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A Systematic Review of Earned Value Management Methods for Monitoring and Control of Project Schedule Performance: An AHP Approach

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Abstract: Successful project management depends on ensuring the project's objectives. Within these objectives, technical success is associated with achieving the expectations of the project baseline. The baseline of the project is made up of the definition of the scope (WBS), time (schedule) and costs (S curve) of the project. Directly, the project is expected to be technically successful if it manages to deliver its full scope on schedule and without associated cost overruns. Baseline performance management is how project managers track and control the progress of deliverables, timelines and associated costs. In a traditional approach, for waterfall-type projects that use the critical path paradigm, the baseline performance management tool par excellence is earned value management (EVM). Earned value management, in practice, works well when project costs are monitored and controlled; however, applying this approach to measure the status of the schedule presents serious inconsistencies. Over the last several decades, different variations of the original earned value have been developed to overcome some of these inconsistencies when used to measure project schedule status. Within these variations, we have the critical path earned value; the work in progress earned value; the critical path earned value and the work in progress; the earned schedule; and the critical path earned schedule. Each of these proposals tries to address some weakness of the original earned value management applied to time monitoring and control, for example, considering critical tasks as a focus on monitoring the progress of the schedule, solving the problem of task recognition late finishers, reporting schedule variances in time units and measuring adherence to the project's schedule (P factor). Due to the exposed situation, it is necessary to determine which alternative of the versions of the original earned value is the most appropriate for the management of the project schedule, considering that there are several evaluation criteria that must be considered. In the present research, a systematic review and comparison of EVM and its variations for measuring project baseline schedule performance are performed to determine the most suitable methods for monitoring and controlling the project baseline schedule. For this purpose, the analytic hierarchy process (AHP) is used, and five comparison criteria are considered: schedule variation focused on critical tasks, recognition and measurement of the delay of tasks that finish late, schedule variation in time units, measurement of schedule adherence (P factor) and software support and development. The result of the AHP performed for comparing the methods shows that the best method for monitoring and controlling the project baseline schedule is the critical path earned schedule because it behaves adequately in comparison with the other methods for the evaluated comparison categories.

Keywords: earned value management (EVM); baseline performance management; project scope; project baseline schedule; project monitoring and control; earned schedule (ES); analytical hierarchical process

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1. Introduction

The project baseline is derived during the planning and scheduling of a traditional project using the critical path approach—which is derived from results or deliverables (scope), tasks and activities that would be performed over time (schedule) and the project budget (S curve). Project status is monitored and controlled following its performance in comparison to the proposed project baseline. Earned value management is the method of choice for this monitoring. The concept of earned value is associated with the measurement of the work (scope) performed at the proposed cost, and when it is combined with the joint measurement at the baseline (scope, schedule and cost), it is referred to as earned value management (EVM) [1].

Earned value management can adequately identify and estimate cost overruns and savings in project execution. However, using this method to monitor and control schedule variations is inadequate. Delays and/or advances in the duration of tasks and/or activities could not be adequately identified with the original earned value management. There are multiple scenarios where monitoring and controlling the schedule through earned value are inadequate [2,3].

Earned value management does not solely focus on the critical tasks of the project. It includes all tasks, both critical and non-critical, while it is the project's critical path that plays a predominant role in determining the total project duration. The critical path is the extended sequence of activities without slack (zero slack) known as critical tasks. This implies that monitoring and control of the project schedule progress should focus on these critical tasks because they have no room for delay, and a delay in one of these steps delays the whole project [2]. In the execution of project tasks, some tasks may finish late. However, the original earned value method would be unable to identify such delays, and the schedule management indicators would show an optimal value even after the delayed task (schedule variance: SV = 0 or schedule performance index: SPI = 1) when it is not.

In the original earned value management, it is not possible to report schedule variations (advances and delays) in time units; this is done in monetary units, which limits the understanding of the dimension of these variations [3]. The original earned value management does not allow tracking schedule adherence (the performance factor: P factor), i.e., monitoring how what was completed should have been completed. Based on these drawbacks, several variations to the original earned value management have been developed in recent decades to address and overcome some of the difficulties described in the proper use for monitoring and control of the project baseline schedule [4].

The present research study includes a detailed systematic review of the original earned value management and its five variations: the critical path earned value; work in progress earned value; critical path earned value and work in progress; earned schedule; and critical path schedule. In addition, a comparison of these methods is made using the analytic hierarchy process (AHP), considering five comparison criteria: schedule variation focused on critical tasks, recognition and measurement of the delay of tasks that results in delayed project, schedule variation in time units, measurement of schedule adherence (P factor) and the support and development of software to determine which of the methods is adequate for monitoring and control of a project baseline schedule.

2. Literature Review

2.1. Project Baseline Definition and Performance Management

In today's competitive and globalized world, companies define their business vision and deploy strategies to achieve their short-, medium- and long-term objectives. For the implementation of these strategies, investment projects are formulated and proposed. Once prioritized, evaluated and approved, traditional investment projects must be executed. The success of the strategy ultimately depends mainly on the success of the projects. A waterfall project with a critical path approach is technically successful if it essentially meets its triple objectives: scope, time and cost. These constraints on the project must be managed jointly and integrally. The "Project Baseline" is defined for this purpose, which includes the scope, schedule and cost baselines and should be controlled throughout the project life cycle. The scope baseline includes all work performed and is defined in the work breakdown structure (WBS) and the WBS dictionary. The time baseline determines the tasks and activities to be performed; their duration, dependencies, sequence, overlaps or mismatches and are scheduled with the project evaluation and review technique (PERT)/critical path method (CPM) approach and defined in a schedule of tasks or Gantt.

The cost baseline determines the project's cost by estimating the costs associated with each scheduled task and calculating the cumulative cost during the schedule period to determine the project's S curve. The logical sequence of the determination of the project baseline is first to define "what results" are to be achieved in this project, i.e., determine the scope (WBS). Then, decide "how the deliverables are to be completed", i.e., define the tasks or activities and sequence them in a schedule (Gantt), and finally define "how much it cost", i.e., estimate the costs associated with the defined tasks and then accumulate the recurring costs according to the schedule to determine the project cost (S curve).

2.2. Earned Value Management (EVM)

Project monitoring and control involve knowing how to answer the following questions: expected completion date of the project; expenses incurred on the project so far; and the total cost of project completion.

To answer these questions, one must be aware throughout the duration of the project whether the project is on schedule (time), on budget (cost) and how much work has been done (scope). The traditional analysis of the deviations of a management variable consists of comparing and measuring the gap between the planned value and the actual value of that variable. For example, you could compare the actual accumulated cost of the project vs. the proposed cost of the same and try to determine the variation in the cost of the project; however, this analysis is incomplete as one may have spent 90% of the budget but only 50% of the project has been completed. In other words, this traditional cost analysis does not indicate whether the project is going well, since it does not provide information on the work executed (scope completed) [4].

In the above-mentioned traditional analysis, only two variables are being compared: the planned value (PV), which is the budgeted cost of the planned work and the actual value (AC: Actual/Real Cost), which is the actual cost of the work performed. The plan value (PV) is associated with and represents the project schedule in monetary units, and the actual value (AC) is associated with the project's actual cost in monetary units. The gap comparison does not include the third variable: scope of the project. To include it in the gap analysis, its value must first be conditioned to monetary units. This is achieved through the concept of earned value (EV) or the budgeted cost of work performed, which are associated with the project scope variable in monetary units [5].

The term "Earned Value" comes from the idea that each project deliverable has a budgeted cost, its "value". When the deliverable is completed, the "value" is "earned" for the project. Earned value management (EVM) combines the three types of relevant project baseline variables: scope, schedule and budget. For this, it is necessary to calculate three values: (a) planned value (PV), associated with the schedule in monetary units); (b) actual/actual cost (AC), associated with the actual cost in monetary units); and (c) earned value (EV) associated with the scope in monetary units [6].

