?
9. Is there a deterministic connection between the actual cost curve and the PMB? Is the baseline assumption that the PMB and the actual (planned) curve are identical always correct?
10. Instead of arbitrary statistical thresholds, is there a deterministic basis for performance-based thresholds which could be relied on to evaluate risk.
11. Can past EVM performance inform future time planning and performance in a way that conduces to the creation of more reliable schedules and earlier completion?

Answers to these questions are provided by the new analytics described in Part 2.

Part 2: FULLY INTEGRATED CPM AND EARNED VALUE ANALYTICS: A CAUSAL, DETERMINISTIC CONNECTION

2.1 New Causal Duration Formula: Productivity and Resource Inputs determine Activity Duration

In Part 1 it was observed that the available activity duration formula is output-based. It was proposed that the need for improved performance analysis required a formula to causally connect the resource and productivity inputs to activity duration. Equation 1 connects output to the causal productivity and resource inputs that determine duration.

Equation 1 - New Causal Duration Formula connecting Output to Resources and Productivity Inputs

$$\textbf{\textit{Causal Activity Duration}}\ (\boldsymbol{w.d.}) = \frac{\textbf{\textit{Quantity}}}{\textbf{\textit{Productivity}} \times \textbf{\textit{Resource Supply}}}$$

Using the causal duration formula, the productivity and resource supply inputs are made transparent. In the following worked example of the above-described formwork activity, the baseline performance assumptions for this activity are now clear: the assumed productivity rate is 10 square feet per labor hour, and a crew expending 100 labor hours per day is required in order to complete the activity in 10 working days.

$$\textbf{\textit{Causal Activity Duration}}\ (\boldsymbol{w.d.}) = \frac{\mathbf{10,000}\ (\cancel{\boldsymbol{s.f.}})}{\mathbf{10}\left(\frac{\cancel{\boldsymbol{s.f.}}}{\cancel{\boldsymbol{m.h.}}}\right) \times \mathbf{100}\left(\frac{\cancel{\boldsymbol{m.h.}}}{\boldsymbol{w.d.}}\right)} = \mathbf{10}\ \boldsymbol{w.d.}$$

2.1.1 The Compounding Effect of Low Productivity and Resource Supply

To see how activity duration can be adversely impacted (lengthened) when one or both of the causal productivity and resource input factors are unfavorable, Figure 8 provides a comparison using the causal (input) duration formula. When one factor (either productivity or daily resource supply) is below plan, and the other is at plan, duration will increase in linear fashion. However, when two factors are both equivalently unfavorable, the effect is multiplied and the curve grows exponentially instead of linearly. For example, if both factors are 50% of plan, the activity duration will be increased by 15.8 working days (or 132%), versus an extended duration of 6.3 days (or 52%) if only one factor is below plan. The risk of this multiplier effect needs to be taken into account in delay analysis and schedule forecasting.

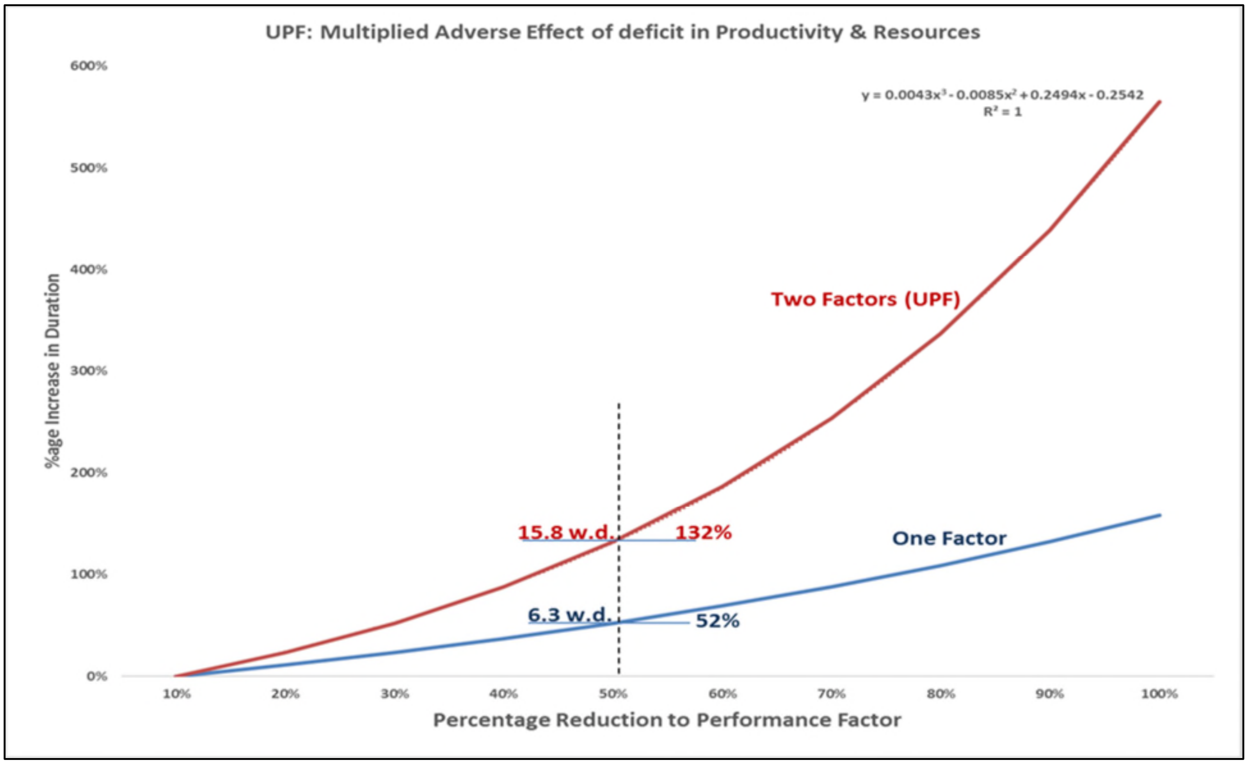


Figure 8 - Delay Effect of declining Resources and Productivity

2.2 New EV Variance Metrics connect Inputs to Outputs

2.2.1 Importance of SV in Measuring Variance from the PMB

According to current EV theory, SV is of limited or no value in evaluating time performance, and even as an EV metric, it should be considered secondary to CV. This thinking should be discarded from EVM theory and practice because it is the source of the serious flaws and limitations in EVM theory and practice. In fact, SV is the *primary performance* metric measuring variance from the PMB (or output), and, since achievement of the PMB is the avowed goal of EVM, should be of central importance in EVM analysis.

2.2.2 PMB Output Performance is a Function of Time

Achievement of the PMB, which is generated by an integrated time-cost CPM schedule model, is the stated objective of EVM. On typical construction projects, the PMB is a cumulative progress curve that defines planned output (planned values) over time (in percentage complete, dollars, or man-hours). Progress on a construction project is a function of time, and the performance profile on successful projects typically exhibits the characteristics of an S-curve (see, for example, Figure 9). For the purpose of this discussion, the empirically derived *Miller* S-Curve [12, pp 102-103] has been used. However, this, or other empirical curves are useful only as heuristics. They should not be used as a substitute for a project-specific PMB generated by the project's resource-loaded CPM schedule.

During the first third of the time (see Figure 9), there is a build-up (or acceleration) of resources and work accomplishment as efficiency steadily improves with familiarization and with increasing availability of work. The success or failure of a project may be determined during the early stages because, as the S-curve profile suggests, accelerating progress through the first third of time is essential so that momentum is established, and output is maximized, during the middle third. During this middle period, the production rate is 150 percent of the average (made possible by peak productivity as well as resource supply), and 50 percent of the work is completed. Finally, during stage three, which is the wind-down period, there is deceleration as available scope of work is diminished, resources are drawn down, deficiencies corrected, and the project is closed out. As will be discussed below, inputs determine the output profile, but there is a symbiotic relationship between productivity and output in the sense that if output levels are not achieved when expected (especially by around 30 percent of time), productivity may suffer and in turn, contribute to reduced output, which defeats the development of momentum over the middle of the project, which is so important to timely completion.

Since the PMB is a function of time, so too should be the SV and SPI metrics which measure it. For example, a negative SV at 30 percent of time is analyzed differently than a negative SV at 130 percent of time. In the first case, the project would normally be entering into its most productive phase and the concern would be that this phase is so delayed as to result in unrecoverable delay; in the second, the project has already suffered unrecoverable critical delay.

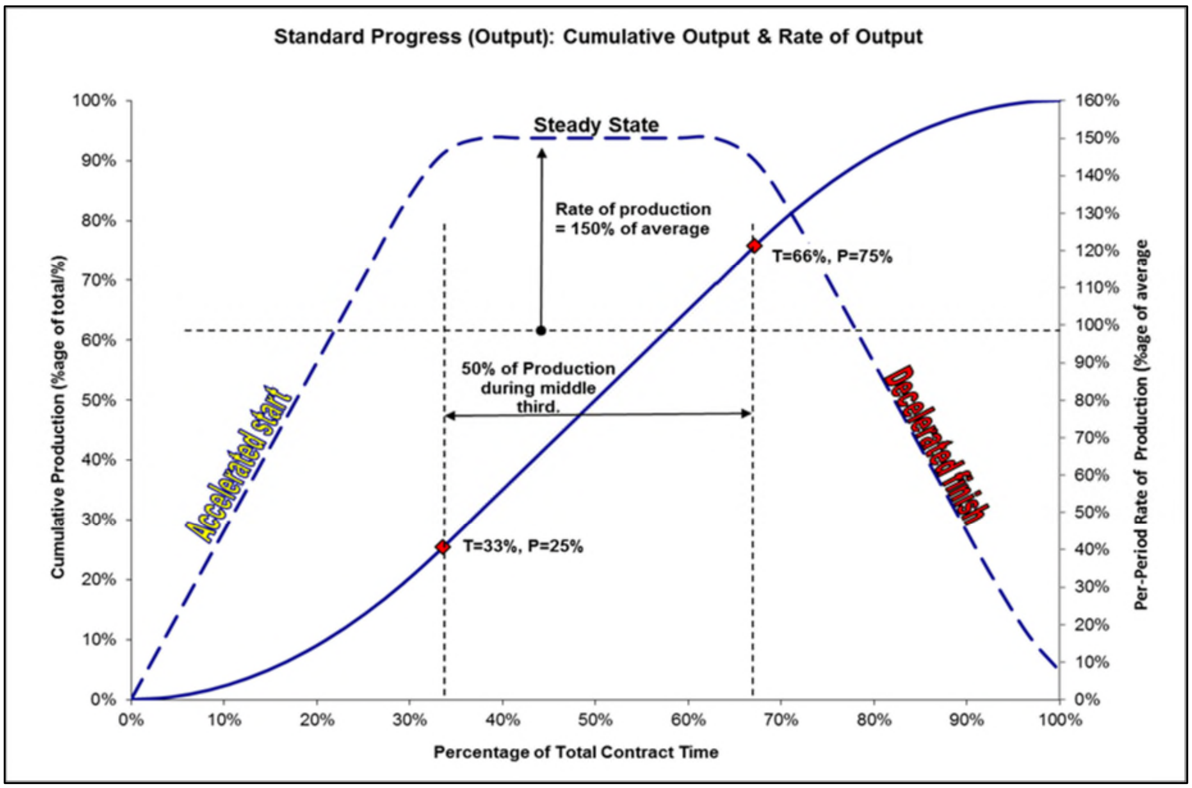


Figure 9 - Standard Output Curve Performance Patterns

2.2.3 CPM Late Curve is the SV/SPI Performance Threshold

The late curve displays the latest possible (planned) progress (per plan) at any given time still permitting timely completion. It was observed above that EVM performance thresholds are arbitrary and lack a deterministic basis. For the most part, EVM theory does not even refer to the late curve, let alone make use of it analytically, but the Late curve provides a deterministic, schedule-based, negative limit for SV.

