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Proposal and Application of a Methodology to Improve the Control and Monitoring of Complex Hydroelectric Power Station Construction Projects

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Abstract: All complex projects take place in environments of great uncertainty. Maintaining a monitoring and control system from the early stages of execution is a critical factor in the success of this type of project. Large hydroelectric power station construction projects are regarded as highly complex because they are affected by factors such as the risks inherent in a variety of fields of engineering, geology and the environment, the long execution times, and the large number of multidisciplinary activities to be carried out in parallel, among others. These types of projects are commonly affected by cost overruns and delays. This work develops a methodology for the monitoring and control of complex construction projects in the hydroelectric sector that enables a periodical calculation of metrics for physical progress, financial progress, and predictions for costs and durations on completion of the project. The verification of the efficiency of this methodology was based on stochastic simulation models applied to real projects in the hydropower sector. The results showed that the proposed methodology improved efficiency compared with existing traditional methodologies. The proposed methodology allows the simultaneous consideration of costs, deadlines, criticality, and risks of the activities of the analyzed projects and also incorporates multicriteria decision techniques to manage the influence of key aspects during the development of the project.

Keywords: complex project; control and monitoring projects; EVM; hydroelectric plant; project management

1. Introduction

The development of complex construction projects around the world has produced statistical evidence that shows the significant cost and duration of execution deviations compared with the planned costs and durations. The study presented by San Cristóbal [1] analyzed a sample of 130 projects and indicated that 81.5% ended outside the planned time period. In this context and specifically in the construction of large hydroelectric power stations, various studies have been performed, such as those published by Ansar et al. [2], Sovacool et al. [3], and Awojobi and Jenkins [4], in which large samples of hydroelectric projects at a global level were analyzed, ranging from 58 to 235 projects. The results are interesting. Mean values were obtained that range from a 27% to 99% increase compared to the planned cost and increases of up to 44% with regard to duration.

In line with the International Project Management Association (IPMA) classification of a complex project [5], and according to the studies by Ammen and Jacob [6], Kermanshachi, Dao, Shane and

Anderson [7], and Brockmann and Kahkonen [8], there are a number of indicators of complexity in a project, such as a high organizational level, multidisciplinary character, overlapping of various phases, the presence of a large number of interdependent components, scale, and difficulty of execution.

Since all of these aspects are found in projects for constructing the installations needed for hydroelectric generation, these can be regarded as complex construction projects. Thus, it is considered that the four selected case studies can serve as appropriate examples for the application and validation of the proposed methodology. In addition, the first author of this work has worked for 19 years in the electricity sector of the Republic of Ecuador and specifically in the development of this type of projects. This professional experience motivated the choice of this type of facility for the application of the methodology proposed in the framework of his doctoral thesis [9], which was developed under the direction of the other two authors, and from whose results this work derives. In any case, the methodology described is applicable to any type of complex construction project, since the aspects considered are not exclusive to hydroelectric power station construction projects.

The level of complexity of a project makes identifying goals and objectives difficult, resulting in potential impacts on the duration, cost, and quality. A critical factor for the success of any project will always be the proper management of its complexity from its initial stages. [7,10–12]. The complexity of a project is related to various factors, the main ones being its size, interdependency and interrelation, goals and objectives, multidisciplinary engineering teams, and technology, among others [13–15]. Carrying out monitoring and control activities during the development of a project makes it possible to track performance and obtain projections and measurements that help administer the contract and anticipate possible planning deviations. Monitoring and control tasks are an essential part of managing the schedule and costs of a project, becoming an important support for the processes necessary to manage the completion of the project on time and within planned costs [1,16–21]. A project with suitable planning in terms of budget, supplies, funding, and contracts facilitates the task of controlling the execution of the project [22].

Despite the large number of studies carried out regarding the planning and programming of projects, it has been found that traditional planning and programming techniques have problems detecting deviations in costs and duration [9] and in identifying their causes in complex construction projects. This is mainly due to the fact that their metrics do not jointly address all the factors that can generate deviations in the execution of the project. Traditional methodologies tend to base their metrics exclusively on the costs associated with project activities, leaving aside the risks, times, and criticality associated with each activity. In that context, there is a need for monitoring and control techniques and methodologies that make it possible to detect and measure deviations from the original planning and the actions needed to minimize them and comply with the project's objectives. Thus, this study proposes a new methodology, called CTCR, that combines and considers simultaneously the costs, deadlines, criticality, and risks of the activities of the analyzed projects. There is no other methodology that combines these four components simultaneously, which represents a novel contribution of this work and whose objective is to help solve previously identified problems when applying traditional methods [9].

Today, the technique called Earned Value Management (EVM) has become one of the most widely used throughout the world to evaluate performance in the execution of all types of projects. Important institutions such as the National Aeronautics and Space Administration (NASA) use it in the management of their projects. The basis of this technique, its terminology and formulation, were provided by the US Department of Defense (DoD) in the 1960s, and subsequently by the American National Standards Institute (ANSI), the Electronic Industries Alliance (EIA), and the Project Management Institute (PMI) [23–28]. However, when considering the use of EVM in complex construction projects such as hydroelectric power projects, this technique does not provide adequate efficiency with regard to managing durations, as a previous research work of the authors establishes [29].