2.3. Planned Value PV: Budgeted Cost of the Planned Work

The baseline cost is determined, and the initial budget planned to carry out the project (BAC: budget at completion) and is represented through the project's S curve (accumulated costs of the periodic tasks in the project schedule). It indicates the estimated value of everything that is planned to be completed. It can be calculated as:

$$\mathrm{PV} = \mathrm{BAC} \times \mathrm{PW} \tag{1}$$

where PW is the percentage of the planned work.

2.4. Earned Value EV: Budgeted Cost of Work Performed

It is the budgeted (not actual) cost to complete the work that has been performed in time. It indicates the value in the budget of the work performed to date. It can be calculated as:

$$EV = BAC \times WD \tag{2}$$

where WD is the percentage of the work done.

2.5. Actual Cost AC: Actual Cost of Work Performed

It is the cost incurred to perform the work that has been performed to date. It is the actual work cost in time, including direct and indirect costs. It tells us how much the work performed has cost us so far. Its value is $\sum$ (quantities performed x actual purchase price).

2.6. Measuring Performance with Earned Value Management

The use of earned value management works well when comparing project cost gaps through indicators such as cost variance (CV = EV − AC) and/or the cost performance index (CPI = EV/AC). These indicators show whether the project has cost overruns (CV < 0 and/or CPI < 1) or cost savings (CV > 0 and/or CPI > 1) [7]. The measurement of deviations from the project schedule with this approach is obtained through indicators such as SV (SV = EV − PV) and/or SPI (SPI = EV/PV), which show the delay (SV < 0 and/or SPI < 1) or advance (SV > 0 and/or SPI > 1) of the project in monetary units. Figure 1 shows the three curves associated with the PV, EV and AC, as well as the cost and schedule variations in monetary units (y-axis) [7]. The use of this method in project schedule deviations does not correctly address cases of the project and does not use time units to report project advances or delays.

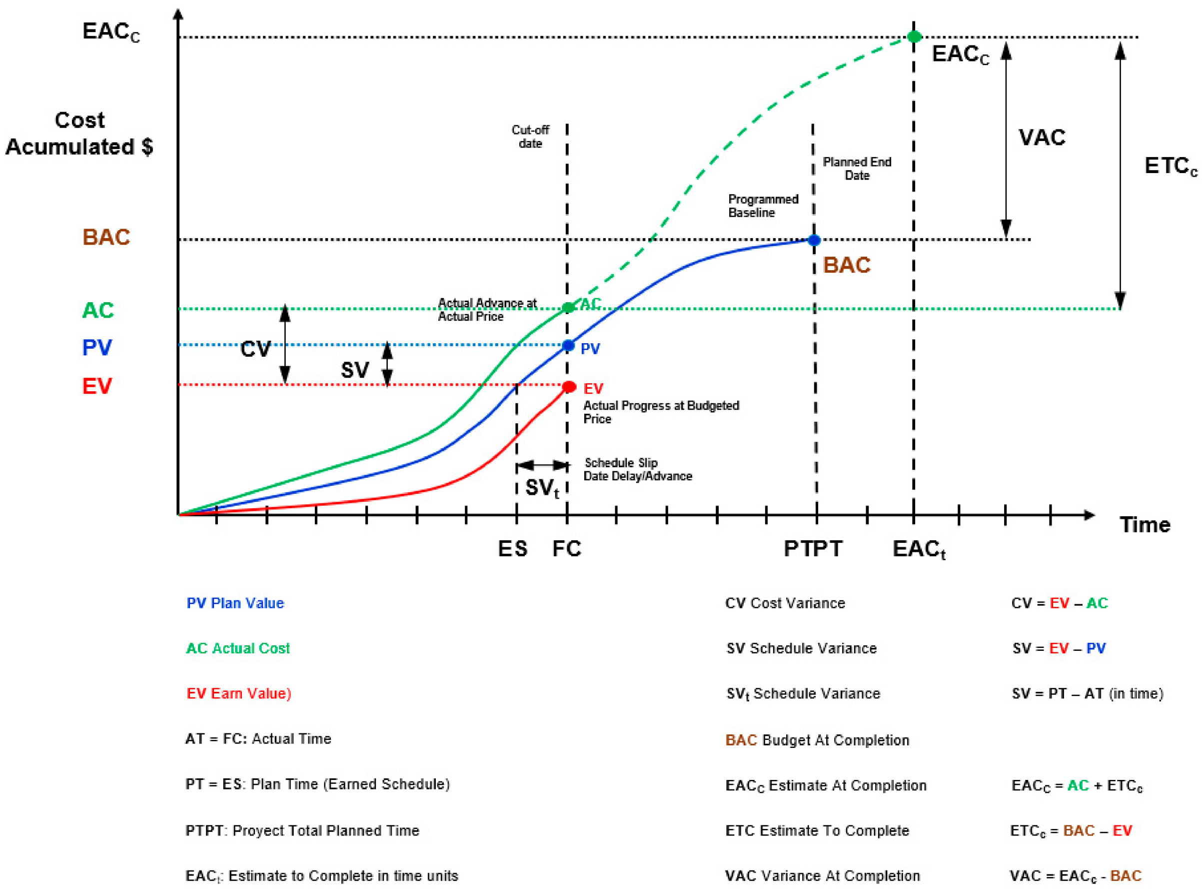


Figure 1. Earned value management: the three curves and cost and schedule variations (source: adaptation and own elaboration).

2.7. Critical Path Earned Value Management (EVM_{RC})

One of the main weaknesses of using traditional earned value management for a schedule variance analysis is taking the project's S curve as a reference. To construct the S curve, the costs of all the scheduled activities must be accumulated. Figure 2 shows the logical sequence of the elaboration of the traditional S curve, highlighting that both "critical" and "non-critical" activities are included in its construction.

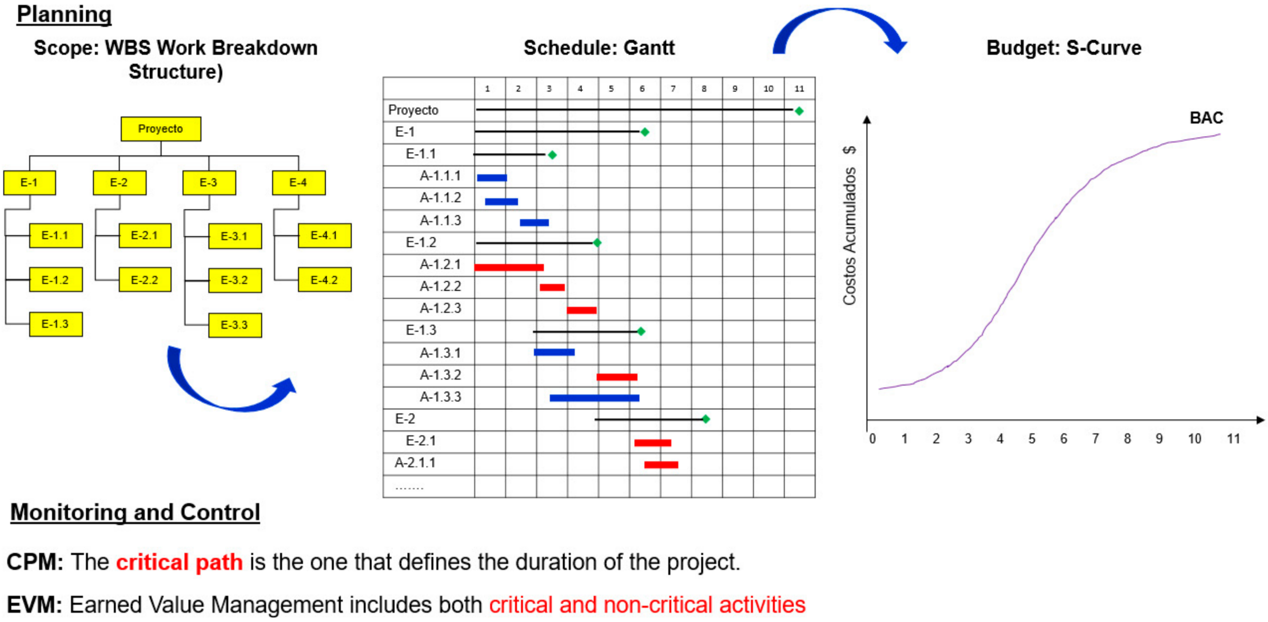


Figure 2. Logical sequence of traditional S curve elaboration (source: adaptation and own elaboration).