As shown in Figure 10, a "*late*" value for SPI can be calculated by dividing planned progress (per PMB) into Late progress (per the Late curve). in this case, Late SPI (30%) = 0.71, which equates to progress float of 0.29. The green-shaded area represents *progress* float diminishing over time, which translates to *time* float consumption if work is delayed according to the Late curve. Negative SV directly indicates float consumption [56] [13, pp 153 – 154] which increases the risk of schedule delay. [5]

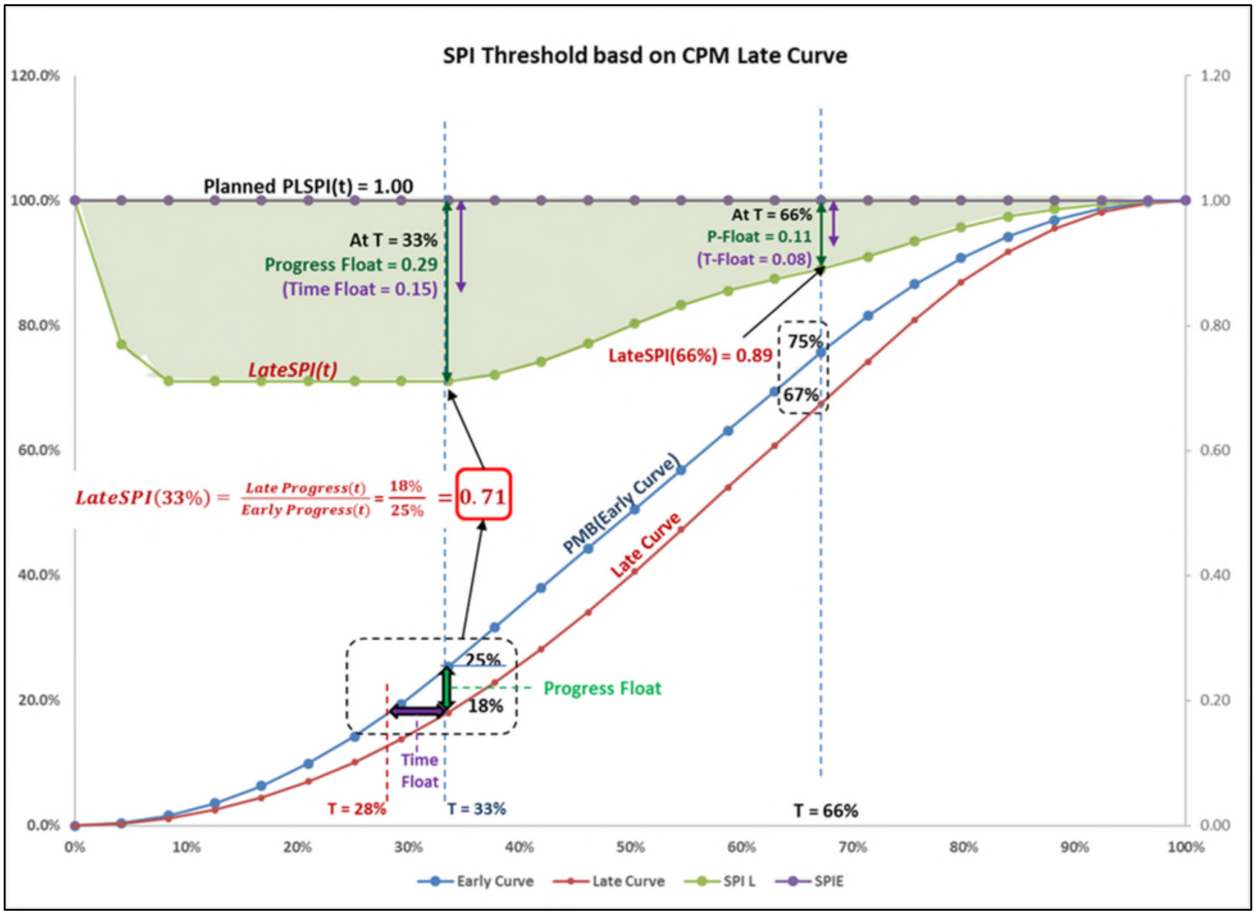


Figure 10 - Late Curve SV/SPI Threshold & Float Analysis

2.2.4 The Missing Causal Metric: Resource Variance (RV) & Resource Performance Index (RPI)

SV and SPI measure a variance in output, and CV and CPI measure variance in the productivity input, but there is not currently an EV metric measuring variance for the other major input, which is the supply of labor[58] resources. An analytical approach that purports to analyze performance on construction projects must account for resources; the Resource Variance (RV) and Resource Performance Index (RPI) metrics fill the existing analytical void.

As shown in Equation 2, RV is calculated by subtracting planned value (PV) from the actual value of resources. When more resources are provided than planned, the RV is positive because providing more resources is assumed to improve time performance.[59] It is an absolute value which conveys an order of magnitude variance as may apply.

[56] For a detailed discussion of the new concepts in float analysis which arise from the new analytics, see “Rethinking Earned Value & Schedule Management on Construction Projects” (Boyle, J. G.) [13].

[58] Labor is typically the primary performing resource, however, equipment (e.g., a backhoe) is also a performing resource, as is a brick-laying machine. For all performing resources, the rate of resource supply and productivity determine duration.

[59] There are exceptions to this premise. For example, on a project that is massively disrupted, adding labor may have no beneficial effect.

Equation 2 - New Resource Variance (RV) Metric

©Resource Variance (RV) = Actual Value - Planned Value

The RPI is calculated by dividing the Planned Value into the Actual Value as per Equation 3. The RPI is a ratio which provides a relative measure of one value to the other.

Equation 3 - New Resource Performance Index (RPI) Formula

©Resource Performance Index (RPI) = Actual Value ÷ Planned Value

Figure 11 shows the RV and RPI metrics calculated along with the CV and SV metrics. RV in this case is a positive 100 hours which means that 100 more hours have been provided than planned. The RPI of 1.20 tells us that the absolute value of excess hours equates to a 20 percent improvement. However, at the same time that the RV and RPI metrics indicate a positive performance level, the SV and CV metrics are both unfavorable.

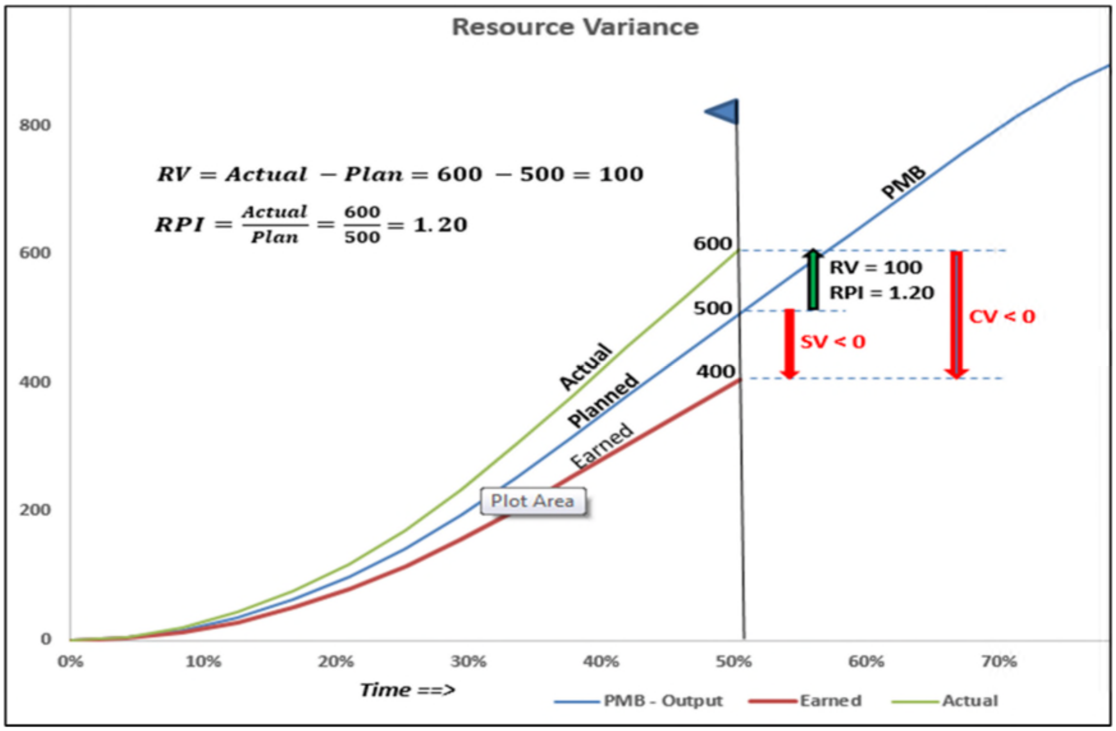


Figure 11 – RV/RPI added to EVM Analysis

How can it be that more resources are provided than planned, but productivity and output are significantly behind plan? What, if any, connection is there amongst these metrics? It will be explained in the next section that, taken together, these variances do in fact tell an interconnected story about (PMB) performance.

2.2.5 New Causal EVM Formulas: Deterministically connecting Output Variance to Input Variances

There is not currently a formula which connects EV output and input variances to each other as well as to the CPM schedule to produce a causal performance analysis. Provided below are new formulas to track performance on construction projects that resolves this analytical deficiency by connecting variance in output (SV or SPI), to the productivity input (CV or CPI) and resource input (RV or RPI) factors which, in combination, determine accomplishment. It is inferable from the output duration formula (Equation 1), that variances from the output and input variances might be similarly related to one another.

It has been explained that SV is an output metric, CV is an efficiency input metric, and RV is a resource or effort input metric. The addition of CV and RV by their expanded EV formulas yields the following results which connect output into one equation.

$$© \, CV + RV = (Earned - \cancel{Actual}) + (\cancel{Actual} - Planned) = Earned - Planned$$

And since,

$$Schedule\ Variance\ (SV) = Earned - Planned,$$

Therefore, SV can be connected to CV and RV as shown in Equation 4:

Equation 4 - New EVM formula connecting Output (SV) to Input (CV,SV) Variances

©UPV formula: SV(t) = CV(t) + RV(t)

The SPI, CPI and RPI metrics can also be connected in a performance evaluation equation. If, as below, the CPI formula is multiplied by the RPI formula, the result, after cancelling out, is ‘Earned Value’ divided by ‘Planned Value’.

$$©CPI \times RPI = \frac{Earned\ Value}{\cancel{Actual\ Value}} \times \frac{\cancel{Actual\ Value}}{Planned\ Value} = \frac{Earned}{Planned}$$

And since,

$$Schedule\ Performance\ Index\ (SPI) = \frac{Earned}{Planned}$$

Therefore, SPI can be connected to CPI and RPI as shown in Equation 5:

Equation 5 - New EVM formula connecting Output (SPI) to Input (CPI, RPI) Indices

$$@UPI\ formula: SPI(t) = CPI(t) \times RPI(t)$$

2.2.6 Revisiting the Formwork Activity Delay – Causal Analysis using the New EVM metrics

Armed with the new EVM and causal activity duration formulas, the earlier formwork delay can now be causally analyzed, and the results, versus the output analysis, are significantly different. It will be recalled that the contractor argued that formwork experienced lost productivity, and was delayed, because of a CO alleged to have caused conditions of trade stacking, congestion, and other disruptions. Moreover, the contractor alleged that the work force was increased in an attempt to mitigate delay.

Figure 12 displays both the causal duration and the causal EVM formulas for the activity. The originally planned duration was based on an assumed productivity rate of 10 s.f./hr., and 100 hours/day of labor supply. After 10 days of work, actual labor data reveals that productivity is exactly as planned! In fact, ***there is no productivity loss*** as the contractor had contended. Moreover, labor was ***not increased*** to mitigate delay. It turns out the cause of delay was the ***deficit in the supply of labor*** (77 hrs./day instead of 100).