The Earned Value Management (EVM) technique makes a comparison of the planned performance with the actual performance, both in terms of schedule and the actual executed costs of the project.

This technique is based on three fundamental metrics: Plan Value (PV), which corresponds to the sum of the planned costs of each task in each period of time; Actual Cost (AC), which refers to the sum of the costs actually executed in each task and in each period of time; and Earned Value (EV), which represents the work actually executed expressed in cost. This metric is calculated by multiplying the percentage of actual physical progress for each activity by the planned cost. Based on these three metrics, EVM calculates a group of indicators that propose an execution progress calculation; among these, the main metrics are the Cost Performance Index (CPI) and Schedule Performance Index (SPI). Likewise, EVM proposes trends in performance in terms of cost and time, based on historical data during project execution. Among the main trend measures are the Estimate at Completion (EAC) and Estimate to Complete (ETC).

This work develops and presents a methodology for monitoring and controlling complex construction projects that enables the periodical calculation of metrics for physical and financial progress and making predictions of cost and durations on the completion of the project. It is worth noting that the proposed methodology improves on the performance of traditionally used techniques such as EVM, with which it is compared in this work through stochastic simulation models applied to real projects in the hydropower sector.

2. Methodology

Monitoring and control processes must be implemented not only on the cost, timeline, and performance of resources, but also on productivity and risk factors [17,30–33]. In this context, the metrics for a monitoring and control methodology for the execution of complex construction projects must consider variables relating to their fundamental basic restrictions: the cost of the activities involved in the project; the time or execution period of the activities involved in the project; the criticality of activities that might create cost overruns and/or overdue periods in the execution of the project (critical path activities); and activities that present a greater risk of creating cost overruns and/or overdue periods in the execution of the project.

From this perspective, the methodology this work proposes is based on measurements of Cost, Time, Criticality, and Risks that affect the execution of a project. Taking the initials of these four variables, we have called it the "CTCR methodology". In order to have the necessary information about the areas identified above, we propose developing planning baselines, progress measurements and indicators, forecasts of cost and periods on completion of the project, and defining factors that give a weighting to cost, time, criticality, and risks.

In this context, the fundamental difference between EVM and CTCR is that EVM bases its entire methodology on a single component, which is project costs, while CTCR is based on four components: Costs, Time, Criticality, and Risks.

2.1. Components of the CTCR Methodology

2.1.1. Baseline

The baseline can be defined as the planning of objectives in relation to durations. This planning will serve for monitoring the project through periodical comparisons between the objectives achieved during the execution of the project and the planned objectives. For the comparison activities to be viable, the baseline objectives must be measurable and quantifiable.

Considering the basic three-part restriction to which all projects are subject, it is necessary to consider baselines that allow the monitoring and control of costs, duration, and scope. The CTCR methodology proposes the construction of three baselines for: physical progress (scope), budgetary progress (costs), and critical path progress (duration).

The baseline for physical progress makes it possible to track completion of the scope of the project periodically. The baseline for physical progress is defined by giving weightings to each of the activities

that comprise the project timeline, resulting in a percentage value distributed over time with a value of 0% at the start and 100% at the end.

The weightings for the activities from the timeline that come into play in each time period are calculated with Equation (1).

$$A_{planned\ progress\ i} = k1 \times \frac{\sum_{i=1}^{n} C_i}{C_T} + k2 \times \frac{\sum_{i=1}^{n} T_i}{T_T} + k3 \times \frac{\sum_{i=1}^{n} RC_i}{RC_T} + k4 \times \sum_{i=1}^{n} R_i \quad (1)$$

where $A_{planned\ progress\ i}$ is the physical progress of the project in period i and i is the period of time of the evaluation. $K1,2,3,4$ are non-dimensional coefficients to provide weightings for the time, cost, criticality, and risk criteria. These coefficients are weighted on the basis of a multicriteria analysis that is developed below. C_i is the planned cost accumulated in period i. C_T is the total planned cost. T_i is the accumulated effort in time periods of all of the activities planned for execution up to period i. T_T is the total effort resulting from the summation of the planned time periods for all of the activities that comprise the project (it is not the project period). RC_i is the accumulated effort in time periods of all of the critical path activities planned to be executed up to period i. RC_T is the total effort resulting from the summation of the planned time periods for all of the critical path activities that comprise the project, and R_i is the risk accumulated in period i.

The baseline for budgetary progress makes it possible to monitor fulfillment of the costs of the project periodically. It is defined by giving weightings to the costs of each of the activities that comprise the project timeline, giving a monetary value distributed over time, with a monetary value of 0 at the start and the total budget cost at the end.

To calculate the baseline budgetary progress, it is necessary to link the weight of the cost of all of the activities on the timeline that come into play in each period of time. This is done with Equation (2).

$$A_{planned\ budget_i} = \sum_{j=1}^{n} C_j \quad (2)$$

where $A_{planned\ budget\ i}$ is the progress of the project's planned budget in period i (monetary value), i is the evaluation period, and j is the number of activities involved in the evaluation period i. C is the total planned cost of the activities in period i (monetary value), and n is the total number of activities planned for period i (units of time).

