

# Investigation of the Earned Value Method (EVM) Applicability for Construction Operations Affected by the Learning Phenomenon



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**Abstract** The Earned Value Method (EVM) has been extensively applied for the analysis of construction projects. However, in cases where the productivity is not constant, but rather varies due to accelerations attributed to the learning phenomenon, it is challenging to assess the implications on productivity estimation and forecasting. In that sense, such an investigation is crucial for the scheduling and coordination of the remaining works in a realistic manner. The purpose of this paper is to compare the progress reporting results using the Earned Value method both for the theoretical project time schedule (without learning) and the actual on-site scheduling following the learning curve. A real, large-scale infrastructure project is used as a case study. The research method involved the “transformation” of productivity data to cost data, with the purpose of quantifying the productivity improvements through the use of statistical learning models. The straight-line model was used, due to its wide acceptance in related studies. An algorithmic approach is developed and assessed via, inter alia, the Schedule Variance (SV) and the Cost Variance (CV) indices. The results of the research indicate that EVM is significantly affected by the learning phenomenon,

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,  
[https://doi.org/10.1007/978-981-15-1910-9\\_20](https://doi.org/10.1007/978-981-15-1910-9_20)

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which, if neglected, leads to ineffective decision making procedures, regarding the deployment of project resources.

**Keywords** Earned Value Method · Construction productivity · Estimation · Learning curves

## 1 Introduction

Contemporary construction projects are complex ventures that can be affected by learning. Learning is a process which may result in increased productivity during the course of each activity, affects the effectiveness of teams and increases efficiency of future construction activities (Afshari et al. 2019). All organizations compete on time and cost effectiveness, therefore it is of critical importance to be able to accurately forecast the project duration and deliver according to the promised schedule (Panas and Pantouvakis 2010). However, the learning effect (stemming either from the crew-level or senior project executives) is rarely taken into account in evaluating project progress, since current project management tools assume that productivity is a constant function over time (Anbari 2003). A typical example of such an approach is the Earned Value Method (EVM) or Earned Value Analysis (EVA), one of the most popular multidimensional project management systems that has been successfully used in many construction projects since the 1960s (Olawale and Sun 2015).

The assumption of constant productivity makes EVM ineffective on projects affected by knowledge and learning, especially in construction projects which entail “sufficiently complex”, repetitive activities (Thomas 2009). In such projects, the average experience and resulting performance of the project team increases at a fast pace, which is called the “Learning Rate”. Due to the learning effects the project team’s performance will continue to increase. Therefore, if “non-linear” factors are excluded from the analysis and the duration is estimated from the linear factors only, the project manager would presume that the performance would stay at a low level until the end of the project and would add more resources in order to compensate for this (Plaza and Turetken 2009). This paper aims at factoring in both the non-linear performance and the learning rate by proposing a project management method that takes into account the learning effect in evaluating project progress. A large-scale infrastructure marine project has been used as case study for the research. It is, to the authors’ best knowledge, the first research attempt to investigate thoroughly the combined implementation of Earned Value Analysis and learning curve theory in marine works from a productivity stance.

The structure of the paper is as follows: First, background information on pertinent research on learning curve theory and Earned Value Method is going to be provided, followed by a concise description of the construction process that served as the research tested. Then, the research methodology is going to be delineated and,

subsequently, the research results will be presented. The main inferences emerging from the study will be described and, finally, the delineation of future research directions will conclude the study.

## 2 Background

### 2.1 Learning Curves

Learning curves are used for the graphical representation of the time span, the cost and/or the labour hours that are required for the execution of a series of “sufficiently complex” construction activities (Pellegrino and Costantino 2018). The learning curve theory suggests that the required time (labour hours) for the production of a single unit (e.g. floor of a high rise building) is incrementally decreasing as a percentage of the time that was demanded for the production of the previous unit (Panas and Pantouvakis 2018). This percentage is called “learning rate” and is a characteristic variable for the extent of the learning phenomenon in a single construction activity (Thomas et al. 1986). From a mathematical point of view, the learning rate coincides with the inclination of the learning curve. The smaller the value of the learning rate, the more intense the learning phenomenon, since each subsequent production cycle is a smaller percentage of the time required for the previous production cycle. For instance, when the learning rate equals 80%, then the required labour-hours for the production of a single unit is 20% less than the time needed for the production of the previous unit. If an activity presents a learning rate equal to 100%, then no learning phenomenon is developed for that specific task.