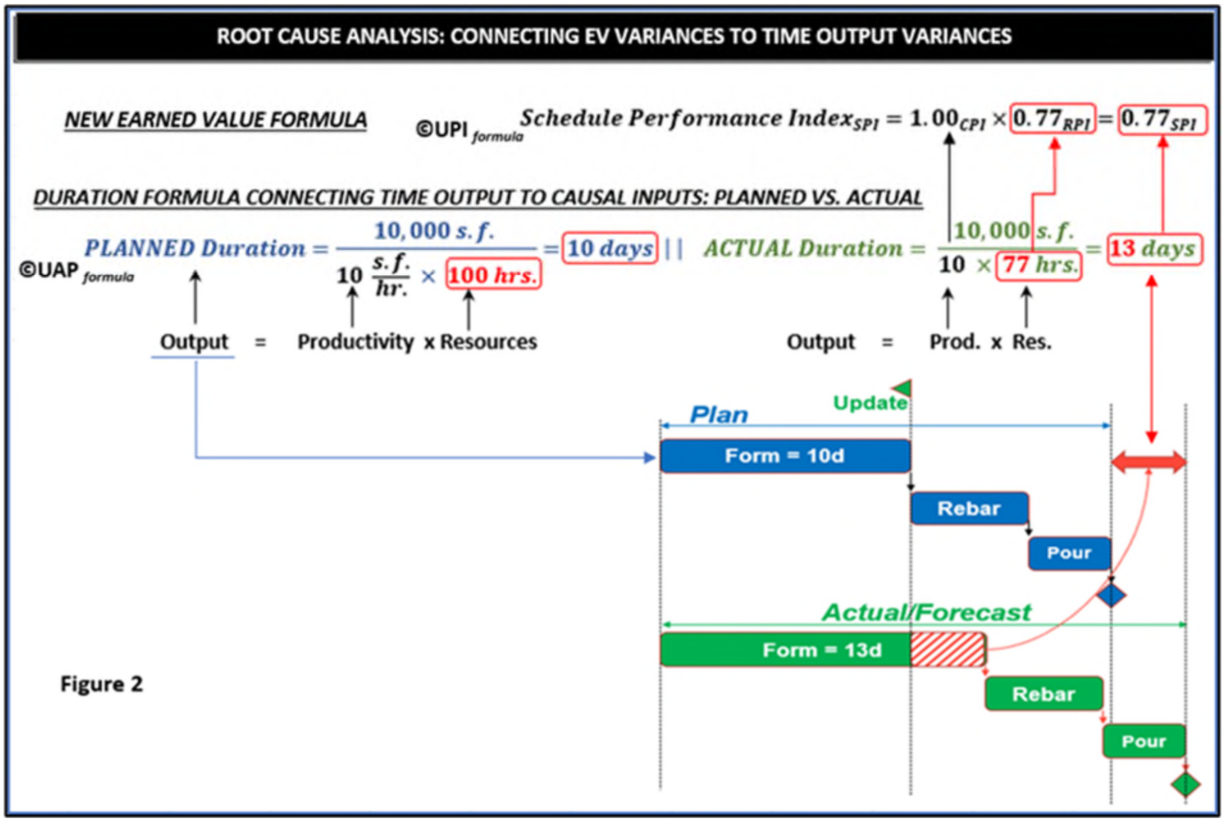


Figure 12 - Root Cause Analysis: Connecting EVM Variances to Time Output Variances

At this point, one should pause to reflect on the many hours and dollars which were wasted on this project, and on many others, because of the absence of causal performance analysis evidenced above. Heads should be shaking over this needless waste as the participants engage in a *wild goose chase* based on spurious "*causes*". The primary reason that planned and actual productivity data is rarely available for contemporaneous performance analysis is that contracts usually do not require it and, it must be assumed, many owners are not interested in getting it. Consequently, instead of project-specific, fact-based, causal analysis, there is probabilistic, non-project-specific speculation about the reasons for variances in terms only of time output. Moreover, opportunities to effectively mitigate are lost when true root causes are unknown.

On construction projects, the past is very often prologue. With the new causal analytics, the current assumption, that a hindsight analysis is more informed than a contemporaneous (so-called) "*blindsight*" analysis, should be revisited, because armed with causal knowledge about activity durations, forecasted durations can be estimated with a high level of precision (as in this example), and may be at least as reliable as a retrospective analysis.

Project managers and delay analysts can avoid the errors in this example if they realize that the required root cause test for delay is the actual impact on the productivity and labor supply performance factors, as calculated by the new formulas, integrated with the resource-loaded CPM schedule. Without it, analysis of performance and delay is bereft of a causal and deterministic foundation.

2.2.7 Project Manager's Analysis Revisited with New Analytics

If these integrated EVM and CPM analytics had been available to the PM in the earlier discussion, the analysis would have been far more insightful in terms of performance analysis and risk mitigation. To begin with, the current monetary fixation on dollar CV would be replaced with a focus on peak PMB performance. Accordingly, the PM would have been concerned about the earned progress deficit revealed by the negative SV at the very first update. Delayed progress means float consumption, which increases schedule risk. Perusal of the cumulative earned curve and the planned curve in Figure 13 shows that by 50% of time, progress is 20 percent behind plan, and has been increasing over time. The deterministic formula can be used to calculate the late threshold, in terms of SPI, by subtracting the late curve hours (350) from the planned (500) hours (SPI = 0.60). Such an unfavorable SPI is a particular concern at this stage because peak production of the work was expected to have been established. Although the progress deficit has not reached the late curve threshold (hatched blue curve), the risk of time delay is becoming ever more serious. Unless performance patterns change, the earned curve will likely fall below the late curve. Using the formulas, the PM determines that this deficit in progress was being caused by low productivity (CPI = 0.67), which was partially offset by a positive resource supply (RPI = 1.20).

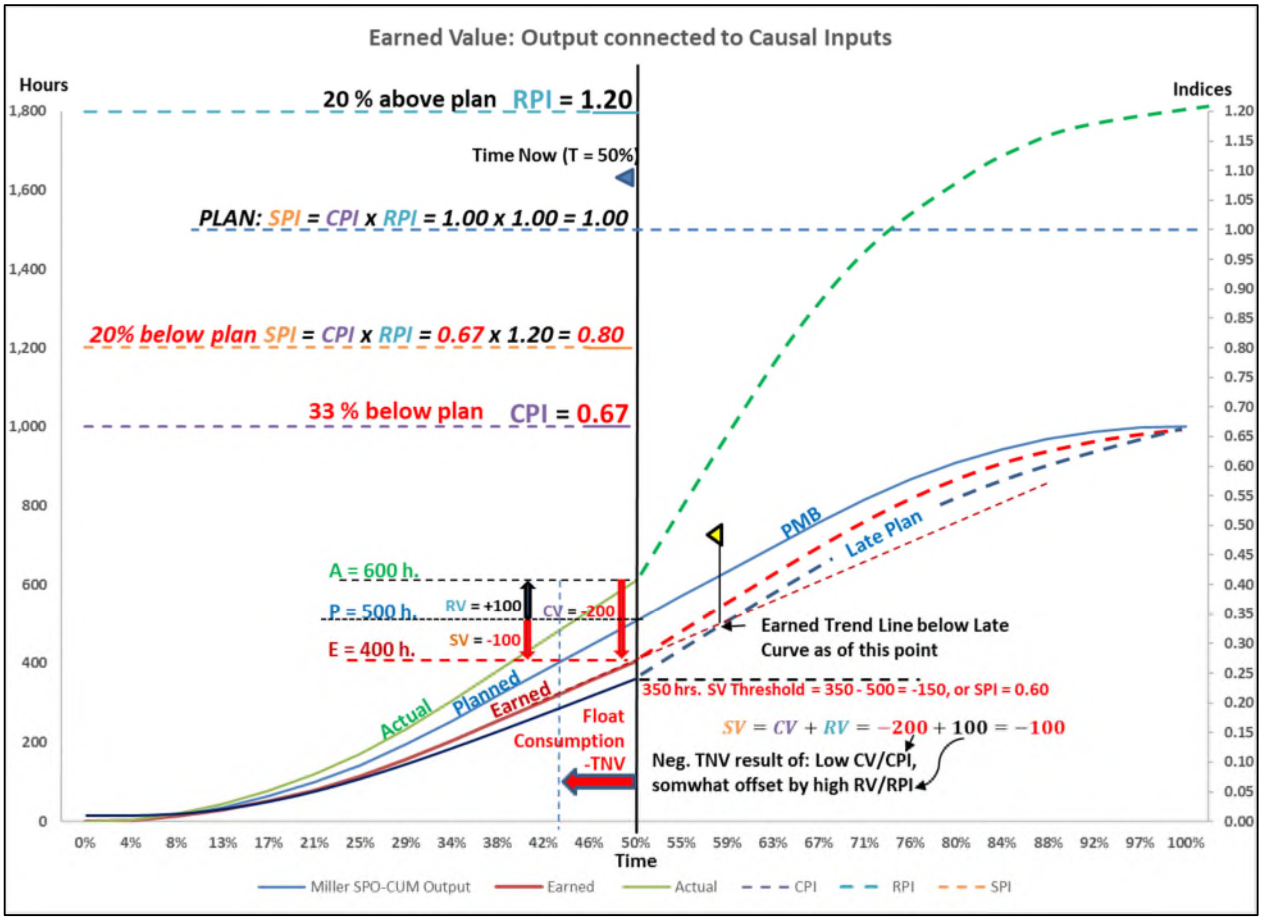


Figure 13 - PMB Output Performance causally connected to Productivity & Resources

The new causal performance formulas also shed light on the actual cost curve, which is the input curve that, along with productivity, determines the PMB (output). The gap between the actual curve and planned curve (currently -100 hours) continues to increase because of the continuing low productivity and added resources. Despite 20 percent more resources being provided than planned (600 instead of 500 hours), only 400 hours have been earned. Negative productivity reduced output by 200 hours. If productivity remains at current levels, then 895 hours (rather than the originally assumed 500 hours) will have to be expended over the remaining 5 months of time. That constitutes considerable acceleration in work crew hours (green hatched line) which may or not be feasible.

It was mentioned in Part 1 that the new deterministic formulas would reveal the "*worst case*" EVM cost forecasting formula to be without a sound basis. The PM calculated the *worst case* formula for forecasting BAC hours, but realized that when the new SPI formula (CPI x SPI) is substituted into the worst case forecasting formula (EAC ÷ [SPI x CPI]), the resulting equation is ***CPI²*** x RPI. Expressed in this way, the formula appears to have no rational basis: why would the *square* of CPI times RPI have predictive value?

The PM embraces the performance-based position that the project schedule, properly updated, is the most reliable predictive model, and so he instructs the contractor to update its schedule to account for: low productivity to-date; resource availability; current scope and issues, and; constructability considerations. He advises the contractor that he and his team will want to have confidence that the forecasted activity durations are realistic given past performance. The forecast must also be a constructible plan accounting for current issues and scope of work. All of this is in service of producing an earliest possible, reliable, bottom-up schedule model. Once the deterministic model is fully developed, probabilistic analysis, such as heuristics or Monte Carlo simulations, can be beneficially applied.

The PM went into the next regular construction meeting with a feeling of control because he had a causal understanding of what was affecting project performance. "*We know that time slippage is occurring*" he began, "*and we know that is because productivity is a serious problem which even the currently high resource levels cannot overcome*. *Let's discuss any current causes for low productivity which may affect the schedule. I want the truth about the cause of the problem, whatever its source. If productivity can't be improved, you're going to have to allocate hundreds of hours more than planned in the current schedule plan forecast. How is that going to work in your schedule? I'll need your thoroughly reviewed, feasible schedule update by the end of the week*." Timely completion was not a certainty, he reflected, but with performance transparency, there was the basis for an actionable schedule plan to reduce the risk of failure.