The baseline for the critical path makes it possible to track compliance with the duration of the project periodically. It is defined by giving weightings only to activities that are in the critical path in the project timeline, giving a percentage value distributed over time with a value of 0% at the start and a value of 100% at the end.

The planned progress of the completion of the critical path for each period is calculated based on the projected times for each critical path activity on the timeline, as represented by Equation (3).

$$A_{planned\ critical\ pathi} = 100 \times \frac{R_i}{\sum_{j=1}^{n} R_j} \quad (3)$$

where $A_{planned\ critical\ path\ i}$ is the planned progress of completion of the critical path in evaluation period i (in %), i is the evaluation period, and j is the number of critical path activities involved in evaluation period i. R is the planned time for the critical path activities (units of time), and n is equal to the total number of critical path activities from the project timeline.

These metrics reflect the periodical planning of the scope, costs, and durations of the project, respectively. To continue with the monitoring and control of the project, it is necessary to define the methodology for defining the real progress of the project to compare with the baselines.

2.1.2. Progress Measurements

By obtaining the data from measuring the physical progress of each activity, costs, and durations executed from the timeline, it is possible to measure the total physical progress of the project in a given period. This is done using Equation (4).

$$A_{physical\ real\ i} = k1\times \frac{\sum_{i=1}^{n} A_{Ri}\times C_i}{C_T} + k2\times \frac{\sum_{i=1}^{n} A_{Ri}\times T_i}{T_T} + k3\times \frac{\sum_{i=1}^{n} A_{Ri}\times RC_i}{RC_T} + k4\times \sum_{i=1}^{n} A_{\mathrm{Ri}}\times R_i \quad (4)$$

where $A_{physical\ real\ i}$ is the real physical progress of the project in period i (in %) and i is the period of time of the evaluation. K1, 2, 3, 4 are non-dimensional coefficients to provide weightings for the time, cost, criticality, and risk criteria. These coefficients are weighted on the basis of a multicriteria analysis that is developed below. A_R is the real progress of the work in period i. C_i is the planned cost accumulated in period i. C_T is the total planned cost. T_i is the accumulated effort in time periods of all of the activities planned to be executed up to period i. T_T is the total effort resulting from the summation of the planned time periods for all of the activities that comprise the project (it is not the project period). RC_i is the accumulated effort in time periods of all of the critical path activities planned to be executed up to period i. RC_T is the total effort resulting from the summation of the planned time periods for all of the critical path activities that comprise the project. R_i is the risk accumulated in period i, and n is the total number of periods at the evaluation date.

With the real budgetary execution, it is possible to calculate the periodical budgetary progress using Equation (5).

$$A_{real\ budget_i} = \sum_{j=1}^{n} C_{Rj} \quad (5)$$

where $A_{real\ budget\ i}$ is the progress of the project's real budget in period i (monetary value), i is the evaluation period, and j is the number of activities involved in the evaluation period i. C_R is the total real cost of the activities in period i (monetary value), and n is the total number of activities planned for the period i (units of time).

With the measurements of the physical progress of each activity on the timeline's critical path, it is possible to calculate the progress of the critical path by applying Equation (6).

$$A_{real\ critical\ pathi} = 100 \times \frac{A_{Ri} \times R_i}{\sum_{j=1}^{n} R_j} \quad (6)$$

where $A_{real\ critical\ path\ i}$ is the real progress of the completion of the critical path in the evaluation period i (in %), i is the evaluation period, and j is the number of critical path activities involved in evaluation period i. A_R is the real progress of the work activities on the critical path in period i. R is the planned time of the activities on the critical path (units of time), and n is the total number of activities on the critical path of the project timeline.

2.1.3. Cost and Duration Projections

The periodical projection of the cost on completion of the project is based on the EVM technique, because its efficiency has been demonstrated in its application to complex construction projects. The efficiency of the predictions improves as the execution of the project advances, to a point where after approximately 60% of the time of the planned duration has passed, it presents cost forecasts that fit the simulated costs with a 100% probability of occurrence. Under this criterion, EVM is an important tool that enables very efficient cost forecasts after approximately 60% of the period has passed, giving a suitable margin of time for decision making to correct deviations from the project budget [29].

Equation (7) uses the EVM criterion for cost forecasts that can be applied periodically during the execution of the project.

$$P_{Costsi} = P_T \times \frac{\sum_{j=1}^{n} C_{Rj}}{\sum_{j=1}^{n} A_{Rj} \times C_{Pj}} \quad (7)$$

where $P_{costs\ i}$ is the projected cost at completion of the project, which is calculated in evaluation period i (in monetary value), i is the evaluation period, and j is the number of activities executed up to the evaluation period i. P_T is the total project budget. C_R is the real executed cost of each activity up to period i (monetary value). C_P is the planned cost of each activity up to period i (in monetary value). A_R is the measurement of the progress of each activity in the work (in %), and n is the total number of activities executed up to period i (units of time).