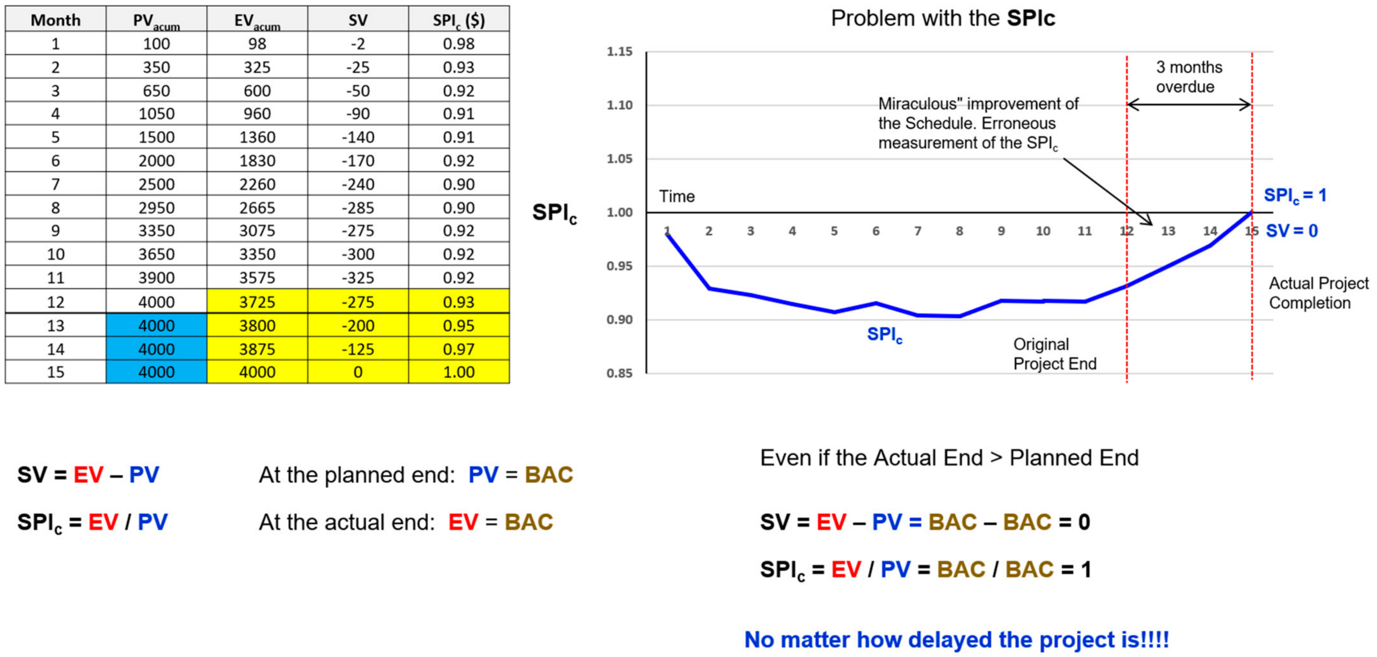
The SV and/or SPI indicators are based on the comparison of earned value [8] with planned value, but the latter value is defined from the project's S curve, and the inclusion of critical and non-critical activities distorts the comparison. On the other hand, the critical path of the project, i.e., the most extended sequence of activities that have zero slack, defines the total duration of the project. This means that the focus of monitoring and control of the schedule should focus on these critical activities because if one of them is delayed the project is delayed. A solution to this impasse is to create the S curve of only the project's critical activities and take this as the basis of comparison for measuring schedule variations. This method is known as critical path earned value management [9].

2.8. Earned Value Management of Work in Progress (EVM_{TC})

Another case in measuring schedule variations is that traditional earned value management cannot recognize and measure the delay in activities (and the project) that finish late. SPI and SV are unable to measure or even record that delay. Both indicators become unreliable after the activity should have been completed but has not been completed and is still ongoing. At the time point when the activity should have been completed, the PV reaches its maximum value (budget at completion: BAC) and remains constant, while the EV continues to increase until the day it ends and reaches its maximum value (BAC). When the activity ends with a delay, and at the time it ends, it is reflected by the following equation:

$$\text{PVaccumulated} = \text{EVaccumulated} = \text{BAC} \quad (3)$$

Figure 3 shows this case in which the planned time of the project was 12 months, but it was not completed on time, which caused a delay of 3 months to complete it. When measuring the classic performance indicators of the schedule such as the SV or SPI, it is observed that the project was always behind with respect to its delivery date (month 12), the variation of the SV schedule was negative because the EV was always less than PV and the schedule performance index (SPI) was always less than 1 for the same reason; however, in month 15, which is the date when the project was completed, they appeared as values optimal, that is, without delay (SV = 0 and SPI = 1), which shows that this indicator does not correctly recognize or measure the delay of activities that finish late.



Month	PV_{acum}	EV_{acum}	SV	SPI_c ($)
1	100	98	-2	0.98
2	350	325	-25	0.93
3	650	600	-50	0.92
4	1050	960	-90	0.91
5	1500	1360	-140	0.91
6	2000	1830	-170	0.92
7	2500	2260	-240	0.90
8	2950	2665	-285	0.90
9	3350	3075	-275	0.92
10	3650	3350	-300	0.92
11	3900	3575	-325	0.92
12	4000	3725	-275	0.93
13	4000	3800	-200	0.95
14	4000	3875	-125	0.97
15	4000	4000	0	1.00

Figure 3. The problem of recognizing and measuring the delay of activities ending late (source: adaptation and own elaboration).

Calculating the SPI of the project and incorporating in its calculation all the activities that have been completed and are in progress would result in a biased result if the activities completed with delays were incorporated. These would be averaged with an SPI = 1, as if they were according to plan, when in fact, they are delayed, and this delay is neither reflected nor measured by the schedule status indicators (SV and SPI) of earned value management. In other words, the result is skewed, misleadingly improving the performance of the project schedule. To make the calculation of the project SPI schedule performance indicators more accurate and honest, it is recommended to exclude completed activities and only consider those in progress, which is essentially earned value management of work in progress (EVM_{TC}) [10].

This approach seeks to mitigate the bias towards an erroneous conclusion by incorporating activities completed late. However, if all completed activities are not considered in general, activities that have been completed ahead of schedule would also be left out, resulting in an undue bias toward negative performance. When applying the earned value management of work in progress (EVM_{TC}) approach, two alternatives and six possible cases must be considered. The first alternative is activities to be taken into account for the calculation of schedule performance indicators (SPI or SV) and can be one of the following four cases: (a) activities that are planned to be completed at the time of the control and are being finished (in progress); (b) activities that at the scheduled date should have been completed but are still pending; (c) activities that are not yet planned to be finished at the scheduled time, but were started earlier than planned and are in progress; and (d) activities that were completed in advance of the time of the control. The second alternative is activities that should not be considered for calculating the schedule performance indicators (SPI or SV) and can be one of the remaining two cases: (e) activities already completed at the time of control (ahead or behind schedule) and whose completion date has passed; and (f) activities that are not planned to be completed at the time of control and that are not being completed. Figure 4 shows the details of these alternatives.