2.3 A New Causal Chain – Direct Causation is a Missing Link[60]

It was noted above that, by definition, causation is the act or agency which produces the effect. All root-cause-based discussions about PMB performance on construction projects, where labor is a significant and determining component—which is the majority of cases—should properly begin with an analysis of the productivity and resource supply factors, integrated with the CPM, to directly determine performance. If neither productivity nor resource supply is adversely impacted by the alleged delay or disruption circumstances on the project, there simply is no adverse activity duration effect.

The concept of "*causal chain*", as it is currently applied in delay analysis (see the Cause-Effect Matrix Figure 7 above), explains time effect (delayed activity start or extended activity duration) in terms of a mix of what might be called "*proximate*" causes and "*direct*" causes". Proximate cause is an event or issue sufficiently related to the delay that it can be deemed to be the cause of delay; it may be sufficient, but is not necessary, for the effect. The key distinction between proximate causes and the direct, performance factor, causes, is that proximate causes cannot side-step direct causes and have an effect on the duration.

A "*direct*" cause is determined by the "*but-for*" test: it is necessary, but not sufficient to fully understand the cause of delay. Figure 14 conveys the necessary order of delay analysis: first, assess whether one or both of productivity and resources have negatively contributed using EVM and CPM analysis, and only then, consider proximate causes which might explain the time effect. The problem with existing causal analysis is that it by-passes the but-for test, which requires analysis of the "*direct*" cause of delay. The formwork example[61] above reveals how an approach which fixates on proximate causes, and bypasses analysis of direct causation, may be entirely incorrect.

[60] This article does not provide a legal opinion.
[61] See 1.3.6.

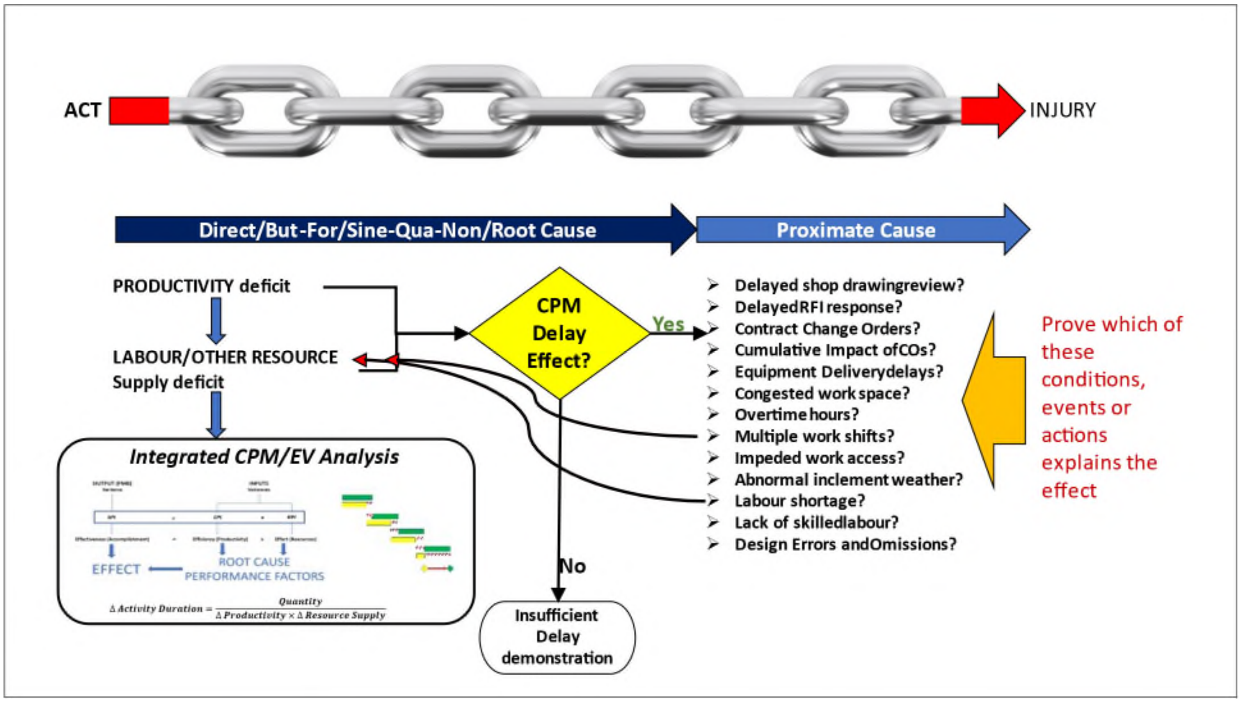


Figure 14 - New Causal Chain: Direct and Proximate Causes

2.4 Contemporaneous Period Analysis Integrating EVM with CPM

A resource-loaded CPM schedule conforming to best practices is the necessary, though not sufficient, first step in creating a reliable basis to plan, evaluate and improve performance on construction projects. Resource loading, including labor and equipment hours and material quantities, as well as dollars, is required so that the inputs required to achieve the planned output over time can be validated and monitored throughout the execution of the project. Using resource data, the input-based duration formula reveals the causal role of the productivity and resource supply inputs in determining output performance. The following discussion builds on this understanding of the interconnection between input and output to develop a comprehensive and integrated EV and CPM analytical system. Under this enhanced system, EV metrics not only account for the dynamic nature of construction schedules but can also inform project management decision-making to optimize future performance.

In this section, earned value and CPM analysis are integrated at both a detailed and summary level. The performance of subcontractors performing[62] the work is analyzed. A rudimentary baseline schedule model (Figure 15) shows the work being completed in thirty-two working days. The planned hours required for the formwork, rebar, concrete placement, and other work to be accomplished in the stipulated time are provided in the figure.[63]

The schedule model is composed of a couple of schedule fragnets[64] involving concrete work on building foundations and including formwork, reinforcing steel, and concrete placement operations. According to the baseline plan, the formwork activities (F1 and F2) will each be completed in ten working days, and each assumes a total resource input of one thousand labor hours. Similarly, durations for the rebar and concrete placement activities are based on an estimated material quantity, as well as the labor hours required to construct that quantity, based on an assumed linear level (CPI = 1.00) of labor productivity. The red lines indicate activities on the critical path.

[62] Although not typically the case on Design-Bid-Build projects, the general contractor may self-perform some of the work.
[63] Productivity has been shown to vary as a function of progress, and therefore also of time, but for the purpose of this simplified analysis, the work hours are based on an assumed uniform productivity rate for each activity.
[64] A “*fragnet*” is a fragment of a schedule network.

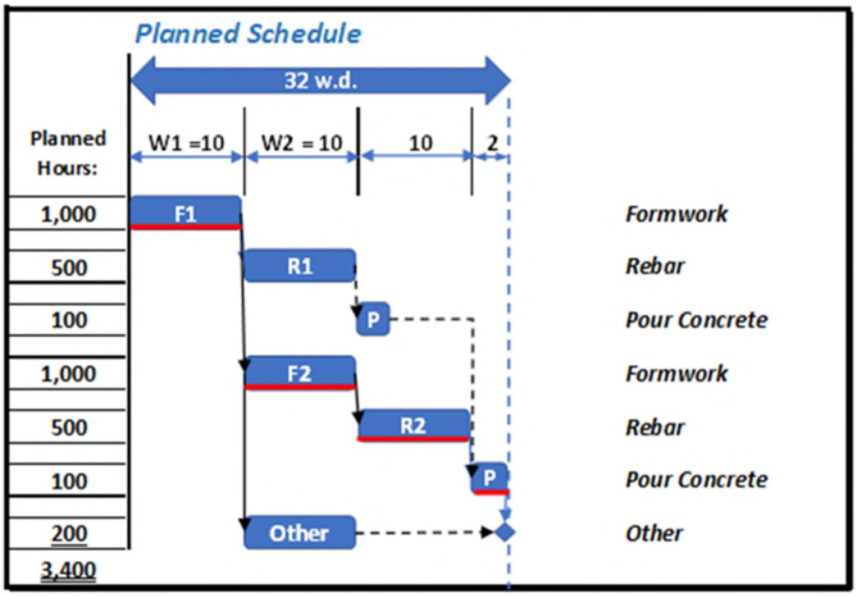


Figure 15 - Contemporaneous Period Analysis (CPA): Baseline Schedule

In Figure 16, the activities are logically connected using CPM schedule software in a view that combines the time-phased plan and the resources required to achieve it. Labor hours are loaded at an activity level and the critical path early and late curves, both cumulative and per-period, are generated. A major assumption in the labor histogram is that when it comes time to actually perform the work, each hour (or dollar-cost) expended will *earn* an hour of progress – in other words, productivity is linear. As the schedule is updated in the sections below, variances in progress (output), as well as the resource supply and productivity assumptions, are analyzed using the new formulas integrated with the CPM.

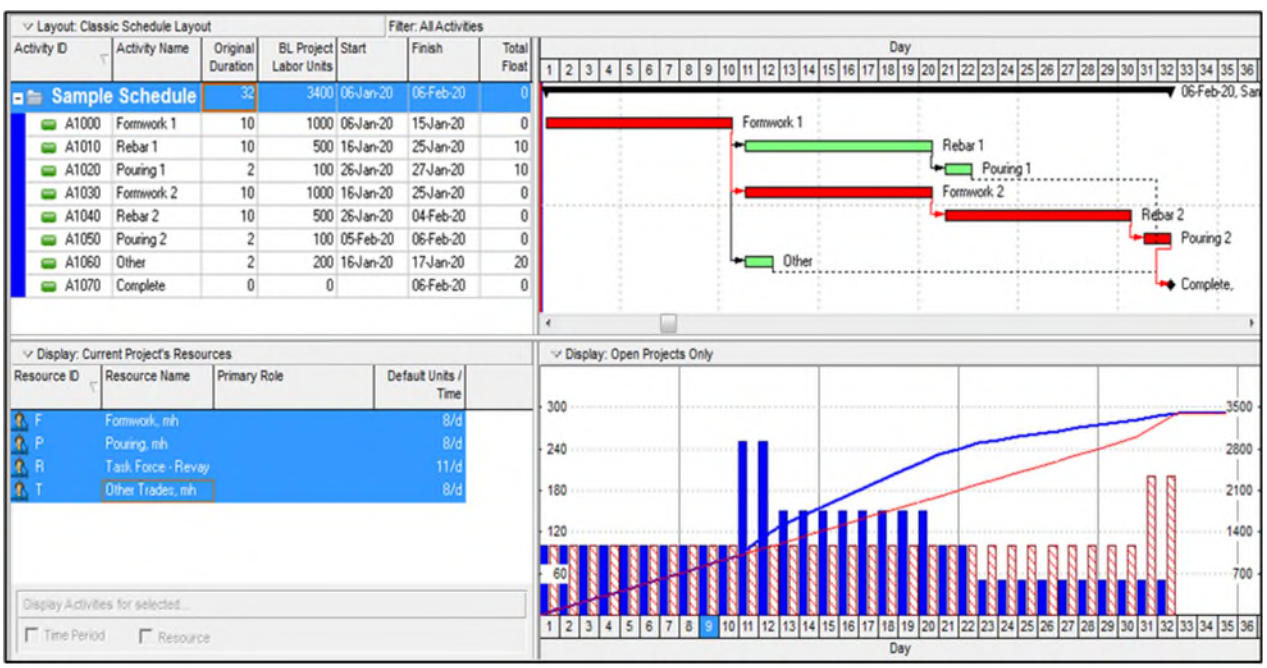


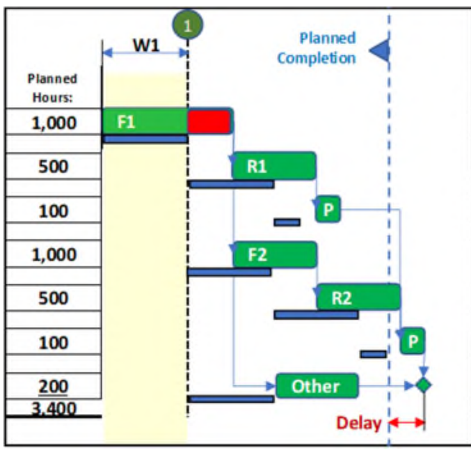
Figure 16 - Resource Loaded CPM Baseline Schedule: Activity/Resource View

2.4.1 First Analysis "Window"

Figure 17 depicts the first schedule update, which was performed one week after the start of the work. Much can change on a construction project on a regular basis, so the truncated time periods (called "windows") created by regular schedule updates—in this case weekly —serve to make an analysis of what may have delayed or disrupted a project much less unwieldy. Window number 1 ("W1" in the figure) is the subject of the first review.