The periodical projection of the duration to completion of the project is based on the real and planned physical progress curves over the course of time. The horizontal projection of the real physical progress over the planned physical progress on the time axis is calculated giving a value in units of time that indicate whether execution of the project is ahead of or behind schedule. In Equation (8), the calculation of the projection is presented.

$$P_{Timei} = T_A - T_P \quad (8)$$

where $P_{time\ i}$ is the projected time up to completion of the project, which is done in evaluation period i (in units of time), and i is the evaluation period. T_A is the actual evaluation time in the period i, and T_P is the projected time in the planned physical progress.

2.1.4. K Factors

These factors introduce a relative weight to the cost, time, critical path, and cost overrun and/or overdue period risk components in Equations (1) and (4). To calculate them, a decision-making model has been prepared using an adaptation of Analytical Hierarchy Process (AHP) [34]. The application of this method is based on matrix calculations, starting with a comparison between criteria, giving numerical values based on ratio scales proposed by Saaty [35] in terms of preference, importance, or probability. At the end, the "matrix of priorities" through which the priorities for each of the criteria that correspond to the K factors are summarized can be constructed [36–41].

The AHP method uses a hierarchical structure with a series of criteria levels and a final level of options. However, its use in this research requires the technique to be adapted by eliminating the options level. Applying the K factors is not optional. Instead, they represent the weighting of the time, cost, criticality, and risks of the activities in a project, which are criteria that must be applied in the project monitoring and control method but with different weightings.

Accordingly, the criteria structure designed for this research has the objective of reaching a ranking of K factors, and to do so, it distributes the criteria considered into two levels. The first level includes the specific criteria for each project, such as the principal technical, environmental, and social characteristics of each project. At a second level, there are general criteria for all types of projects, such as the costs of activities, the execution time of all of the activities, the execution time of critical path activities, and the risks of cost overruns/overdue periods for activities.

2.2. Validation Method

The method this work proposes for verifying the applicability, consistency, and efficiency of the CTCR methodology is based on the construction and application of stochastic models in real hydroelectric plant construction projects. With these models, we intend to generate thousands of scenarios, applying the CTCR methodology to each scenario and obtaining at the end a database that, through statistical tools, makes it possible to validate the fit and power of the methodology. In addition, a comparison of the CTCR and EVM methods is performed. EVM is regarded as one of the most comprehensive methods and is one of the most widely used at a global level for estimating

the physical–financial progress and forecasts of costs and duration. To simulate the model, the Monte Carlo method was used. Through the use of sampling techniques, this random numerical method aims to find approximate solutions to quantitative problems [42].

The main inputs in the models are the project timelines, which consist of a distribution of interrelated tasks where each of the tasks is assigned a probable cost and duration range. The dependency relation between tasks and their assigned cost and duration is traditionally studied using the Program Evaluation and Review Technique (PERT) and Critical Path Method (CPM). PERT was created as a weapon development planning tool by the United States Navy in 1958 [43], while the development of CPM dates back to 1957 with the DuPont company from the USA in the context of tackling the challenge of closing and reopening chemical plants owing to their maintenance requirements [44]. CPM makes it possible to find the total duration of the project if the durations of the activities are known, while PERT makes it possible to include uncertainty in these durations [45,46]. Cost and duration variables are characterized by probability distributions based on recommendations from the Association for the Advancement of Cost Engineering, AACE International [47].

The models' output variables are defined in a range of response of cost and duration, which are calculated in different project execution periods. For each project, the variables are calculated in various initial periods depending on the planned duration and in the last ten periods prior to completion of the project. The calculations are performed for both the CTCR and the EVM methods.

The simulation results create a database that makes it possible to carry out a statistical analysis based on a comparison of means for the period from the simulations performed in each period of execution and the means for the final completed period in each simulation. A method displays efficiency when the means for each period are equal or similar to the means for the last period obtained. Statistically, the method used for carrying out a hypothesis test that determines whether the means of two or more populations are equal is an ANOVA analysis or analysis of variance. ANOVA was developed and presented by R.A. Fisher in 1935. It enables the importance of one or more factors to be evaluated when comparing the means of response variables at different levels [48,49]. For the ANOVA analysis, the continuous response variable is the method's prediction period.

The base of the models was constructed in Microsoft Excel, and the stochastic component and simulation were developed using the specialized @Risk software from Palisade Corporation [50]. With an estimated 150,000 users, the Palisade program is used in over 100 countries and has been translated into seven languages: English, Spanish, Portuguese, French, German, Russian, Japanese, and Chinese. Other widely used software options are Crystal Ball by Oracle and Risk Simulator by Real Options Valuation [51,52]. In addition, the Minitab® V18 (Pennsylvania State University, USA) program was used as a tool for statistical testing of the results and databases of the models. The company that developed this is one of the main suppliers of software and services to improve the quality and teaching of statistics [49].