Consider				Do not consider			
Case	**% Progress Plan**	**% Avance Plan**	**SPI SV**	**Case**	**% Progress Plan**	**% Avance Plan**	**SPI SV**
Case 1: Activities that are planned to be done at the time of the control and are **in progress.** These may be ahead or behind schedule (**SPI** of the activity may be **greater or less than 1**).	<100%	<100%	SPI < 1 SV < 0 SPI > 1 SV > 0	**Case 5:** Activities already **completed** at the time of control (ahead or behind schedule) and **whose completion date has passed.** These activities already have **SPI equal to 1.**	=100%	=100%	SPI = 1 SV = 0
Case 2: Activities that at the control date should have been completed but are **still in progress**. The **SPI** of these activities is **less than 1.**	=100%	<100%	SPI < 1 SV < 0				
Case 3: Activities that **are not planned** to be done even at the time of the control but **were started earlier than planned and are in progress.** That is, they are ahead of schedule. For these activities, the **SV** is greater than zero and their **SPI** is **indeterminate**, since **PV** = 0 (**% planned progress** = 0)	= 0%	<100%	SPI: ∞ SV > 0	**Case 6:** Activities that **are not planned** to be done at the time of control and **are not being done.**	= 0%	= 0%	
Case 4: Activities that were **completed ahead of schedule**. That is, they were completed ahead of schedule and whose end date has not yet been reached. The **SPI** of these activities **will be greater than 1.**	<100%	=100%	SPI > 1 SV > 0				

WIP (Cases 1–3)

Undue bias toward **worse performance** (Case 4)

Undue bias toward **better performance** (Case 5)

Figure 4. Criteria to be taken into consideration in defining ongoing activities.

Figure 4 shows the criteria to define the activities in progress and those that are not in progress. Cases 1, 2, 3 and 4 are ongoing activities to be considered, and Cases 5 and 6 are not ongoing activities and should not be considered. The "Case 1: Activities that are planned to be carried out at the time of the control and are being carried out" occurs when both the % plan progress and the % real progress are less than 100%; the "Case 2: Activities that at the date of control must have finished but are still being done" occurs when the % plan progress is 100% and the % real progress is less than 100%; the "Case 3: Activities that are not planned to be done even at the time of the control, but started earlier than planned and are in progress" occurs when the % plan progress is 0% and the % actual progress is less than 100%; the "Case 4 Activities that ended before the time of control" occurs when the % plan progress is less than 100% and the % real progress is 100%; the "Case 5: Activities already completed at the time of control and whose completion date has already passed" occurs when both the % plan progress and the % real progress is 100%; and "Case 6 Activities that are not planned to be done at the time of control and it is not are doing" is presented when both the % plan progress and the % actual progress are 0%.

2.9. Critical Path Earned Value and Work-in-Progress Management ($EVM_{RC\ y\ TC}$) (Source: Adaptation and Own Elaboration)

In order to further specify the performance of the project schedule, the earned value of the critical path (EVM_{RC}) and the earned value of work in progress (EVM_{TC}) approaches could be integrated. This integration is known as work in progress and critical path earned value management ($EVM_{RC\ and\ TC}$).

This approach considers in the calculation of the schedule variance (SV) and in the schedule performance index (SPI) the critical activities that are in progress, with which it adequately measures the progress or delay of the schedule considering the activities that finish late. However, it does not measure schedule status in units of time [11,12].

2.10. Earned Schedule (ES)

The earned schedule (ES) is the actual progress expressed (or valued) in time units [13–17]. It is the equivalent of the earned value that is expressed in other units. What the earned schedule and earned value have in common is that they incorporate actual progress as their starting point [18–21]. The difference lies in how the actual progress is expressed. On the one hand, earned value expresses the actual progress in monetary units (money), while earned programming expresses the same actual progress in units of time. The earned schedule technique generates indicators that measure the status of the project schedule that is reflected correctly throughout the project life cycle [22–26], which allows the expression of the progress or delay of a project in units of "time" and also recognizes and measures the delay in activities that finished late. In other words, it solves the two main limitations of earned value management (EVM) as a project control technique. Figure 5 shows the graphic definition of the earned schedule (ES), in which the value of the earned schedule is obtained when the planned value is equal to the earned value on the control date (in the figure, this is 9 months).

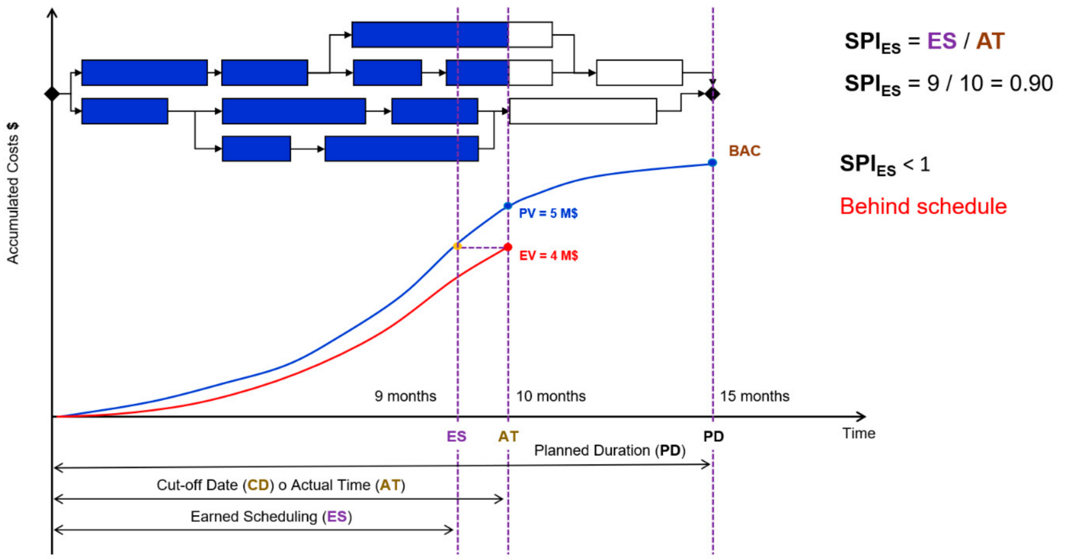


Figure 5. Definition of earned schedule (ES) (source: adaptation and own elaboration).

Figure 6 shows a comparison of the schedule performance index (SPI) based on the earned value and the schedule performance index (SPI_{ES}) based on the earned schedule. It can be seen that the earned schedule better measures the performance of the schedule of the project throughout its entire life cycle because it recognizes activities that finish late, as is the case of weeks 11 to 14 in which the SPI_{ES} of the earned schedule has values consistently less than 1.

Week	PV acum ($)	EV acum ($)	ES acum (sem)	EVM SPI acum	ES $SPI_{ES\ acum}$
0	0	0	0	0	0
1	120	150	1.15	1.25	1.15
2	320	400	2.23	1.25	1.12
3	670	720	3.09	1.07	1.03
4	1220	1250	4.01	1.02	1.00
5	2150	1950	4.78	0.91	0.96
6	3520	3200	5.77	0.91	0.96
7	4770	4120	6.48	0.86	0.93
8	5720	4950	7.19	0.87	0.90
9	6540	5600	7.87	0.86	0.87
10	7000	6100	8.46	0.87	0.85
11	7000	6500	8.95	0.93	0.81
12	7000	6750	9.46	0.96	0.79
13	7000	6900	9.78	0.99	0.75
14	7000	7000	10.00	1.00	0.71

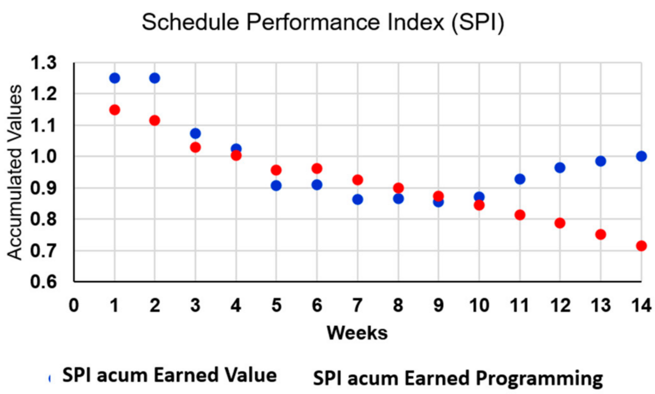


Figure 6. Earned value management (EVM) vs. earned schedule (ES) (source: adaptation and own elaboration).

2.11. Earned Scheduling Critical Path (ES_{RC})

As in the case of earned value management, earned schedule uses the S curve as a frame of reference for estimating schedule variations and does not distinguish between critical and non-critical activities. This detail makes the schedule variance measurement inaccurate as only critical path activities need to be considered to manage the duration of the project.