The first formwork activity (F1) was not completed in ten days as planned and is now causing critical delay (see the red bar extending past the status date). As has been emphasized, the PMB is the objective of EVM, and so the foremost question is, or should be: what has caused this delay and can time be recovered? There is an unfavorable Schedule Variance: the plan anticipated that one thousand hours would be earned on activity F1, but only 770 hours have been earned. Thus, there is a negative SV equaling 250 (hours), and an unfavorable SPI of 0.77.

The new formulas reveal that the variance in output is explained by a variance of one or both of the input variances. Considering first the CV and CPI productivity metrics, both are found to be favorable and exactly as planned. However, the contractor has only expended 770 hours, even though the plan required one thousand labor hours of effort to accomplish the work, and the RV and RPI values, -230 and 0.77 respectively, are unfavorable. The deficit in progress, which has resulted in a time delay, is caused by a deficit in resource supply. Applying the new EVM formulas (4 and 5) makes transparent that all of the negative SV (-230) and unfavorable SPI (0.77) are caused by the failure to provide sufficient resources as indicated by the RV (-230) and RPI (0.77).



Earned Hours:	Actual Hours:	Planned Hours:	SV = CV + RV			SPI = CPI x RPI		
			SV	CV	RV	SPI	CPI	RPI
770	770	1,000	-230	0	-230	0.77	1.00	0.77
0	0	0						
0	0	0						
0	0	0						
0	0	0						
0	0	0						
0	0	0						
770	770	1,000	-230	0	-230	0.77	1.00	0.77

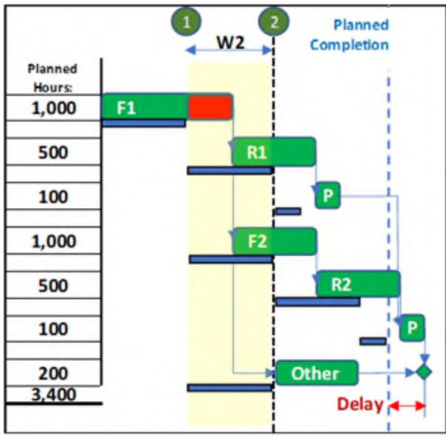
Figure 17 - CPM/EVM: Windows Analysis No. 1

Armed with this information, performance analysis should be directed to determining why resources were not allocated per plan. Was it a contractor decision or a failure of oversight? Are there job conditions depriving the contractor of full access to the work? Was there a change to the scope of the work? Knowing the conditions and secondary causes impacting the root cause—in this case, an inadequate labor supply—is the necessary first step in effectively correcting a performance problem. Once this is known, an action plan can be developed to recover lost output, or at least to mitigate the problem.

Since resources are usually not loaded into construction schedules, the direct cause of delay, and even the delay itself, is often unknown. At the time of the update, the contractor might simply have changed the activity logic (e.g., created a negative lag to critical successors) so that delay is eliminated, and on-time completion is forecasted, without the PM even noticing. That might well be a legitimate schedule adjustment reflecting reasonable steps to mitigate delay, but the problem is that the risk is unknown to the PM and owner. The concealment of risk increases project risk because the truth needs to be known in order to effectively monitor and control a project.

2.4.2 Second Analysis "Window"

According to the next schedule update forecast, the critical delay experienced in the first window of time has not been recovered. Activity variances as of the second schedule update are shown in Figure 18 and discussed in the following analysis of the variances that have appeared in this second update.



Earned Hours:	Actual Hours:	Planned Hours:	SV = CV + RV: SV	CV	RV	SPI = CPI x RPI: SPI	CPI	RPI
1,000	1,000	1,000	0	0	0	1.00	1.00	1.00
250	300	500	-250	-50	-200	0.50	0.83	0.60
0	0	0						
500	520	1,000	-500	-20	-480	0.50	0.96	0.52
0	0	0						
0	0	0						
0	0	200	-200		-200	0.00		0.00
1,750	*1,820*	*2,700*	*-950*	*-70*	*-880*	*0.65*	*0.96*	*0.67*

Figure 18 - CPM/EVM: Windows Analysis No. 2

Activity F1—Formwork: In W1, this activity was forecasted to require an additional three days to complete. In W2, this forecast was proven to be correct, and so the activity was completed in thirteen days rather than the planned ten days. If mitigation is available, it has not been incorporated into the schedule forecast, and so the project completion date has been delayed by an equivalent three days.

As is always the case at completion of an activity (or a project), SV returns to zero because the work was completed in this window; there is no more variance between planned and actually earned accomplishment because the work is done.

However, the EVM practitioner might ask why the RV is now zero when, in the previous month, it was negative? Is RV like SV in that it always returns to zero?

To answer these questions, it should first be understood that the performance goal is not only to avoid an unfavorable *final* resource (or cost) variance. It is equally important to evaluate a resource variance as a *function of time*, because if resources are not provided *when required* per plan, there may be a deficit in progress, as happened here. In this case, even though the resources provided eventually (at completion) equalled the plan (RV=0), the activity (and the overall schedule) was delayed because the resources were not provided *at the time and rate they were required*.

This concept is conveyed by a comparison of the *planned* input assumptions to the *actual* input. In the calculation below (using Equation 5), the planned supply *rate* of hours is one hundred hours per day.

$$\textbf{Planned Duration} = \frac{\textbf{Quantity}}{\textbf{Prod.} \times \textbf{Rate Resource Supply}} = \frac{10{,}000}{10 \times 100} = 10\ w.d.$$

However, as shown in the calculation below, the actual rate of resource supply was only seventy-seven hours per day, or 23 percent less than planned (note that the RPI equaled 0.77 during first window). As result of the lower rate of resource supply, daily output is reduced from the planned 1,000 square feet per day, to 770 s.f. per day, and the duration is extended to thirteen working days instead of the planned ten working days, even though eventually, all of the planned resources were expended.

$$\textbf{Planned Duration} = \frac{\textbf{Quantity}}{\textbf{Prod.} \times \textbf{Rate Resource Supply}} = \frac{10{,}000}{10 \times 77} = 13\ w.d.$$

Actual labor should be recorded on a daily basis for all major construction trades, as competent contractors regularly do. Had that been done during the first window, and the daily variances reported, the delay to F1 might have been avoided or mitigated.

Unlike the SV, which always returns to zero at completion (because it is a measure of variance of a defined and unchanging output, and eventually the output is achieved), the RV input, like the CV input, may have a positive or negative end value because it is measured against the planned hours (which are a percentage of the budget). The "*average rate of resource supply*" is an absolute value, not related to the plan, which is calculated as follows: *RRS = Total Hours ÷ Total no. of days*.

2.4.3 Labor Cost is Determined by Productivity

A very important point is that activity F1 is an example of an activity that has longer duration than planned, but labor cost will not exceed the budgeted cost. That is because productivity determines labor cost, as is proven in the calculations below:

The new duration formula (Equation 1) can be used to mathematically demonstrate that increased duration does not necessarily increase cost, as well as that increasing crew size does not necessarily increase cost. To prove this, cost is calculated by multiplying the duration by the "*burn rate*" (hours per day) by the dollar cost of one hour of labor (Equation 6).

Equation 6 – Labor Cost Equation

$$Cost(\$) = Duration(d) \times (Burn\ Rate)RRS\,\frac{hrs.}{d} \times Labour\ Rate\,\frac{\$}{hr.}$$

The activity duration formula (Equation 1) can be rearranged to yield Equation 7 for the burn rate (or RRS).

Equation 7 – Burn Rate connected to Causal Inputs

$$(Burn\ Rate)RRS(\frac{Hrs.}{d}) = \frac{Quantity(s.f.)}{Duration(d) \times Productivity(\frac{s.f.}{hr.})}$$

In Equation 8, the burn rate formula is inserted into the cost formula (Equation 6).

Equation 8 – Substitution of Causal Burn Rate Formula into Cost Formula

$$Cost(\$) = \cancel{Duration(d)} \times \frac{Quantity\ \cancel{(s.f.)}}{\cancel{Duration\ (d)} \times Productivity\ \left(\cancel{\frac{s.f.}{hr.}}\right)} \times Labour\ Rate(\frac{\$}{hr.})$$

The resulting formula (Equation 9) shows that, contrary to view of some EVM analysts, labor resource cost is not deterministically connected to time.

Equation 9 – New Labor Cost Formula

$$Cost(\$) = \frac{Quantity\ (s.f.)}{Productivity\left(\frac{s.f}{hr.}\right)} \times Labour\ Rate\ (\frac{\$}{hr.})$$

Activity F2—Formwork: The second formwork activity (F2) commenced in W2, but was not completed as originally planned. To date, only 50 percent of planned progress has been achieved (SPI = 0.50). This is mostly, though not only, attributable to the delay caused by its predecessor (F1). However, unlike its predecessor, F2 productivity is lower than planned (CPI = 0.96). Fewer resources than planned have been allocated (RPI = 0.52) because the activity started later. If productivity does not improve, the final activity duration will be more than the planned ten working days.

A best-practice EVM system should: (a) contemporaneously identify these productivity and resource supply problems; (b) then evaluate the reasons for them, and the potential for mitigation; (c) take corrective action where possible; and (d) adjust the schedule forecast as necessary to reflect a realistic current plan and duration based on reasonably anticipated performance.

Activity R1- Reinforcing Steel: Unfavorable output and input variances have arisen in this second window of time. Similar to the F2 activity described above, only 50 percent of the planned progress has been achieved (SPI = 0.50), but in this case, both of the input performance factors are significantly below plan. Planned productivity is 17 percent unfavorable (CPI = 0.83), and 40 percent fewer resources have been provided (RPI = 0.60). The UPI formula captures the multiplier effect of both inputs being unfavorable: a deficit in resource supply is magnified in its effect when accompanied by low productivity. Some amount of unfavorable resource variance was inevitable because the start of this activity was delayed, but the conditions or secondary causes that are impacting productivity, and also reducing the daily rate of resource supply, must be determined and risk mitigation action be taken, as described above. If CPI remains at the current level of 0.83, an RPI of 1.20 would be required to achieve favorable progress as per the following calculations.

Summary-Level Variance Analysis (W2): When moving from an activity-level analysis to a summary-level analysis as provided in the table below, it is apparent that there is a very significant deficit versus the PMB (only 65 percent of planned progress has been achieved) and this has resulted in a critical delay that first appeared in the first window.

Earned Hours:	Actual Hours:	Planned Hours:	SV = CV + RV			SPI = CPI x RPI		
			SV	CV	RV	SPI	CPI	RPI
1,750	1,820	2,700	-950	-70	-880	0.65	0.96	0.67

Figure 19 - EVM Summary Analysis

The root cause of unfavorable output is primarily the deficit in supply of resources (RPI = 0.67). Overall productivity is also slightly less than favorable (RPI = 0.96). However, this summary level productivity number conceals a potentially significant productivity problem that exists at an activity level (see R1, discussed above). The lesson is that one should be vigilant about the potential masking effects of summary-level analysis. On a project of any size, major trades should be analyzed at both an activity and summary level.