3. Case Studies

This work presents four case studies in the hydropower sector in the Republic of Ecuador, corresponding to the Cardenillo, Mazar Dudas, Sopladora, and Santiago hydroelectric power projects located in the south-east of the country in the Amazon hydrographic region. Table 1 shows some basic technical data and the principal characteristics of the timelines. It is important to note that the first author of this work participated in the development of these projects at various stages having acted as a technical specialist in the electrical sector of the Republic of Ecuador.

Table 1. Basic technical details and characteristics of the schedules for the projects under analysis.

Technical Information	Santiago	Cardenillo	Mazar Dudas	Sopladora
Installed capacity (W)	3630	595.65	20.8	487
Plant factor (%)	47	65	65	60
Geographical location	809378 E	786371 E	760500 E	782422 E
Coordinates UTM	9665812 N	9710800 N	9715480 N	9713831 N
Total tasks	797	120	1306	562
Summary task	29	37	29	29
Scheduled duration (months)	68	75	27	47
Planned cost (million US$)	2684	996	56	678

These timelines were developed within the studies and designs of the projects analyzed. Depending on the criteria applied in each project, the timelines give more or less detail with regard to the total number of tasks, with a range of 120 to 1306 tasks. The estimated durations of these four projects vary from 27 to 75 months. For their part, the cost estimation for the four projects range from USD 56 to 2684 million.

The models were constructed with exactly the same components for each case study. A first phase considered the programming, where the principal activities, structure of the work breakdown, and planned execution dates are generated. Subsequently, timelines were constructed with a cost breakdown, where each activity that comprises the planning has an attached cost. Next, a timeline was developed with period breakdowns, where a period is linked to each activity and which in the end provides a total duration for the project. Finally, the timeline with a breakdown of the durations of the activities that comprise the critical path is constructed.

To apply the equations developed in the CTCR methodology, it is necessary to define the K factors, which introduce a relative weighting to the cost, time, critical path, and risk of cost overrun and/or overdue period components. In this sense, the structure of the AHP model applied to the case studies considers eight criteria for the first level, which are distributed into technical, social, and environmental issues. This analysis of criteria is specific according to the conditions of each project; it allows achieving adequate weights for each of the four CTCR components through the K factors. Figure 1 presents the structure of the AHP decision model for defining the K factors.

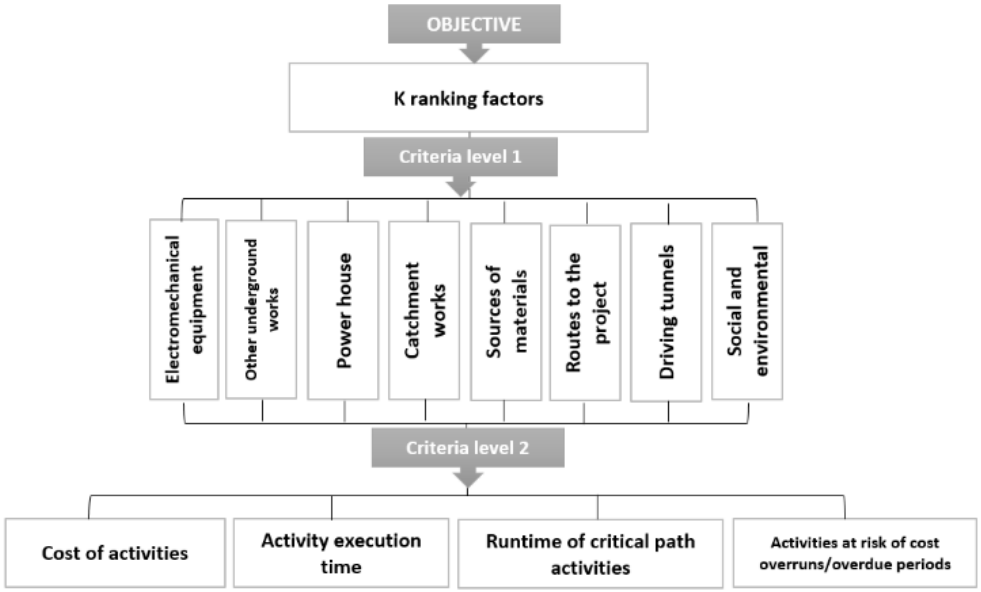


Figure 1. Analytical Hierarchy Process (AHP) decision model for K factors.

The level 1 criteria were defined on the basis of each hydroelectric project's own particular conditions and on the judgement of the authors of the work. The first author has 19 years' experience in the hydroelectric sector in the Republic of Ecuador and participated directly in the case studies. The second and third authors both have extensive teaching and research experience in project engineering and decision making.

With the partial results of prioritizing alternatives of the K factors of each hydroelectric project analyzed, Table 2 presents the results once they have been consolidated according to the logic of AHP and after applying an average to define the final weighting of the K factors. The application to each case is described in detail in the previous research developed by the first author [9].

Table 2. Consolidated results for the k factors of the four projects analyzed.

Factors	Cardenillo	Santiago	Sopladora	Alazán	Mean
K1	0.26	0.32	0.31	0.37	0.32
K2	0.15	0.17	0.13	0.14	0.15
K3	0.42	0.38	0.30	0.27	0.34
K3	0.17	0.13	0.25	0.22	0.19

4. Results and Discussion

The results obtained in the ten thousand simulated scenarios for each case study with regard to total costs and durations are presented in Table 3. It is apparent that all of the case studies have a low probability of compliance with the planned costs and durations. This scenario continues with the results obtained by applying the CTCR and EVM methodologies.