Critical path earned scheduling (ES_{RC}) integrates the concepts of earned scheduling (ES) and critical path to overcome this impasse. For this, the S curve of the critical activities must be defined and used as a reference for the estimation of the schedule variations [27].

2.12. Schedule Adherence (The P Factor)

The earned schedule measures the degree of fidelity with which the project schedule is followed. It is necessary to differentiate between these two parameters: first, whether we are ahead or behind in our schedule; and second, whether the distribution of work performed is consistent at all times with that specified for that moment in time [28–30].

Figure 7 shows the graphical definition of schedule adherence which measures how what has been completed should have been finished, and this is achieved by comparing the work completed (earned value), with what should have been finished according to the delay or advance (earned schedule). It is never with the work that should have been conducted as planned or planned value. The performance factor (P factor) is the percentage of the work performed (or earned) that has been performed according to the earned schedule (ES). That is, the entire earned value portion of Figure 7 remaining to the left of the date given by the earned schedule (EV_{ES}), divided by all work scheduled up to the date corresponding to the earned schedule (PV_{ES}) and is calculated as:

$$\mathbf{P} = \frac{\sum_i \mathbf{EV}_{(\mathbf{ES})\mathbf{i}}}{\sum_j \mathbf{PV}_{(\mathbf{ES})\mathbf{i}}} \tag{4}$$

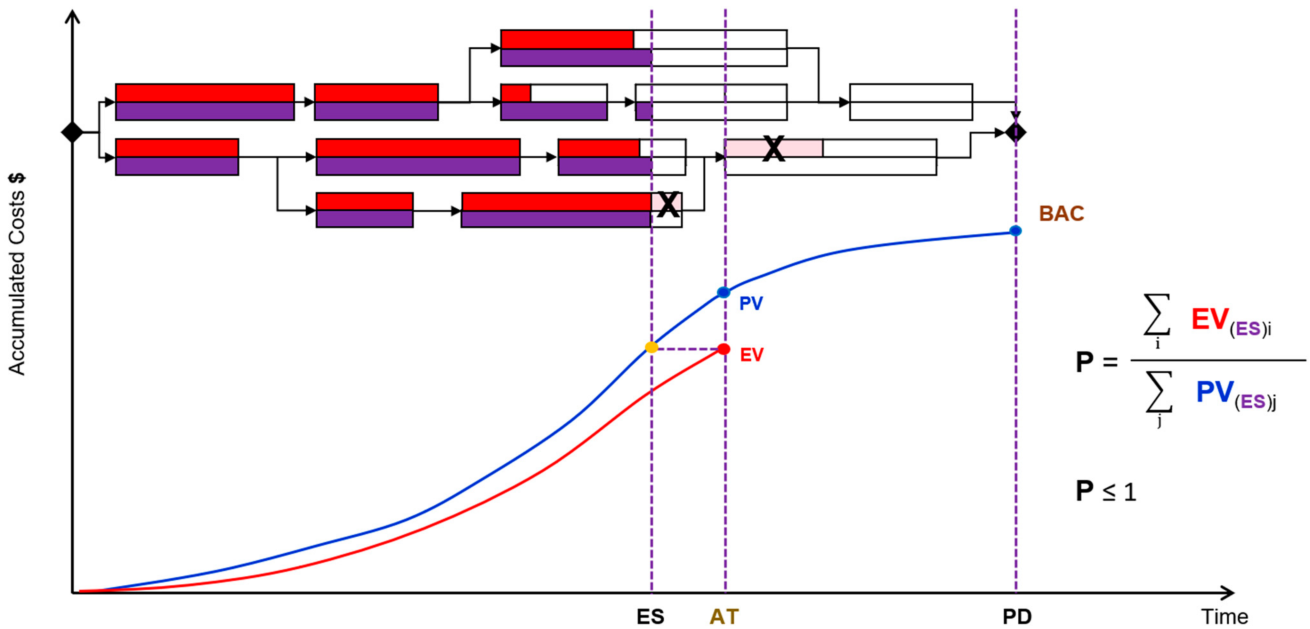


Figure 7. Graphical definition of adherence to programming (P factor) (source: adaptation and own elaboration).

It is important to emphasize that the P factor is not an indicator of schedule advance or delay, as is the SPI_{ES} of the Won schedule, but an indicator that measures whether the work performed corresponds to that which should have been performed according to the schedule at that time and for a given delay or advance.

2.13. Computer Software Development and Support

During the past decade, several types of software have been developed to facilitate the scheduling, monitoring and control of the project baseline performance. These developments are based on traditional earned value management (EVM), e.g., MS Project, MS Project Server, ORACLE Primavera P6, etc., and do not support the measurement of performance indicators of variations in the traditional earned value management method, which generates the difficulty of being able to apply these alternative methods.

3. Methodology

To evaluate, compare and determine which alternative of the versions of the original earned value is the most appropriate for the management of the project schedule, considering that there are several evaluation criteria that must be considered, the analytical hierarchical method (AHP) is taken as a reference framework. This is a method created by Professor Thomas L. Saaty (1980) that aids in decision-making by selecting alternatives based on a series of criteria or variables, usually hierarchical, which are usually in conflict. This method selects an alternative with the highest score following evaluation. For the method to be effective, it is essential to appropriately choose the criteria and sub-criteria, and they must be very well defined [31–36].

Multi-criteria decision-making is based on academic rigor that includes: (1) psychological foundations: pairwise comparison; (2) mathematical robustness: reciprocity, homogeneity and consistency; and (3) empirical contrast through application in different disciplines of study: engineering, administration and marketing, medicine, society, education, production, health, systems, etc. This method uses paired comparison matrices using a fundamental scale that are shown in Table 1. This is the key to the method, since the human brain is well designed to compare two criteria or alternatives with each other, but there are problems in making comparisons of more than two elements or joint comparisons [37].

Table 1. Fundamental pairwise scale, adapted from [32].

Value	Definition	Comments
1	Equal importance	Criterion A is equally important as criterion B.
3	Moderate importance	Experience and judgment slightly favor criterion A over criterion B.
5	Great importance	Experience and judgment strongly favor criterion A over criterion B.
7	Very high importance	Criterion A is much more important than criterion B.
9	Extreme importance	The greater importance of criterion A over criterion B is beyond doubt.
2, 4, 6 y 8	Intermediate values between the above, when it is necessary to qualify.	

Once the criteria (attributes or characteristics) have been defined, they must be weighted; that is, it must be established whether they all influence the interest of the alternative in the same way or whether they differ in the extent of influence. For this purpose, the paired fundamental weighting scale is used, and the criteria comparison matrix is constructed where all the criteria are compared in pairs. Once this matrix is completed, it is normalized, and a consistency check is performed to verify the coherence of the criteria comparisons, using the consistency index ratio (CRI), which is calculated by dividing the consistency index (CI) by the random consistency index (RCI). If the value of the CRI is less than 0.1 that means it has been reasonably weighted, and the process can continue; otherwise, the pairwise relationships must be reevaluated until the required consistency is achieved. Figure 8 shows the basic support structure for decision-making, which is a hierarchical map of the interrelation of criteria (attributes or characteristics) and alternatives (options), in which it is revealed that to select from several options, several criteria have defined that condition as the decision.

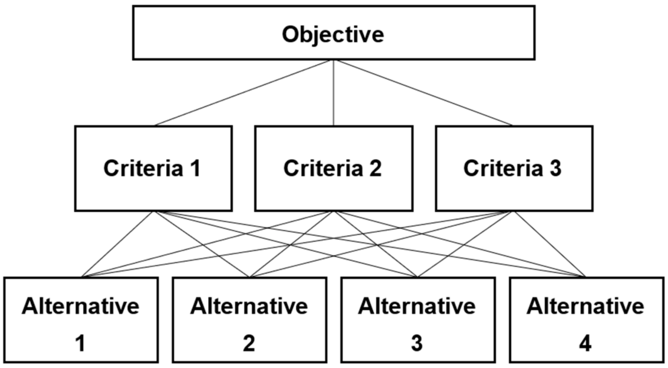


Figure 8. Hierarchy map (source: adaptation and own elaboration).