The planned, earned, and actual data has been entered into this schedule model. Analysis of the EV metrics as above provides a valuable historical performance status evaluation. However, it is equally important to the success of the project that these performance indicators should inform the schedule forecast so there can be confidence that the go-forward plan is realistic and reliable. It is apparent from the schedule below, which compares the baseline schedule to the second progress schedule update, that progress of all activities to date is delayed, and the project is in delay according to the forecast. But how reliable is the forecast? Is there knowledge of why rebar productivity is low, and can it be corrected? Is an extraneous issue the problem, or is the assumed productivity level in error? Must rebar activity durations be lengthened, or can resources be added efficiently to compensate? Similar analysis should be done for the other activities. Why has the "*other*" work been deferred? Are there new risks that may adversely impact one or both inputs? Are the forecasted hours sufficient based on the performance data and existing scope and conditions? On many construction projects, all or most of these questions are not even asked, let alone answered. This is primarily because most schedules are not resource loaded, which reflects the industry's lack of focus on the connection between resources and productivity and overall time performance.

Summary-level analysis is also available in the form of a graphical comparison of the planned, earned, and actual cumulative curves and per-period data generated out of the CPM schedule (Figure 20). Comparing the per-period trend line for the baseline plan to the trend line for the actually provided labor clearly shows the deficit of resources to date. It is apparent that progress has fallen below the late curve and a critical time delay has arisen. This results from the resource and productivity off-trends revealed by the interconnection of the UPV and UPI formulas, which can be quantified by measuring the time differential between the time of update ("time now") and the latest time at which the current earned progress could occur without causing critical delay (called here "time late").

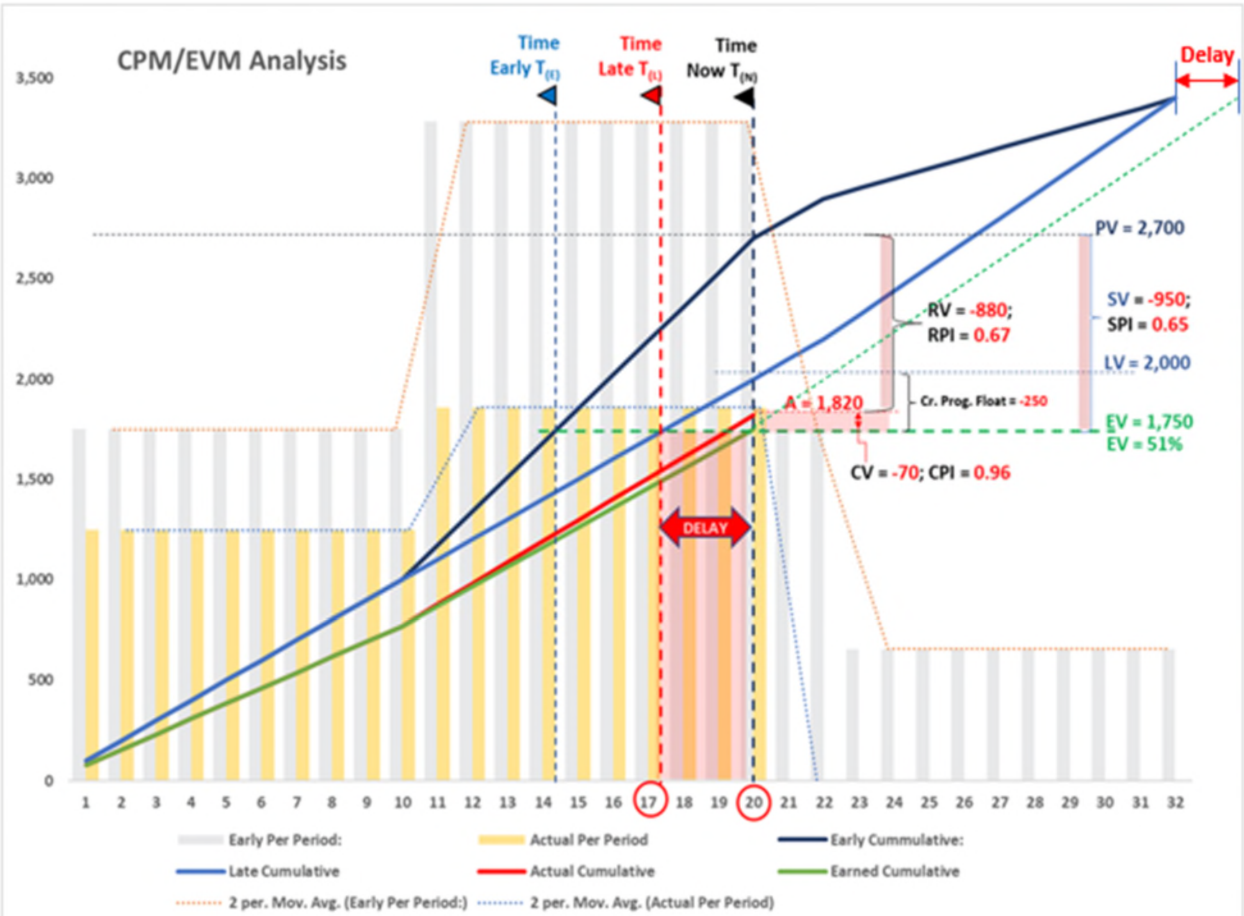


Figure 20 - CPM/EVM Analysis Progress Analysis

2.5 Variable Productivity

Not only does current EV analysis not recognize the distinction between output and input, it has not much considered the characteristic pattern of productivity performance over progress and time, which has important implications for interpreting the EV metrics, and also understanding output performance.

Experts in monitoring productivity on construction projects have empirically demonstrated that productivity on well performing construction projects conforms approximately to a negative parabolic curve, with progress on the x-axis and a productivity index on the y-axis. One such curve is the "*productivity index* (PI) *curve*", [14, p 16.5] shown in Figure 21, which may be applied to a particular trade, or the entire project.

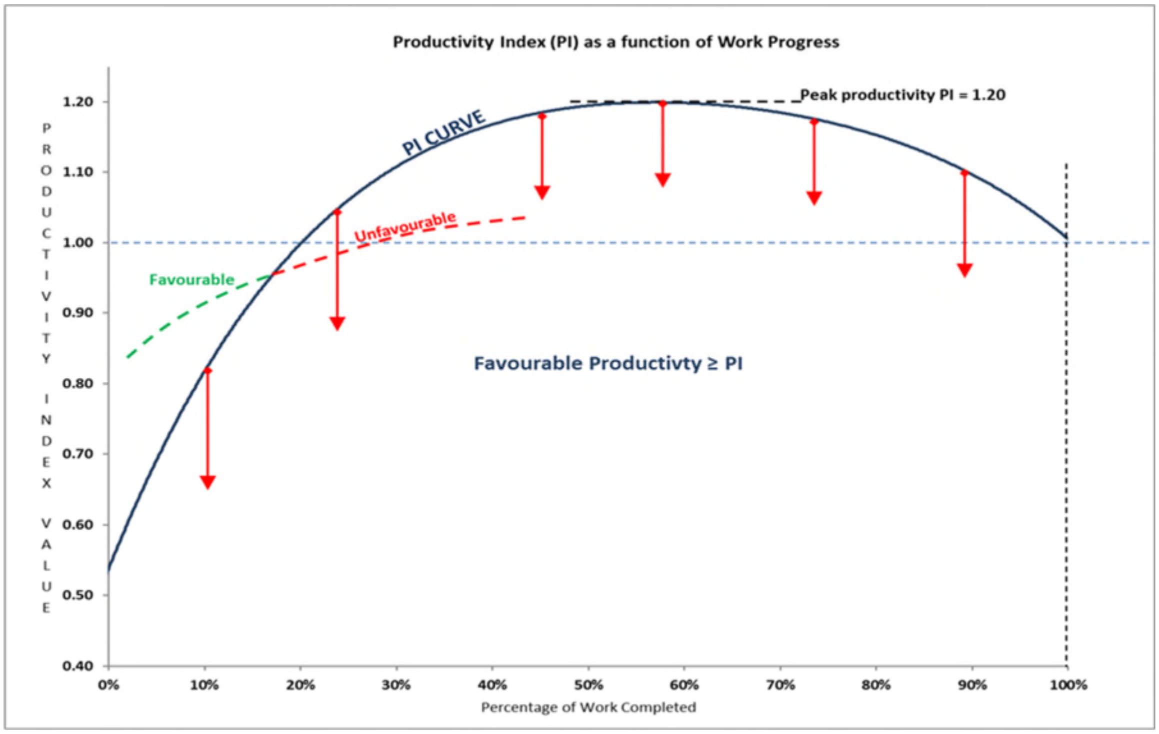


Figure 21 - Variable Productivity vs. Earned Progress

According to the PI curve, early-stage productivity is significantly below favorable, at least according to the assumption of a uniform (1.00) value. For example, at 10 percent progress, PI equals 0.80 (or 20 percent below favorable). As progress accumulates, productivity steadily increases, and by 20 percent progress, the PI is 1.00. Thereafter, productivity continues to increase as progress accumulates, reaching a peak at around 50 percent of progress, where PI is approximately 1:20. As the project winds down, productivity eventually returns to 1:00 with the budget having been achieved.

For this purpose, the PI may be considered synonymous with CPI. What the PI curve shows is that planned productivity varies over time. Even if actual productivity is less than 1.00, if it is above the PI curve, as it is in the above figure (green hatched line), then it is favorable. Similarly, even if actual productivity is greater than 1:00, if it is below the PI value forecasted at a particular level of progress, it is nonetheless unfavorable (see the tail end of hatched red line).

It is possible to plot a productivity curve against time - instead of progress - as the graph below illustrates. (This was done by connecting the timing of progress according to the PMB to progress in the PI curve). At any point in time, all other things being equal, productivity must be at the indicated level in order for planned progress to be achieved.

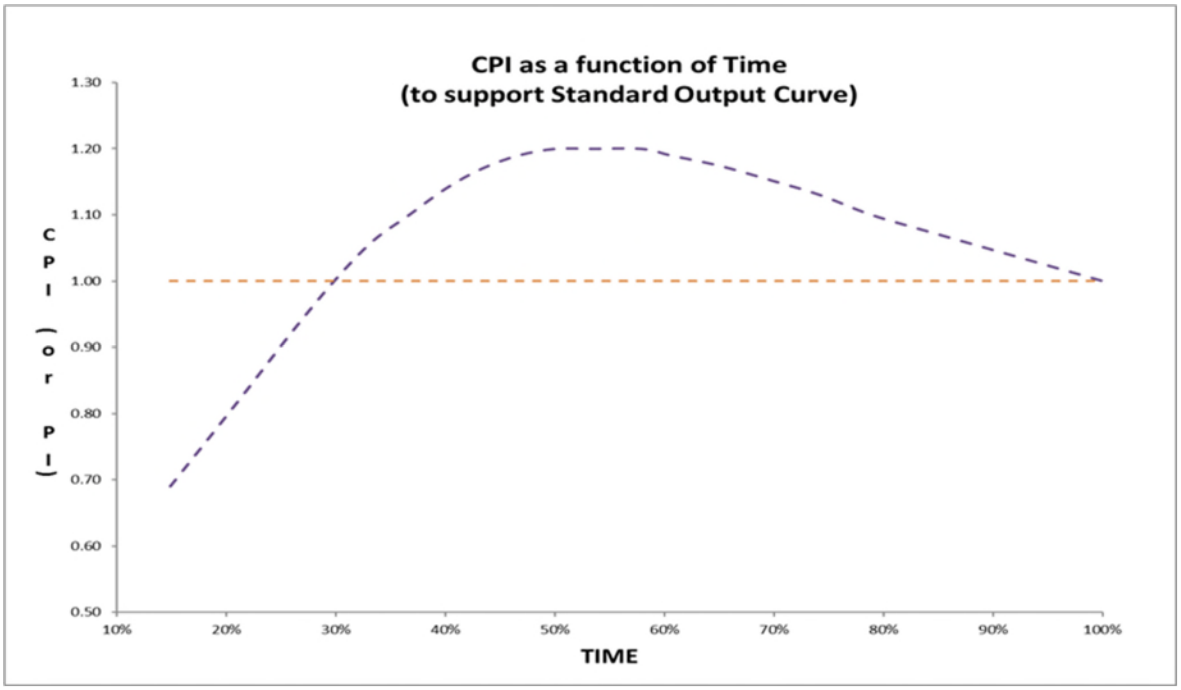


Figure 22 - Variable Productivity as a Function of Time

Traditional EV does not recognize the changing productivity levels of the PI/CPI curve even though productivity experts have identified it as a characteristic of construction labor performance. Instead, EVM analysis deems a CPI under 1.00 to be unfavorable, and a CPI greater or equal to 1.00 to be favorable, however much progress achieved, or how much time has passed.