The learning curve theory may be applied to the effort (typically measured in units of time) related to individual units or to the cumulative average time to complete a number of units (Lee et al. 2015). The learning curve phenomenon is studied through the use of specific mathematical models, which interpret the variation of productivity in relation to critical factors such as the number of units. Although there have been many models presented in published literature, this research adopts the straight-line model, which has been proven to provide very satisfactory results in construction productivity studies (Thomas et al. 1986; Everett and Farghal 1994). A simplified mathematical expression for the estimation of productivity via the straight model is

$$k_n = k_1 * n^b = k_1 * n^{(\log LR / \log 2)},$$

where  $k_n$  = total time or cost for n-th unit;  $k_1$  = total time or cost for the first unit;  $n$  = number of units produced;  $b = \log LR / \log 2$ ;  $LR$  = learning rate.

## 2.2 Earned Value Method

The Earned Value method has been developed as a tool facilitating project progress control. It can determine the project's current status and the scale of current variances from the plan. It also extrapolates current trends and makes inferences on the final effect on the project time and cost. The basic concepts of the Earned Value Method are depicted on Fig. 1 (Czarnigowska 2008). An EVM analysis requires following inputs (assuming "T" is the planned duration of the project) and calculation of project status indicators:

- **BCWS (Budgeted Cost of Work Scheduled):** it represents the baseline for the analysis, by cumulating planned costs related to time of their incurrence. It is also called "Planned Value".
- **BCWP (Budgeted Cost of Work Performed):** it is a measure of physical progress of works expressed by cumulated planned cost of works actually done related to time. It is also called "Earned Value".
- **ACWP (Actual Cost of Work Performed):** it is the cumulated amount payable for works done related to time. It is also called "Actual Value".
- **BAC (Budget at Completion):** it is the total planned cost of the whole project. It equals BCWS at the planned finish.
- **PC (Percentage Complete):** it is calculated as  $PC = BCWP/BAC$ .
- **CV (Cost Variance):** it is a measure of deviation between planned and actual cost of works done until the date of recording progress in money units. If  $CV < 0$ , then the project is over budget. It is calculated as  $CV = BCWP - ACWP$  and  $CV(\%) = CV/BCWP$ .
- **SV (Schedule Variance):** it is a measure of deviation between the actual progress and the planned progress. Though it is interpreted as time deviation, it is expressed

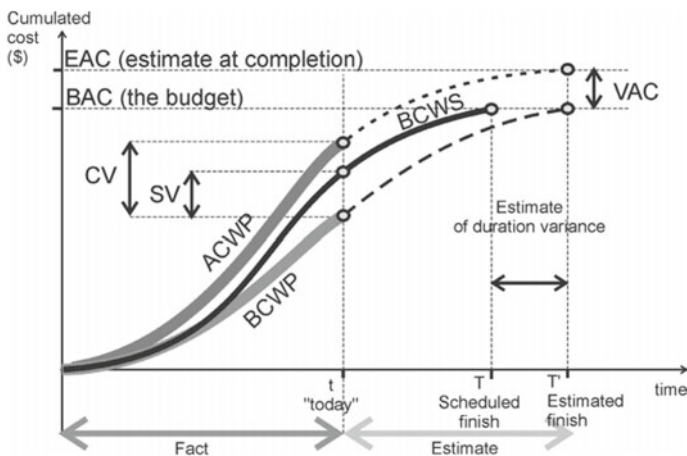


Fig. 1 Graphical representation of EVM concepts (adopted from Czarnigowska 2008)

in money units. In other words, it is the difference between the planned cost of works that have been done and planned cost of works that should have been done by the reporting date. If  $SV < 0$ , then the project is behind schedule. It is calculated as  $SV = BCWP - BCWS$  and  $SV(\%) = SV/BCWS$ .

- **EAC (Estimate at Completion)**: it is calculated at the date of reporting progress (i.e. control point) to serve as an estimate of the effect of deviations cumulated from the project’s start on the total project cost, so it informs how much the project is going to be in the end, for a constant productivity. It is calculated as  $EAC = ACWP/PC$ .