Table 3. Simulation models for total costs and durations of the case studies—results.

	Cardenillo	Mazar Dudas	Sopladora	Santiago
Planned cost (millions of USD)	995.6	56.55	678	2684.3
Planned cost probability (%)	5.40	20	23	26.40
Simulated cost 95% probability (million USD)	1006.36	59.35	714	2839
Planned duration (months)	75	27	47	68
Planned duration probability (%)	4.20	7.70	5.50	6.80
Simulated duration 95% probability (months)	83	32	55	78

4.1. Fit of Costs Simulation

With regard to cost forecasts on the completion of complex construction projects in the hydropower sector, the study by Urgiles, Claver, and Sebastian [29] shows the efficiency of EVM applied to the case studies from the present work, indicating that the efficiency of the predictions improves as the execution of the projects progresses, to the point that after approximately 60% of the time of the planned duration has passed, the cost forecasts it presents fit the simulated costs with a 100% probability of occurrence.

Under this criterion, EVM is an important tool that makes very efficient cost forecasts possible from the time that approximately 60% of the period has passed, giving a suitable time margin for decision making to correct deviations from the project budget.

4.2. Fit of Durations Simulation

In each of the ten thousand scenarios generated in the simulation models of the four case studies, the CTCR and EVM methodologies were applied for the period forecasts on completion of the projects in different months of the progress of the project, using an error range of plus or minus 1 month. The results obtained for each case study are presented below.

4.2.1. Cardenillo Hydroelectric Project

The evaluation was performed in months 10, 20, 30, 40, 50, and 60 after starting the simulated execution of the project, and in months 10, 8, 6, and 1 before the simulated completion of the project. Figure 2 presents the temporal evolution of how the EVM and CTCR methods fit each other in their forecasts of the final completion time of the Cardenillo project, which is in accordance with the ten thousand scenarios in the simulation model.

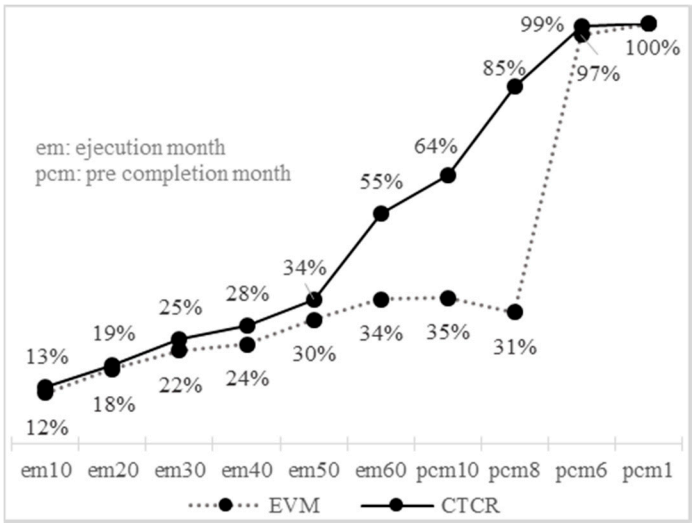


Figure 2. Evolution of the probability of fit of the EVM and CTCR methods to the forecast of the final period of the Cardenillo hydroelectric project.

It is apparent that from the first months of execution, the CTCR methodology displays greater probability of fit than the EVM method. This indicates that CTCR predicts the period to completion of the Cardenillo project more efficiently than EVM. It is apparent that in month 10 before completion of the project, CTCR has a probability of 64.1% of correctly predicting the project's period of completion, while in the same period, EVM achieves a probability of only 34.7%. Similarly, in month 6 prior to completion, CTCR shows a probability of 99.3% compared with 97.4% for EVM.

4.2.2. Mazar Dudas Hydroelectric Project

The evaluation was performed in months 5, 10, and 15 after starting the simulated execution of the project, and in months 10, 8, 6, and 1 before the simulated completion of the project. Figure 3 presents the time evolution of how the EVM and CTCR methods fit in their forecasts of the final completion time of the Mazar Dudas project, according to the ten thousand scenarios of the simulation model. It is apparent that for the Mazar Dudas project, from the first months of execution, the CTCR methodology presents a greater probability of fit than the EVM method. This indicates that CTCR predicts the period to completion of the project more efficiently than EVM. It is apparent that in month 10 before completion of the project, CTCR has a probability of 42.8% of correctly predicting the project's period of completion, while in the same period, EVM achieves a probability of only 30.7%. Similarly, in month 6 prior to completion, CTCR shows a probability of 43.7% compared with 38.2% for EVM.