Once the consistency of the criteria has been verified, we continue creating all the comparison matrices of alternatives by comparison criteria. A criterion is chosen and fixed, and the pairwise evaluation of alternatives is repeated using Saaty's fundamental scale as many matrices are created and as criteria are defined. The alternative comparison matrices are also normalized. The prioritization matrix of the evaluation results is elaborated in which the result is synthesized from the relative contribution of each alternative to each of the criteria and the relative level of preference attributed to them to achieve the general objective. With this, the decision can be made to choose the best-evaluated alternative (the one with the highest priority).

For the realization of the analytical hierarchical comparison (AHP) of earned value management and its variations for the correct measurement of schedule performance in the project baseline, five decision criteria are established: (1) schedule variation focused on critical tasks; (2) recognition and measurement of the delay of tasks that finish late; (3) schedule variation in time units; (4) measurement of schedule adherence (P factor); and (5) computer support and development (software).

On the other hand, six decision alternatives are defined: (1) earned value management (EVM); (2) earned value management of critical path (EVM_{RC}); (3) earned value management of work in progress (EVM_{TC}); (4) earned value management of critical path and work in progress (EVM_{RCyTC}); (5) earned schedule (ES); and (6) earned schedule of critical path (ES_{RC}). Figure 9 shows the decision structure that reflects the hierarchical decision problem approach.

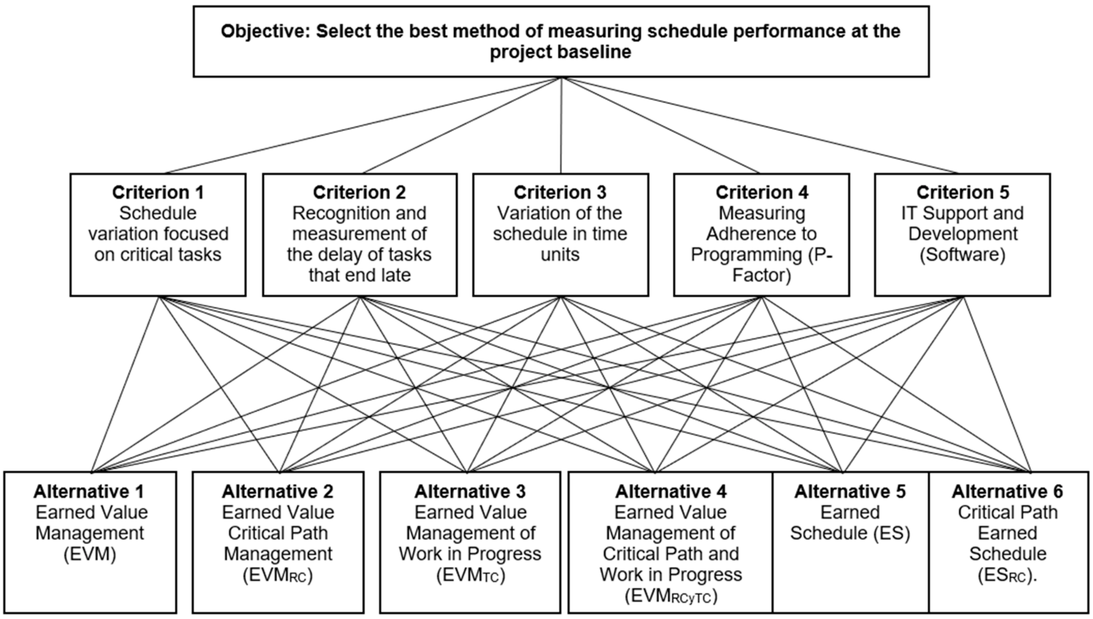


Figure 9. Hierarchical map of the interrelation of criteria (attributes or characteristics) and alternatives (options) (source: adaptation and own elaboration).

4. Results

Table 2 shows the alternative–criterion pairwise relationship. The alternative "M-01 Earned Value Management" only meets the criterion "C-05 Computer Support and Development (Software)"; the alternative "M-02 Critical Path Earned Value Management" only meets the criterion "C -01 Variation of the schedule focused on critical tasks"; the alternative "M-03 Management of the Earned Value of Work in Progress" only meets the criterion "C-02 Recognition and measurement of the delay of tasks that finish late"; the alternative "M-04 Critical Path Earned Value Management and Work in Progress" meets the criteria "C-01 Variation of the schedule focused on critical tasks" and "C-02 Recognition of the delay of tasks that finish late"; the alternative "M-05 Earned Schedule" meets the criteria "C-02 Recognition and measurement of the delay of tasks that finish late", "C-03 Variation of the Schedule in units of time" and "C-04 Measurement of Adherence to Programming (Factor P)"; and finally, the alternative "M-06 Critical Path Win Programming" only does not comply with the alternative "C-05 Computer Support and Development (Software)".

Table 2. Alternative-decision criteria data.

		Evaluation Criteria				
		C-01	**C-02**	**C-03**	**C-04**	**C-05**
Project Baseline Performance Evaluation Methodology		**Schedule Variation Focused on Critical Tasks**	**Recognition and Measurement of the Delay of Tasks Finishing Late**	**Schedule Variation in Time Units**	**Measurement of Schedule Adherence (P Factor)**	**IT Support and Development (Software)**
M-01	Earned Value Management	No	No	No	No	Yes
M-02	Earned Value Management of the Critical Path	Yes	No	No	No	No
M-03	Earned Value Management Work in Progress	No	Yes	No	No	No
M-04	Earned Value Management of Critical Path and Work in Progress	Yes	Yes	No	No	No
M-05	Earned Schedule	No	Yes	Yes	Yes	No
M-06	Critical Path Earned Schedule	Yes	Yes	Yes	Yes	No

For the evaluation of the comparison criteria, two experts from the locality and the sector were consulted. One of them had a Master's in Business Administration (MBA) with experience in project formulation and evaluation; a Master's in Design, Management and Project Management; and experience as a risk manager and director project office (PMO). The other had a Master's in Project Management with experience in international projects, and as a general manager and principal consultant. The first expert is of the opinion that the traditional earned value management method has serious difficulties in measuring progress or delays on the schedule. The second expert affirms that the combination of the critical path approach and earned value is necessary for the measurement of schedule variations.

Table 3 shows the criteria comparison matrix made according to the paired fundamental weighting scale, the normalization of the matrix and the Wi weighting of each criterion obtained by averaging each of the values of the normalized matrix.

One thing to consider is that the value of 1 appears in the matrix diagonal because the purchased pairs correspond to the same criterion. For example, when comparing the criteria, "C-01 Schedule Variation focused on critical tasks" and"C-03 Schedule Variation in time units", a value of 7 is assigned because criterion C-01 is much more important than C-03 for measuring the performance of the project baseline schedule. When comparing the same pair of criteria, but in reverse, a value of 1/7 is assigned because they are reciprocal. This exercise is repeated for all pairs of criteria until the baseline matrix is complete. To obtain the normalized matrix, each of the values of the criteria evaluated per row is divided by the total of the columns (N) to obtain the normalized value, for example, the normalized value of the cell "Row C-01-Column C-01" is 0.560 because it is the result of dividing 1 (evaluated value) by 1.79 (N: a total of column C-01). Before continuing with this evaluation process, the consistency check needs to be performed to verify the coherence of the criteria comparisons, for which the consistency index ratio (CIR) is used. Table 4 shows the data required for the calculation of this ratio. Column A $\times$ P is the vector result of the multiplication of the criteria comparison matrix performed according to the paired fundamental weighting scale by the weighting vector (Wi). The value of Landa Max is the sum of the vector A $\times$ P equal to 5.331. In this case, it is evident that the passing criterion is met, i.e., CIR < 0.10. Once the consistency of the criteria has been verified, the creation of all the alternative comparison matrices by comparison criterion continues. The annex lists all the tables with the data from the paired evaluations using the fundamental Saaty scale, as well as the normalized data and the average for each of the five evaluation criteria.