### 2.3 Caisson Construction Operations

In general, floating caissons are prefabricated concrete box-like elements with rectangular cells that are suited for marine and harbor projects and are usually cast on floating dry docks (Panas and Pantouvakis 2014). Due to the standardized shape of the caissons and the repetitive nature of the works, since caissons are always constructed in batches, the concreting process is most commonly executed with the use of the slipforming construction technique. Slipform is a sliding-form construction method, which is used to construct vertical concrete structures (Zayed et al. 2008). Generally, the concreting and slipforming process comprises three sub-phases (see Fig. 2): (i) slipform assembling phase, (ii) slipforming phase (including an initial concreting phase) and (iii) slipform dismantling phase. Although Pantouvakis and Panas (2013) identified nineteen activities for the construction of a caisson, this study focuses only on the aforementioned activities, because a fundamental prerequisite for the learning phenomenon to develop is for productivity improvements to be able to occur as a result from repeating “sufficiently complex” activities (Thomas 2009). As such, in the case of caissons construction operations, only these activities were found to inherently possess such characteristics, since the observed productivity of the other activities did not fluctuate significantly during the construction phase. The selected project under study was executed in 2015 and comprised the construction of 40 caissons.



Fig. 2 Floating caisson production cycle

### 3 Research Methodology

The research methodology is depicted in Fig. 3, while an analytical description of the implemented steps follows in the next paragraphs.

- **Step 1—Field data management:** All field data from the case study project (caisson construction) are entered in an electronic database and categorized in two types—time data (labour workhours, days based on project calendar) and cost data (cost per caisson, equipment/labour costs).
- **Step 2—Specification of work scenarios:** There are two main work scenarios. The first one represents a theoretical time scheduling scenario where the productivity unit rates are determined based on average values and are held constant (no improvement or deterioration) during the whole project duration. The second scenario is a historical record of the actual productivity (time/cost) data of the project. In addition, progress evaluation milestones or control points are specified. In our case, progress controls were performed every 10 caissons.
- **Step 3—Production of Gantt charts:** The two aforementioned scenarios are graphically represented in a Gantt chart, so as to be able to visually compare the achieved progress. The assumed productivity is measured on a crew-level and does not refer to management or team members.
- **Step 4—Earned Value Analysis:** All metrics presented in the previous section (i.e. BAC, BCWS, PC, ACWP, BCWP, SV, SV%, CV, CV%, EAC) using data stemming from both work scenarios. The comparative analysis of the results will enable the assessment of the learning phenomenon impact on productivity in terms of the Earned Value.
- **Step 5—Learning model implementation:** The straight-line model is going to be implemented so as to determine the Learning Rate (LR) at the control points, namely the progress evaluation milestones set at every 10 caissons. The solver function of MS Excel has been used in conjunction with the least squares method, so as to determine the optimum Learning Rate value at each milestone.
- **Step 6—Comparative analysis:** A comparison of the theoretical (no learning) and actual (learning prone) scenarios delineates the variations in productivity from the Earned Value perspective. As such, the project manager is provided with valuable

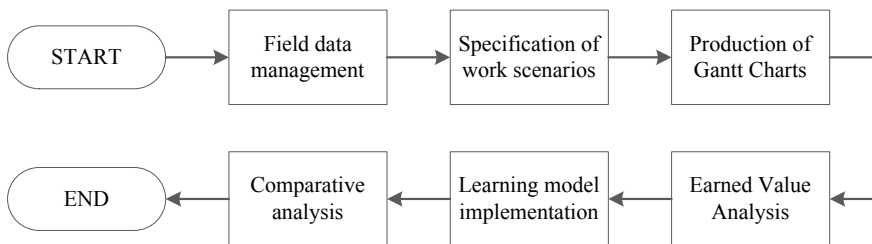


Fig. 3 Research methodology

information that quantifies the learning effect on project progress which directly affects decisions relating to the amount of deployed resources.

## 4 Results

### Step 1—Field data management

The electronic database contains grouped field data which depict the workhours per caisson, the cost per caisson and the time period (in days) that is required for the completion of each caisson.

In addition, the cumulative work-hours and cost is estimated along with the cost per day per caisson. For brevity reasons, Table 1 presents an excerpt of the created database for the first 10 caissons. In total, 71,255.35 labour-hours were required, with a total cost of 943,822.56€ and a total duration of 626 days for the construction of all caissons.