Moreover, EVM theory supports the Christensen study which found that CPI does not improve more than 10 percent after 20 percent of progress is achieved.[66] Although this does not necessarily support the EV assumption of uniform productivity, it is clearly not consistent with the PI curve since, according to the PI curve, productivity improves by 20 percent after 20 percent progress, which exceeds the Christensen limit by 100 percent.

Future studies may resolve the discrepancy between the Christensen study and the empirical PI curve, but the important point in this discussion is that the contractor's planned productivity may be variable over time (and progress), and if it is, then the actual feasible productivity plan varying over time, developed for a given project, should be the baseline against which performance is measured.

Since the current EV assumption is that productivity is uniform over time, then a CPI less than 1.00 arising at any time is considered a very high priority risk requiring corrective action. But if the productivity plan calls for a CPI less than 1.00 at the time (as the PI curve does until about 20% of time), there is no need for "correction". In fact, the action taken if that is assumed may hurt performance: for example, labor might be reduced, resulting in reduced work accomplishment. Conversely, a CPI equal to, or even greater than, one, may be lower than the plan, in which case, if no action is taken, performance may suffer. As, for example, if CPI at 50 percent progress is only 1.00, but according to the PI curve should be 1.20: if no action is taken, the project may complete late.

It should be understood that variable productivity should not assumed any more than uniform productivity should be assumed. If a feasible labor plan supporting a validated schedule does not anticipate significant variation of the CPI based on time (or progress), then a uniform CPI value *is* properly the basis of variance analysis. Where peak performance is the priority, a primary concern (along with resource supply) is that the actual productivity required to support the targeted completion, whether or not it changes over time, is being achieved. If the productivity plan

[66] AACE RP 80R-13, p. 4.

is not achieved, it may be a cause of delayed completion (unless resources are increased), which constitutes a failure versus the objective of achieving the PMB.

2.6 EVM Model based on Variable Productivity

The baseline EVM performance model based on an empirically derived productivity model is shown in Figure 23. (EVM variance analysis, in the case of varying productivity, requires customized metrics which are not discussed here).[67] [13] As against the uniform productivity model, distinguishing characteristics of the variable productivity model are as follows:

- The productivity profile assumes progress will be achieved as expected on a well-performing project not significantly impacted by delays which are not contemplated per contract;
- Reflecting the PMB objective as a priority, which requires a favorable SPI (1.00) throughout, RPI and CPI are symmetrical about the SPI axis.
- The PMB in this case is based on an empirical curve, but the bottom-up project schedule should be used in particular cases;
- The baseline resource input curve, or "*actual cost*" curve in EVM, is not the same as the PMB. That is because it accounts for variable productivity over time. During the critically important early stages – i.e., prior to one third of time – low productivity is offset by a high resource supply input so as to achieve a favorable SPI according to the SPI formula. After this point, resource levels are below 1.00 because improved productivity reduces the resource level requirements.
- As the project moves beyond the maximum momentum phase into the latter third of time, CPI and RPI converge.

[67] New formulas are introduced to analyze variances in the context of variable productivity assumed as a baseline. [13]

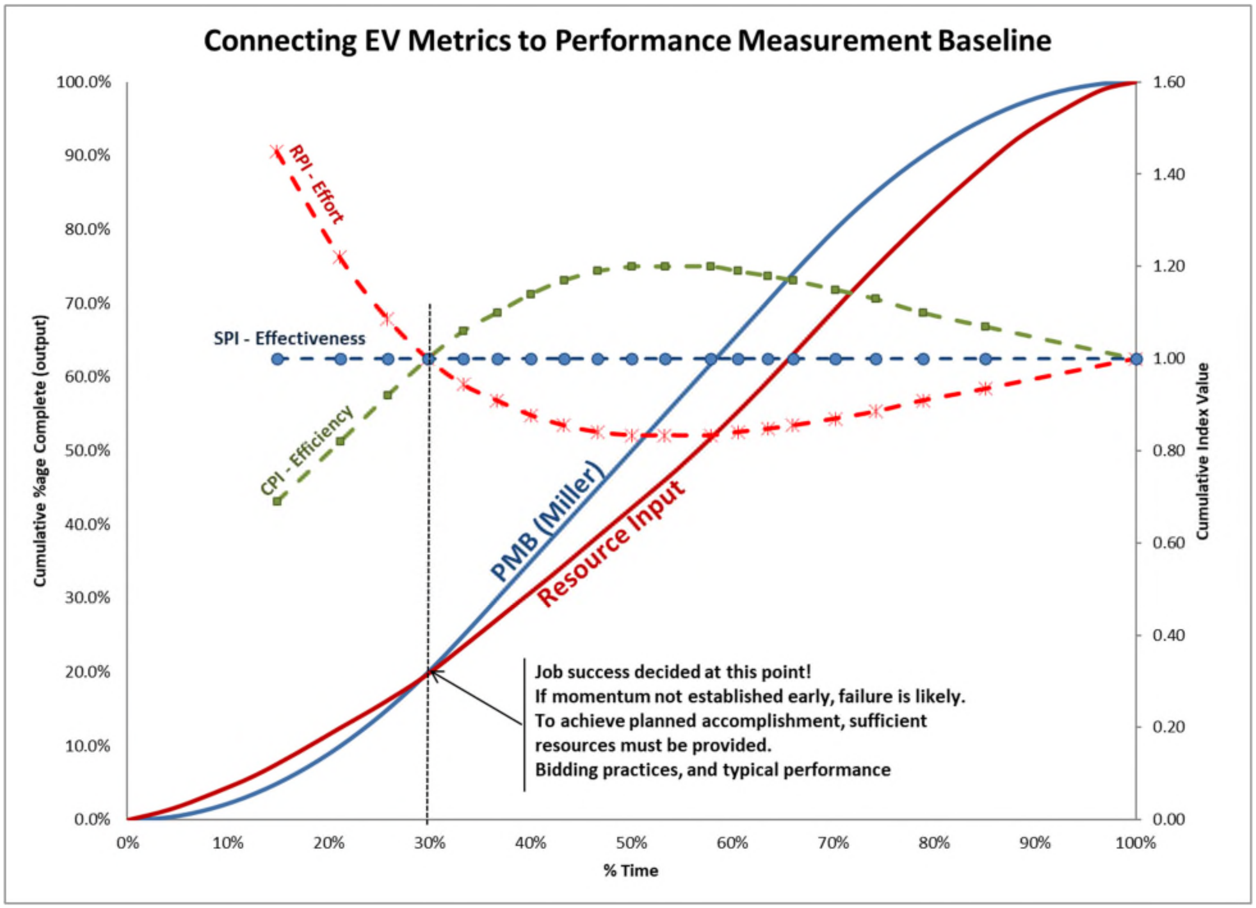


Figure 23 - EVM Analysis based on Variable Productivity - Standard Model

2.6.1 Implications of Variable Productivity on Construction Performance Analysis

Figure 24 provides a graph of a somewhat obscure standard resource input curve, called the "*Allen*" curve[68], which is plotted along with a standard progress output curve. It is apparent that the curves are different: the resource supply (input) curve lags behind the progress (output) curve throughout the period of the work, only to converge at completion. To the extent this has been noticed at all, commentators have been perplexed by the difference between the curves, with some speculating that it may be explained by the effects of the "*learning curve*"[69] or increased experience working on the site.

[68] Allen, W. 1979. Developing the Project Plan. Notes prepared for Engineering Institute of Canada Annual Congress Workshop. Toronto. Pp 3-9.

[69] The learning curve, or experience curve, is the graphical representation of the rate of learning against repeated experiences or over time. It depicts how a boost in learning happens because of greater experience. The learning curve provides insight into productivity, efficiency, cost, and experience.

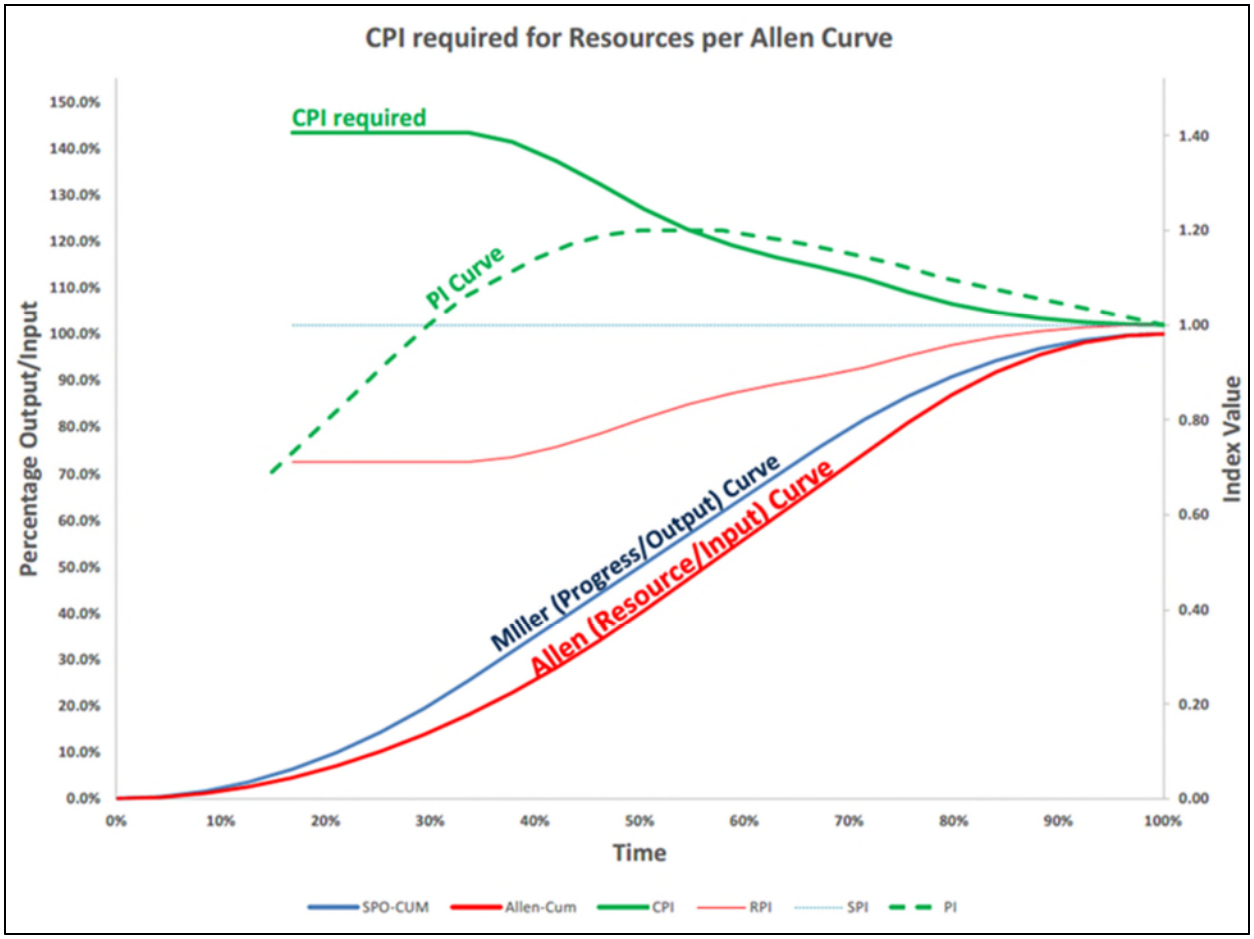


Figure 24 - Validating Plan by considering Input Assumptions: A Lesson for the Industry?