Table A1 shows the comparison matrix of the six alternatives in reference to the criterion "C-01 Schedule Variation focused on critical tasks". The alternative "M-06 Critical Path Earned Schedule" has a higher score in relation to the other alternatives, and this is because this alternative does consider the impact of critical activities in its definition. Table A2 shows the comparison matrix of the six alternatives in reference to the criterion "C-02 Recognition and measurement of the delay of tasks that end late", and it can be seen that the alternatives "M-01 Earned Value Management" and "M-02 Critical Path Earned Value Management" are the ones with the lowest score in relation to the other alternatives; this is because both alternatives do not recognize or measure the delay of the tasks that finish late.

Table A3 shows the comparison matrix of the six alternatives in reference to the criterion "C-03 Variation of the Schedule in units of time". It can be seen that the alternatives "M-05 Earned Schedule" and "M-06 Critical Path Earned Schedule" are the ones with the highest score in relation to the other alternatives, and this is because both alternatives measure the variation of the schedule in units of time. Table A4 shows the comparison matrix of the six alternatives in reference to the criterion "C-04 Measurement of Programming Adherence (Factor P)". It can be seen that the alternatives "M-05 Earned Schedule" and "M-06 Critical Path Earned Schedule" are the ones with the highest score in relation to the other alternatives; this is because both alternatives facilitate the measurement of adherence to the programming (P factor).

Table 3. Criteria comparison matrix.

Criteria		**C-01**	**C-02**	**C-03**	**C-04**	**C-05**						
Project Baseline Performance Evaluation Methodology		**Variation of the Schedule Focused on Critical Tasks**	**Recognition and Measurement of the Delay of Tasks That End Late**	**Variation of the Schedule in Time Units**	**Measuring Adherence to Programming (P Factor)**	**IT Support and Development (Software)**	**Normalized Matrix**					**Weighting (Wi)**
C-01	Schedule variation focused on critical tasks	1	3	7	5	9	0.560	0.646	0.429	0.517	0.360	0.502
C-02	Recognition and measurement of the backlog of tasks that finish late	1/3	1	5	3	9	0.187	0.215	0.306	0.310	0.360	0.276
C-03	Schedule variation in time units	1/7	1/5	1	1/3	3	0.080	0.043	0.061	0.034	0.120	0.068
C-04	Measurement of schedule adherence (P factor)	1/5	1/3	3	1	3	0.112	0.072	0.184	0.103	0.120	0.118
C-05	IT support and development (software)	1/9	1/9	1/3	1/3	1	0.062	0.024	0.020	0.034	0.040	0.036
	Total (N)	1.79	4.64	16.33	9.67	25	1	1	1	1	1	1

Table 4. Data for the calculation of the consistency index ratio (RIC).

A × P	**Calculation of the Consistency Index Ratio (RIC)**		
2.71995397	N	No. of Criteria	5
1.46201276	Landa Max	Sum A x P	5.331
0.34259578	Consistency Index: CI	(Landa Max − n)/(n − 1)	0.083
0.62230158	Random Consistency Index: RCI	1.98*(n-2)/n	1.188
0.18459628	Consistency Index Ratio: CIR	CIR= IC/RCI	0.070
5.33146037	Approval Criteria	Complies if: CIR < 0.10	If complies: 0.07 < 0.10

Table A5 shows the comparison matrix of the six alternatives in reference to the criterion "C-05 Computer Support and Development (Software)". The alternative "M-01 Earned Value Management" has the highest score in relation to the other alternatives, and this is because there is a lot of support and computer development (software) for this option. Finally, Table 5 shows the prioritization matrix of the evaluation results. The matrix data are completed with the average columns of each alternative comparison matrices, and the last row "Weighting" corresponds to the Wi weighting data for each criterion obtained in the criteria comparison matrix. With this data, the prioritization of the alternatives is calculated, which is the result of the weighted sum of the values of each alternative with the weighting value of each criterion. The prioritized value of the alternative "M-01 Earned Value Management" is 5.04% because it is the result of the weighted product: $0.0431 \times 0.5022 + 0.0272 \times 0.2757 + 0.0490 \times 0.0677 + 0.0490 \times 0.1182 + 0.3346 \times 0.0362$. Similarly, it is obtained that the prioritized value of the alternative "M-02 Critical Path Earned Value Management" is 10.47%, the prioritized value of the alternative "M-03 Earned Value Management of Work in Progress" is 8.4%, the prioritized value of the alternative "M-04 Management of the Earned Value of the Critical Path and Work in Progress" is 21.25%, the prioritized value of the alternative "M-05 Earned Programming" is 16.19% and the prioritized value of the alternative "M-06 Critical Path Programming Won" is 38.21%.

Table 5. Alternatives prioritization matrix.

Alternatives		Criteria					Prioritization
		C-01	C-02	C-03	C-04	C-05	
		Variation of the Schedule Focused on Critical Tasks	Recognition and Measurement of the Delay of Tasks That End Late	Variation of the Schedule in Time Units	Measuring Adherence to Programming (P Factor)	IT Support and Development (Software)	
M-01	Earned Value Management	0.0431	0.0272	0.0490	0.0490	0.3346	5.04%
M-02	Critical Path Earned Value Management	0.1678	0.0317	0.0490	0.0490	0.0726	10.47%
M-03	Work in Process Earned Value Management	0.0398	0.2067	0.0490	0.0490	0.0649	8.84%
M-04	Earned Value Management of Critical Path and Work in Progress	0.2469	0.2801	0.0490	0.0490	0.0596	21.25%
M-05	Earned Schedule	0.0865	0.1752	0.3010	0.3010	0.3919	16.19%
M-06	Critical Path Earned Schedule	0.4159	0.2791	0.5031	0.5031	0.0765	38.21%
	Weighting	0.5022	0.2757	0.0677	0.1182	0.0362	100.0%

5. Discussion

In light of the results and answering the research question of which of the methods is more suitable for the monitoring and control of the project's baseline schedule, it can be concluded that the analytical hierarchical process (AHP) carried out evidence that the method with the highest priority is "M-06 Critical Path Earned Schedule (ES_{RC})" with a score of 38.21%, followed in order of priority by "M-04 Critical Path and Earned Value Management" with 21.25%, "M-05 Earned Schedule" with 16.19%, "M-02 Critical Path Earned Value Management" with 10.47%, "M-03 Work in Progress Earned Value Management" with 8.84% and finally "M-01 Earned Value Management" with 5.04%.This is supported by the fact that this method performs better in measuring schedule performance in almost all evaluation criteria when compared in a paired manner with the evaluated alternatives.

One criterion in which the earned schedule critical path (ES_{RC}) is somewhat unsatisfactory is related to software development and support, which significantly limits its practical use in project execution. It is essential to highlight that this method considers the variation of the schedule focused on critical tasks, recognizes and measures task delays, facilitates the reporting of the variation of the schedule in time units and helps in the measurement of the adherence to the schedule (P factor). One detail to consider in project monitoring and control for the schedule and cost performance is the type of information generated. The Cartesian paradigm based on optimization and perfectly reflected in the critical path method proposes that if all the critical path tasks are finished on time, the project would finish on time. This statement forgets that the tasks proposed in the schedule are not estimates; nobody knows the exact duration of the activities, and there is much uncertainty on this when building the project baseline. We assume that those estimates are the reference, and we measure the deviations comparing with that initial plan, unaware that the plan is not specific because it is based on estimates.

What further complicates this analysis is that traditional performance indicators (CV, SV, CPI and SPI) are calculated by a cut-off date based on an estimate, and then they try to predict correct future patterns, i.e., they therefore become reactive measurements all the time. This fact and the existence of many variations of methods to measure performance are the reasons to warn that the paradigm is not working correctly. We should not be interested in whether a task is behind or ahead of schedule; what we should be interested in is that the project finishes on time. This statement is based on the systemic paradigm, which does not favor local improvement but global improvement. The critical chain project management (CCPM) methodology is based on this principle and proposes proactive performance indicators.