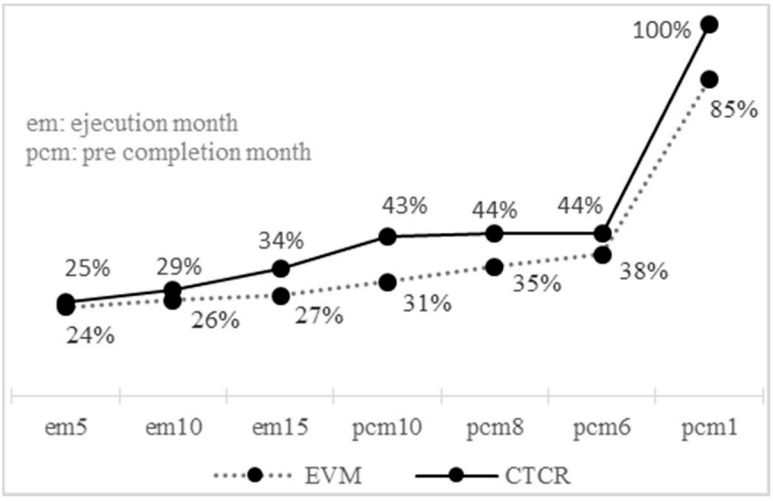


Figure 3. Evolution of the probability of fit of the EVM and CTCR methods to the forecast of the final period of the Mazar Dudas hydroelectric project.

4.2.3. Sopladora Hydroelectric Project

The evaluation was performed in months 10, 20, 30, and 35 after starting the simulated execution of the project, and in months 10, 8, 5, and 1 before the simulated completion of the project. Figure 4 presents the time evolution of how the EVM and CTCR methods fit in their forecasts of the final completion time of the Sopladora project, according to the ten thousand scenarios of the simulation model. It is apparent that from the first months of execution, the CTCR methodology presents a greater probability of fit than the EVM method. This indicates that CTCR predicts the period to completion of the Sopladora project more efficiently than EVM. It is apparent that in month 10 before completion of the project, CTCR has a probability of 57.3% of correctly predicting the project's period of completion, while in the same period, EVM achieves a probability of only 28.5%. Similarly, in month 5 prior to conclusion, CTCR shows a probability of 81.7% compared with 51.8% for EVM.

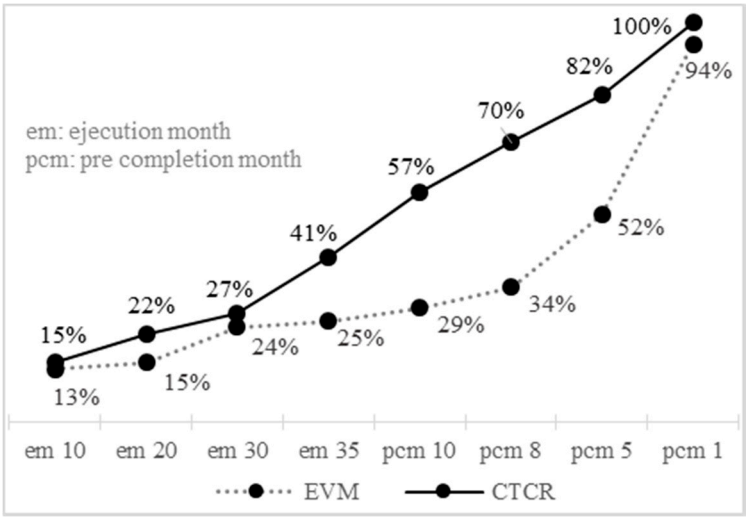


Figure 4. Evolution of the probability of fit of the EVM and CTCR methods to the forecast of the final period of the Sopladora hydroelectric project.

4.2.4. Santiago Hydroelectric Project

The evaluation was performed in months 10, 20, 30, 40, 50, and 60 after starting the simulated execution of the project, and in months 10, 8, 5, and 1 before the simulated completion of the project.

Figure 5 presents the time evolution of how the EVM and CTCR methods fit each other in their forecasts of the final completion time of the Santiago project, according to the ten thousand scenarios of the simulation model. It is apparent from the first months of execution that the CTCR methodology presents a greater probability of fit than the EVM method. This indicates that CTCR predicts the period to completion of the Santiago project more efficiently than EVM. It is apparent that in month 10 before completion of the project, CTCR has a probability of 43.6% of correctly predicting the project's period of completion, while in the same period, EVM achieves a probability of only 33.9%. Similarly, in month 5 prior to completion, CTCR shows a probability of 92.1% compared with 59.8% for EVM.

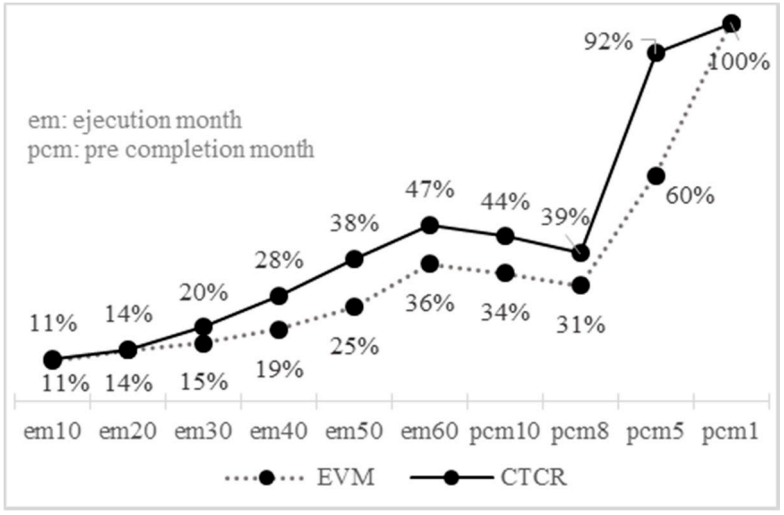


Figure 5. Evolution of the probability of fit of the EVM and CTCR methods to the forecast of the final period of the Santiago hydroelectric project.