For this example, it is assumed that productivity varies over time according to the standard PI curve model. One now has the tools to understand that the above hypotheses - that lagging early productivity effects explain lagging (Allen) resource supply (vs. plan) - is erroneous. In fact, the underlying assumption on which this input curve relies in order to achieve the (Miller) output curve [12] is that productivity commences at an extremely high level. This is shown by applying the new formulas, and using the new baseline analytical model (above), which displays the CPI, RPI, and SPI index curves. If resources are provided according to the Allen curve, and the output curve is to be achieved, productivity would immediately need to reach a level (CPI = 1.41, or 40 percent favorable) that is much (20 percent) higher than would be expected even at the mid-point in the project when efficiency would be at its peak. The required CPI curve bears no resemblance to the PI curve over the first 50 percent of time, and obviously exhibits no signs of early productivity lagging, as has been opined. Nothing in the productivity literature suggests anything like it. At least in the case of variable productivity, the productivity profile on which the Allen curve is based must be considered highly unlikely, if not impossible, to achieve.

The salient point is that a validation of the resource plan for a construction project needs to assess the feasibility of not only the level of resources, but also the productivity of those resources. A possible lesson for the construction industry at large, if indeed there is a widespread practice of early under-resourcing of projects (based on no, or unrealistic, productivity assumptions), as suggested by the Allen curve, is that such under-resourcing may be a significant cause of delay. It might help to explain why so many projects finish late. What is needed is reliable industry data to determine if this is actually the case.

2.7 Answering the Unanswered EVM Questions

In Part 1, after providing a critique of existing EVM practices, the following questions which arose from that critique, were asked. Based on the new theoretical approaches presented in Part 2, answers to these questions are provided.

1. *In a system dedicated to achieving the PMB, is the current EVM prioritization of CV, as oppose to SV, analytically sound?*
   [Answer] No. SV is always a key (output) metric because it measures variance from the PMB. Moreover, CV and RV (input metrics) provide the root causal explanation for off-trends in SV. This is proven by the New Causal Duration Formula (Eq. 1) and the new EVM variance formulas (Eqs. 4 and 5).
2. *In a system dedicated to achieving the PMB, why does EVM not offer analytics that are integrated with time performance analysis?*
   [Answer] As noted above, the new analytics fill this analytical void and provide a truly causal analysis of duration.
3. *Is EVM theory correct in separating CV and SV as unconnected independent metrics? Do the CV and SV metrics have a connection to the CPM schedule which would aid in time performance analysis?*
   [Answer] SV is an output variance metric which is connected to the CV and RV metrics according to Equations 4 and 5.
4. *Is the EVM assumption correct that linear productivity at a favorable level is indicative of optimal performance? Put another way, is it possible that even on well-performing projects, negative productivity should be expected at certain stages as an accepted performance pattern?*
   [Answer] The EVM assumption that uniform productivity (CV = 0, CPI = 1.00) throughout performance is necessarily favorable in all cases is incorrect. Studies have shown that productivity is often planned to conform to the PI curve, which is a variable productivity model.
5. *Are the normally cited reasons for negative activity start or duration variances, such as deficient drawings, disruptive contract change orders, equipment delivery delays, and so on, really root causes?*
   [Answer] These are not root causes; they are proximate causes. For the duration of a labor performance activity to be affected, productivity and resources must, in combination cause it to be, as per Equation 1.
6. *Why is EVM and CPM analysis output based? Might there be a deterministic formula to connect duration to the productivity and resource inputs? If so, could this be used in causal, input-based schedule analysis?*
   [Answer] Equation 1 is that deterministic formula which connects output to the causal inputs. Equations 4 and 5 provide the new EVM formula which connects EVM metrics according to the same principle.
7. *Why is there not an EVM metric to measure variance in resources even though there are metrics to measure variance in earned progress (i.e., SV and SPI) and productivity (CV and CPI)?*
   [Answer] This void is filled with the RV (Eq. 2) and RPI (Eq. 3) equations.
8. *Should EVM analysis take account of the PMB performance characteristics over time that would be expected on well-performing construction projects?*
   [Answer] To understand the significance of variances from the PMB (i.e. SV) on construction performance, the performance characteristics over time must be considered.
9. *Is there a deterministic connection between the actual cost curve and the PMB? Is the baseline assumption that the PMB and the actual curve are identical always correct?*
   [Answer] There is a deterministic connection between the PMB and the actual cost curve. In the case of assumed uniform productivity, the Actual planned resource curve will, as a baseline, match the PMB. In the case of variable productivity, the RPI will dictate differing profiles. [8, p 95]
10. *Instead of arbitrary statistical thresholds, is there a deterministic basis for performance-based thresholds which could be relied on to evaluate performance risk.*
    [Answer] An important threshold relative to PMB (CV) variances is provided by the CPM late curve. It is especially important in evaluating the seriousness of float consumption.
11. *Can past EVM performance inform future time planning and performance in a way that conduces to the creation of more reliable schedules and earlier completion?*
    [Answer] The root causal variance information revealed by Equation 1, 4 and 5, should inform the activity duration assumptions going forward based on historical variances. EVM is fully integrated with the CPM schedule according to this approach.

Part 3.0 CONCLUSION

As reported at the beginning of this paper, labor productivity in the construction industry has languished for decades, and projects regularly over-run their time and cost targets. EVM has been cited as failing to deliver on its promise to improve results on construction projects. This paper has identified fundamental flaws in existing EVM theory. Despite its expressed objective to achieve the PMB by integrating program, scope and cost objectives, it is really *not* integrated with the schedule; EVM and CPM schedule analysis reside in separate silos. In fact, EVM's focus is on dollar cost performance; not PMB (time) performance, and it is reluctant to speculate on how CV or SV might impact time. Relative to schedule, existing EVM offers limited or no value in CPM analysis, and yet, as Part 2 demonstrates, EVM has the potential to provide root causal analysis that is essential to understanding schedule performance.

It turns out that in terms of the duration of performance-based activities such as labor, a renowned economist was correct when he observed: "*Productivity isn't everything, but in the long run, it is almost everything*."[70] More correctly, it is productivity *and* resource supply which determine time. Productivity is centrally important in construction performance analysis because it, along with resources supply, is a root cause of time performance. Moreover, productivity, not duration, determines labor cost (see Equation 9), which is important to understand for those invested in peak performance on construction projects because decisions on resource allocation which could improve time outcomes should not be based on flawed risk assumptions about cost.

The deterministic formula, which connects duration (time output) to the root causal productivity and resource inputs, is provided in Equation 1. This new equation compelled the new EVM metrics which are introduced here. Given the causal nature of resources, it is surprising that there has not been a Resource Variance. That void is filled with the RV and RPI metrics (Equations 2 and 3). And, armed with the RV and RPI metrics, and informed by the causal duration formula, a new EVM formula was introduced (Equations 4 and 5) which connects SV (output) variance to the causal input variance metrics (CV and RV). Assuming a fully resource loaded CPM schedule is available, these new formulas make possible the full and complete integration of schedule and EVM. In Part 2, a worked example of this fully integrated analytical approach was provided.

A new, and fundamentally changed, understanding of the casual chain with respect time delay logically follows from the causal duration formula. The problem with the existing causal chain was that it mixed proximate causes (delayed RFI's, adverse weather, etc.) with direct causes (productivity and resources). However, in order for activity duration to be affected, productivity and/or resources must be affected in accordance with Equation 1. If neither of these root causal input factors are affected, then a proximate cause will not affect duration.

Can the paradigm of failed performance be changed? These new EVM analytics integrated with CPM schedules are necessary, but will not be sufficient, unless the quality of schedules is improved and schedules are fully loaded with resources - especially labor hours. Performance experts can point the way, but buyers of construction control the rules of the game, and so can dictate change. Now armed with effective analytics, customized for construction, the gauntlet it thrown down to owners to demand EVM and schedule analysis that will reveal the performance truth, and thereby create transparency and accountability, which is required to improve time and cost outcomes.

.

[70] Paul Krugman, Professor of Economics and International Affairs Emeritus at Princeton University

REFERENCES

[1] McKinsey Global Institute, “Reinventing Construction: A Route to Higher Productivity”, February 2017.
[2] Practice Standard for Earned Value Management, Second Edition, Project Management Institute.
[3] David Christensen, and Scott Heise, “Cost Performance Index Stability”, National Contract Management Journal, Vol. 25, National Contract Management Association, Arlington, VA, 1993.
[4] Total Cost Management Framework—“An Integrated Approach to Portfolio, Program, and Project Management”, 5th Edition, 2006, AACE International.
[5] K. R. MacKrimmon and C. A. Ryavec, “An Analytical Study of Pert Assumptions”, Memorandum RM-3408-PR, The RAND Corporation, December 1982.
[6] Hannah Fry,” Your Number’s Up”, The New Yorker, September 9, 2019.
[7] O’Brien, Farris, Plotnick, Wickwire, “Critics can’t Find the Logic in many of Today’s CPM Schedules”, Engineering News-Record (ENR), May 26, 2003,.
[8] J. G. Boyle (author), A. Podolny, Dr. W. Menesi, “Evaluating CPM Schedules for Best Practices: A First Principles Approach”, PS.2324, 2016 AACE International Technical Paper.
[9] AACE International Recommended Practice No. 56R-08, Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Building and General Construction Industries, Morgantown, WV: AACE International, Latest Revision.
[10] AACE International Recommended Practice No. 27R-03, Schedule Classification System, Morgantown, WV: AACE International, Latest Revision.
[11] AACE International Recommended Practice No. 29R-03, Forensic Schedule Analysis, Morgantown, WV: AACE International, Latest Revision.
[12] Lawrence C. Miller, “Successful Management for Contractors”, McGraw-Hill book Company.
[13] J. Gerard Boyle, “Rethinking Earned Value & Schedule Management on Construction Projects – Solving the World’s Construction Performance Problem”, (Friesen Press, 2021).
[14] “Skills and Knowledge of Cost Engineering”, 5th Edition, AACE International, Chapter 16, “Tracking Cost and Schedule Performance”, Dr. Joseph J. Orczyk.
[15] The Electronic Industries Alliance (EIA) 748 Earned Value Management Systems Revision ‘D’ (EIA-748-D).
[16] AACE International Recommended Practice No. 80R-13, Estimate At Completion (EAC), Morgantown, WV: AACE International, Latest Revision.
[17] AACE International Recommended Practice No. 86R-14, Variance Analysis and Reporting, Morgantown, WV: AACE International, Latest Revision.
[18] Gary C. Humphreys, Humphreys Associates, “Project Management Using Earned Value, Fourth Edition”, (2018).
[19] Fleming, Quentin W.; Joel M. Koppelman. Earned Value Project Management - Fourth Edition . Project Management Institute. Kindle Edition. Location No. 2653 – 2676.