### Step 2—Specification of work scenarios

The actual scenario is easily derived from the historical project data contained in the respective database. The theoretical scenario required the determination of constant unit rates and productivity data, as stated above. In order to increase the research validity the estimated productivity data were not set arbitrarily, but stemmed from the average values of the first four caissons, which represent the 10% of the whole project (4 out of 40 caissons). In addition, the first units are not heavily affected by the learning phenomenon, because it has not been fully developed yet. Taking into account the aforementioned assumptions, Table 2 was constructed as follows:

Therefore, the theoretical scenario is built upon (a) 2482.13 total labour-hours per caisson, (b) 32,874.96€ average total cost per caisson, (c) 18 actual productive days per caisson (rounded up to the next integer from 17.25 → 18), (d) 23 total calendar days (including any delays, disruptions etc.) per caisson (rounded up to the next integer from 22.75 → 23) and (e) 1429.35€ average labour cost per day per caisson (derived from 32,874.96€/23).

### Step 3—Production of gantt charts

Due to limited space, an excerpt of the actual and theoretical Gantt Chart for the first six caissons is presented in Fig. 4a/b. It is evident, that there is a “delay” in the project progress for the first two caissons, which is absorbed though by the improvement in the completion of the next pair of caissons due to the learning phenomenon. On the other hand, the theoretical scenario presents a constant productivity rate, as expected.

At this point, we should highlight that the observed delay was attributed to the lower sliding rate due to the initial learning rate. As the learning rate improved, the sliding rate improved as well. Indicatively, sliding operations started with an average sliding rate of approx. 12 cm/h and the project was completed with an average sliding

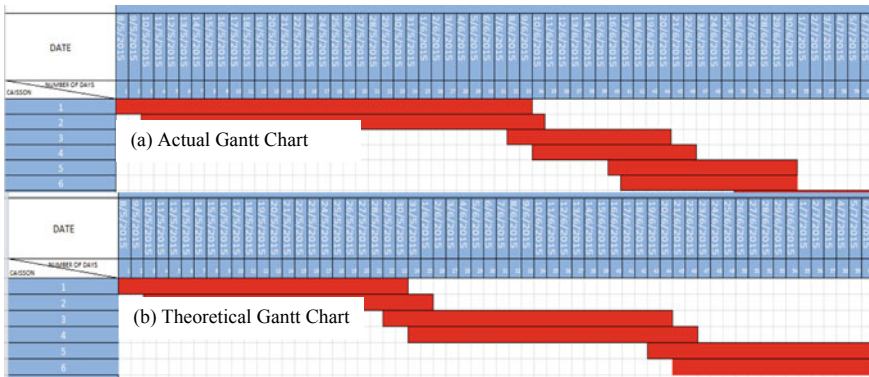
**Table 1** Field data representation in the project database

| Caisson | Labour-hours/caisson | Cost (€)/caisson | Days/caisson | Cost (€) (cumulative) | Labour-hours (cumulative) | Cost (€)/day/caisson |
|---------|----------------------|------------------|--------------|-----------------------|---------------------------|----------------------|
| 1       | 2,976.33             | 39,314.38        | 33.00        | 39,314.38             | 2,976.33                  | 1,191.34             |
| 2       | 2,890.50             | 38,328.44        | 32.00        | 77,642.81             | 5,866.83                  | 1,197.76             |
| 3       | 1,947.00             | 25,806.72        | 13.00        | 103,449.53            | 7,813.83                  | 1,985.13             |
| 4       | 2,114.67             | 28,050.31        | 13.00        | 131,499.84            | 9,928.50                  | 2,157.72             |
| 5       | 1,824.50             | 24,146.56        | 15.00        | 155,646.41            | 11,753.00                 | 1,609.77             |
| 6       | 1,770.83             | 23,442.19        | 14.00        | 179,088.59            | 13,523.83                 | 1,674.44             |
| 7       | 1,718.00             | 22,742.50        | 15.00        | 201,831.09            | 15,241.83                 | 1,516.17             |
| 8       | 1,667.67             | 22,081.88        | 12.00        | 223,912.97            | 16,909.50                 | 1,840.16             |
| 9       | 1,675.00             | 22,215.63        | 35.00        | 246,128.59            | 18,584.50                 | 634.73               |
| 10      | 1,535.00             | 20,309.38        | 32.00        | 266,437.97            | 20,119.50                 | 634.67               |