6. Conclusions

It is essential to recognize that traditional earned value management works well for measuring project cost performance but has serious weaknesses when used to measure schedule performance.

The hierarchical analysis carried out shows that the critical path earned schedule, which is a method based on the critical path Cartesian paradigm, has a better behavior for the adequate measurement of the project schedule performance compared to the other versions of the traditional earned value evaluated. The prioritization score obtained is 38.21%, which is higher than the score obtained by the other methods. In the evaluation carried out, the absence of computer support (software) that facilitates the use of the critical path earned programming is evident, and this can become a major problem, to the extent that the complexity of the projects increases.

As discussed in the previous section, earned value management and all its variations are based on the Cartesian critical path paradigm. This leads to reporting metrics associated with the past, which in turn prompt corrective action all the time. Managing yourself correctly in the execution of the project is a problem that has to be overcome. For this, it is recommended to change the paradigm and use a systemic approach such as the critical chain project management (CCPM).

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Appendix A

Table A1. Alternative comparison matrix—C-01 schedule variation focused on critical tasks.

Comparison of Alternatives Matrix								C-01 Variation of the Schedule Focused on Critical Tasks						
Alternatives		M-01	M-02	M-03	M-04	M-05	M-06							
Method of Measuring Schedule Performance at Project Baseline		Earned Value Management	Critical Path Earned Value Management	Earned Value Management of Work in Progress	Critical Path Earned Value Management and Work in Progress	Earned Schedule	Critical Path Earned Schedule	Normalized Matrix						Mean
M-01	Earned Value Management	1	1/7	1	1/9	1	1/9	0.036	0.015	0.045	0.022	0.088	0.052	0.043
M-02	Critical Path Earned Value Management	7	1	5	1/3	3	0.20	0.250	0.103	0.227	0.067	0.265	0.094	0.168
M-03	Work in Process Earned Value Management	1	1/5	1	1/5	1/3	1/7	0.036	0.021	0.045	0.040	0.029	0.067	0.040
M-04	Earned Value Management of Critical Path and Work in Progress	9	3	5	1	3	1/3	0.321	0.310	0.227	0.201	0.265	0.157	0.247
M-05	Earned Schedule	1	1/3	3	1/3	1	1/3	0.036	0.034	0.136	0.067	0.088	0.157	0.086
M-06	Critical Path Earned Schedule	9	5	7	3	3	1	0.321	0.517	0.318	0.603	0.265	0.472	0.416
Total (N)		28	9.68	22	4.98	11.33	2.12	1	1	1	1	1	1	1

Table A2. Comparison of alternatives matrix—C-02 recognition and measurement of the delay of tasks that end with a delay.

Comparison of Alternatives Matrix								**C-02 Recognition and Measurement of the Backlog of Tasks That Finish Late**						
Alternatives		**M-01**	**M-02**	**M-03**	**M-04**	**M-05**	**M-06**							
Method of Measuring Schedule Performance at Project Baseline		**Earned Value Management**	**Critical Path Earned Value Management**	**Earned Value Management of Work in Progress**	**Critical Path Earned Value Management and Work in Progress**	**Earned Schedule**	**Critical Path Earned Schedule**	**Normalized Matrix**						**Mean**
M-01	Earned Value Management	1	1	1/7	1/9	1/7	1/9	0.029	0.038	0.029	0.052	0.012	0.015	0.029
M-02	Critical Path Earned Value Management	1	1	1/5	1/7	1/5	1/7	0.029	0.038	0.040	0.067	0.016	0.019	0.035
M-03	Work in Process Earned Value Management	7	5	1	1/3	3	3	0.206	0.192	0.200	0.157	0.243	0.395	0.232
M-04	Earned Value Management of Critical Path and Work in Progress	9	7	3	1	5	3	0.265	0.269	0.599	0.472	0.405	0.395	0.401
M-05	Earned Schedule	7	5	1/3	1/5	1	1/3	0.206	0.192	0.067	0.094	0.081	0.044	0.114
M-06	Critical Path Earned Schedule	9	7	1/3	1/3	3	1	0.265	0.269	0.067	0.157	0.243	0.132	0.189
Total (N)		34	26	5.01	2.12	12.34	7.59	1	1	1	1	1	1	1

Table A3. Alternative comparison matrix—C-03 variation of the schedule in time units.

Comparison of Alternatives Matrix								C-03 Variation of the Schedule in Time Units						
Alternatives		**M-01**	**M-02**	**M-03**	**M-04**	**M-05**	**M-06**	**Normalized Matrix**						**Mean**
Method of Measuring Schedule Performance at Project Baseline		**Earned Value Management**	**Critical Path Earned Value Management**	**Earned Value Management of Work in Progress**	**Critical Path Earned Value Management and Work in Progress**	**Earned Schedule**	**Critical Path Earned Schedule**							
M-01	Earned Value Management	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-02	Critical Path Earned Value Management	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-03	Work in Process Earned Value Management	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-04	Critical Path Earned Value Management and Work in Process	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-05	Earned Schedule	7	7	7	7	1	1/3	0.350	0.350	0.350	0.350	0.219	0.188	0.301
M-06	Critical Path Earned Schedule	9	9	9	9	3	1	0.450	0.450	0.450	0.450	0.656	0.563	0.503
	Total (N)	20	20	20	20	4.57	1.78	1	1	1	1	1	1	1

Table A4. Comparison of alternatives matrix—C-04 measurement of adherence to schedule (P factor).

Comparison of Alternatives Matrix								C-04 Programming Adherence Measurement (P Factor)						
Alternatives		M-01	M-02	M-03	M-04	M-05	M-06							
Method of Measuring Schedule Performance at Project Baseline		Earned Value Management	Critical Path Earned Value Management	Earned Value Management of Work in Progress	Critical Path Earned Value Management and Work in Progress	Earned Schedule	Critical Path Earned Schedule	Normalized Matrix						Mean
M-01	Earned Value Management	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-02	Critical Path Earned Value Management	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-03	Work in Process Earned Value Management	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-04	Earned Value Management of Critical Path and Work in Progress	1	1	1	1	1/7	1/9	0.050	0.050	0.050	0.050	0.031	0.063	0.049
M-05	Earned Schedule	7	7	7	7	1	1/3	0.350	0.350	0.350	0.350	0.219	0.188	0.301
M-06	Critical Path Earned Schedule	9	9	9	9	3	1	0.450	0.450	0.450	0.450	0.656	0.563	0.503
	Total (N)	20	20	20	20	4.57	1.78	1	1	1	1	1	1	1

Table A5. Comparison of alternatives matrix—C-05 IT support and development (software).

Comparison of Alternatives Matrix								**C-05 Computer Support and Development (Software)**						
Alternatives		**M-01**	**M-02**	**M-03**	**M-04**	**M-05**	**M-06**							
Method of Measuring Schedule Performance at Project Baseline		**Earned Value Management**	**Critical Path Earned Value Management**	**Earned Value Management of Work in Progress**	**Critical Path Earned Value Management and Work in Progress**	**Earned Schedule**	**Critical Path Earned Schedule**	**Normalized Matrix**						**Mean**
M-01	Earned Value Management	1	3	5	7	1	5	0.348	0.214	0.313	0.350	0.366	0.417	0.335
M-02	Critical Path Earned Value Management	1/3	1	1	1	1/7	1	0.116	0.071	0.063	0.050	0.052	0.083	0.073
M-03	Work in Process Earned Value Management	1/5	1	1	1	1/7	1	0.070	0.071	0.063	0.050	0.052	0.083	0.065
M-04	Earned Value Management of Critical Path and Work in Progress	1/7	1	1	1	1/9	1	0.050	0.071	0.063	0.050	0.041	0.083	0.060
M-05	Earned Schedule	1	7	7	9	1	3	0.348	0.500	0.438	0.450	0.366	0.250	0.392
M-06	Critical Path Earned Schedule	1/5	1	1	1	1/3	1	0.070	0.071	0.063	0.050	0.122	0.083	0.076
	Total (N)	2.88	14	16	20	2.73	12	1	1	1	1	1	1	1

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