**Table 2** Average productivity values based on first four caissons

| Caisson | Total labour-hours | Total cost (€) | Actual days/caisson | Total (calendar) days/caisson |
|---------|--------------------|----------------|---------------------|-------------------------------|
| 1       | 2,976.33           | 39,314.38      | 23.00               | 33.00                         |
| 2       | 2,890.50           | 38,328.44      | 22.00               | 32.00                         |
| 3       | 1,947.00           | 25,806.72      | 12.00               | 13.00                         |
| 4       | 2,114.67           | 28,050.31      | 12.00               | 13.00                         |
| Average | 2,482.13           | 32,874.96      | 17.25               | 22.75                         |



**Fig. 4** a Actual gantt chart. b Theoretical gantt chart

rate of almost 30 cm/h. No other factors were statistically significant in influencing the achieved on-site productivity.

**Step 4—Earned value analysis**

The Earned Value Analysis was implemented for the labour cost, while the control points were set (as already explained) at 10, 20, 30 and 40 caissons. BAC, BCWS, PC and ACWP must be estimated and the rest of the EVM metrics (ACWP, BCWP, SV, CV, EAC) can be calculated subsequently. The budget at completion (BAC) is estimated by multiplying the average total cost by the total number of caissons to be constructed, i.e.  $BAC = 40 * 32,874.96€ = 1314,998.44€$ . The Budgeted Cost of Work Scheduled (BCWS) should be calculated by multiplying the average labour cost per day per caisson (1429.35€) by the amount of constructed caissons and the required time (in calendar days) for their completion.

For example, we know that the first 10 caissons were completed on 10th August 2015 (control point on the actual Gantt Chart). On the theoretical Gantt Chart, on the same day, it was programmed that 8 caissons would be completed with an average of 23 calendar days per caisson and some works on the 9th and 10th caisson would already have started, which represent an additional time period of 20 calendar days. Therefore, for the first 10 caissons  $BCWS = 1429.35 * (23 * 8 + 20) = 291,586.61€$ .

**Table 3** Earned value analysis data

| Control point | BAC (€)      | BCWS (€)   | PC (%)     | ACWP (€)   | BCWP (€)     |
|---------------|--------------|------------|------------|------------|--------------|
| 10 caissons   | 1,314,998.44 | 291,586.61 | 25%        | 274,959.04 | 328,749.61   |
| 20 caissons   | 1,314,998.44 | 451,673.38 | 50%        | 516,793.21 | 657,499.22   |
| 30 caissons   | 1,314,998.44 | 586,031.91 | 75%        | 736,372.36 | 986,248.83   |
| 40 caissons   | 1,314,998.44 | 708,955.68 | 100%       | 943,822.56 | 1,314,998.44 |
| Control point | SV           | SV%        | CV         | CV%        | EAC (€)      |
| 10 caissons   | 37,163.00    | 12.75%     | 53,790.57  | 16.36%     | 1,099,836.16 |
| 20 caissons   | 205,825.84   | 45.57%     | 140,706.01 | 21.40%     | 1,033,586.42 |
| 30 caissons   | 400,216.92   | 68.29%     | 249,876.47 | 25.34%     | 981,829.81   |
| 40 caissons   | 606,042.76   | 85.48%     | 371,175.88 | 28.23%     | 943,822.56   |

The Percent Complete is estimated proportionally according to the pace of works (i.e.  $PC(10) = 10/40 = 25\%$ ).

The Actual Cost of Work Performed is derived from the actual Gantt Chart (Fig. 4a), where the actual direct labour cost is estimated for each day and then cumulatively added up to each control point. For brevity reasons, the analytical calculations for all metrics are omitted and indicative calculations are presented for the first 10 caissons (Table 3).

$$BCWP = PC * BAC = 25\% * 1,314,998.44\text{€} = 328,749.61\text{€}$$

$$SV = BCWP - BCWS = 328,749.61\text{€} - 291,586.61\text{€} = 37,163.00\text{€}$$

$$SV\% = SV/BCWS = 37,163.00\text{€}/291,586.61\text{€} = 12.75\%$$

$$CV = BCWP - ACWP = 328,749.61\text{€} - 274,959.04\text{€} = 53,790.57$$

$$CV\% = CV/BCWP = 53,790.57\text{€}/328,749.61\text{€} = 16.36\%$$

$$EAC = ACWP/PC = 274,959.04\text{€}/25\% = 1,099,836.16\text{€}$$

### Step 5—Learning model implementation

The straight-line learning model was implemented to simulate the construction of all 40 caissons. The estimation of the Learning Rates at the 10, 20, 30 and 40 caissons control points yielded 83.50%, 84.30%, 85.17% and 85.89% respectively. It is evident that the LR was more intense for the first batches of caissons and it smoothed as the construction process neared completion. It should be noted that all construction and operational parameters were held constant throughout the project duration, namely construction process, main equipment (e.g. floating barge) and crew composition.

### Step 6—Comparative analysis

The improvement of productivity in the studied construction process due to the development of the learning phenomenon was evidently proven by the EVM metrics. It is very characteristic that the budgeted cost based on the average values of the first four caissons (1,314,998.44€) for the theoretical works scenario (no learning) was ~40% higher than the actual cost of works performed (943,822.56€) under the influence of the learning phenomenon. In addition, the Schedule Variance indicates that the project was ahead of schedule ( $SV > 0$ ) even from the first 10 caissons. Same

goes for the Cost Variance as well, namely the project was under-budget ( $CV > 0$ ) from its essential beginning. In fact, both SV and CV metrics incrementally increased, which means that there was a constant improvement in productivity throughout the course of the project. The latter highlights the importance of the achieved Learning Rate, as stated above.

It should be noted that numerous other factors may affect the achieved on-site productivity per se, since the activities were executed in an open environment which is prone to other influencing factors that can deviate the project performance. In our case though, no significant changes have been observed to either operational or managerial factors. In other words, the main operational framework for the execution of the works was held unchanged during the project duration. All project crews started and finished the project with the same composition. Same goes for the deployed equipment and materials, as stated above. In addition, a quantitative statistical analysis was performed to identify any significant correlations of productivity to other factors, without ultimately getting any such indication. In that sense, it was derived that the main productivity driver for the observed improvements was the achieved learning rate. The latter is also corroborated by the improvement rates in the examined learning models. This direct relationship of learning and productivity improvement is reflected on the EVM metrics and highlights the significance of this research.

## 5 Conclusions

The research intended to interpret Earned Value Method metrics under the effect of learning phenomena for complex construction operations. The research framework was presented in a step-wise fashion and its implementation was conducted for a large-scale infrastructure project which served as a case study. The estimations evidently proved that if learning effects are not included in the analysis, then planning becomes unreliable. The most important issue is that neglecting learning effects leads to a false project progress assessment, since the classic EVM approaches assume a constant productivity rate throughout the project duration. However, under the influence of the learning effect, the productivity is gradually improving, leading to significant savings in time and cost as demonstrated in the previous section.

In terms of their applicability, the examined models are well established in relation to their internal mathematical robustness. However, it should be highlighted that research results cannot be extended beyond the scope of the studied construction process and with similar operational parameters (e.g. construction method, equipment etc.). In that framework, it would be practical to gradually examine the introduction of the studied learning models to “similar” activities, namely high-rise constructions such as silos or industrial chimneys.

On any case, however, the research has clearly demonstrated that, if learning is not taken into account in EVM analyses, there is a risk of misjudging project progress and deciding to enhance its resources to the detriment of the project’s cost. Of course, the EVM analysis should be based on reliable data which may be

difficult to gather or handle especially in large-scale construction projects. As such, the implementation of the learning models should be aligned with the organisation's managerial maturity in order to ensure sufficient support (e.g. IT, backoffice, PM Office) along the project duration. In general, project managers should always assess how prone to learning phenomena the project activities are, before taking managerial decisions that affect the deployment of project resources. Possible extensions of the current research approach could be the development of a software tool that would be able to capture real-time project progress data and through the implementation of one or more learning curve models yield EVM metrics that are realistic and dynamically estimated. In addition, the computational capabilities of the algorithmic approach could be enhanced by the addition of stochastic tools, such as discrete-event simulation, in order to overcome the limitations of the deterministic statistical analysis.

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