4.3. Anova Analysis

This statistical analysis is based on a comparison between the means of the duration of the simulations carried out in each execution period and the means of the final completed duration in each simulation. The method displays efficiency when the means for each period are equal or similar to the means for the final obtained duration. In each period analyzed, there are 10,000 data points resulting from the 10,000 simulations performed. The simulation is applied in two stages. The first corresponds to the initial execution periods of the project and, depending on the projects in the case study, they are applied every 10 or 5 months according to the total planned period of each case study. The second stage corresponds to applying the simulation in the last 10 consecutive months prior to completion of the execution of the project.

The hypotheses for the one-way ANOVA analysis are as follows: null hypothesis (H0), all of the measurements are equal; alternative hypothesis (Ha), the measurements are not all equal; and, significance level $\alpha = 0.05$.

The application of the ANOVA analysis begins with the equal variance test, using a simultaneous Bonferroni confidence level of 95%. The multiple comparison test and Levene's test applied to the four study cases generated values equal to zero for p-value, both for EVM and CTCR. These results indicate that there is no equality of variances. These values, lower than the 0.05 significance level, indicate that neither CTCR nor EVM predict a correct duration of the project in all the simulation periods.

However, both methods show that they become more efficient during the process until forecasting becomes efficient. The Games–Howel test is applied to both methods to identify that moment. This test makes it possible to compare all the pairs in the group, with simultaneous control of the confidence level. The results obtained show differences between CTCR and EVM regarding the period in which efficient prediction values are achieved. The results for each case study are shown below.

Cardenillo hydroelectric project ANOVA. The results obtained for Cardenillo are shown in Table 4, where the *p*-value for the CTCR methodology shows equal means for the factor levels 6 months before the simulated completion of the project. Table 4 presents the results obtained with the EVM method, where equal means can be seen for the factor levels 5 months prior to the simulated completion of the Cardenillo project. However, it also shows an exception in month 4 prior to completion where the EVM prediction is not efficient.

Table 4. Results of the Games–Howell *p*-value test for equal means when applying the CTCR and EVM methodologies to Cardenillo.

Level Difference	CTCR		EVM	
	Mean Difference	*p*-Value	Mean Difference	*p*-Value
Completion-7 month	−0.2698	0.000	−0.6509	0.000
Completion-6 month	−0.0135	1.000	−0.2619	0.000
Completion-5 month	0.0754	0.675	0.0336	1.000
Completion-4 month	0.0455	0.995	0.1395	0.002
Completion-3 month	0.0233	1.000	0.0904	0.331
Completion-2 month	0.0071	1.000	0.0384	0.999
Completion-1 month	−0.0004	1.000	0.0093	1.000

Mazar Dudas hydroelectric project ANOVA. The results obtained for Mazar Dudas are shown in Table 5, where the *p*-value for the CTCR methodology shows equal means for the factor levels 4 months prior to the simulated completion of the project. Table 5 also shows the results obtained with the EVM methodology, where equal means can be seen for the factor levels 2 months prior to the simulated completion of the Mazar Dudas project.

Table 5. Results of the Games–Howell *p*-value test for equal means when applying the CTCR and EVM methodologies to Mazar Dudas.

Level Difference	CTCR		EVM	
	Mean Difference	*p*-Value	Mean Difference	*p*-Value
Completion-5 month	−0.3317	0.000	−10.866	0.000
Completion-4 month	−0.0442	0.603	−0.4190	0.000
Completion-3 month	−0.0415	0.723	−0.1990	0.000
Completion-2 month	−0.0444	0.636	−0.0519	0.340
Completion-1 month	−0.0086	1.000	−0.0190	0.999

Sopladora hydroelectric project ANOVA. In the model of this project, the *p*-value for the CTCR methodology shows an equality of means for the factor levels 4 months prior to the simulated completion of the project. Meanwhile, with the EVM methodology, equality of means is only obtained for month 4 prior to the simulated completion of the Sopladora project. These results are shown in Table 6.

Santiago hydroelectric project ANOVA. Finally, in the fourth case study, the *p*-value with the application of the CTCR method displays equal means for the factor levels 5 months prior to the simulated completion of the project. The *p*-value results obtained with the EVM methodology show equality of means for the factor levels 4 months prior to the simulated completion of the project. These results are presented in Table 7.

Table 6. Results of the Games–Howell *p*-value test for equal means when applying the CTCR and EVM methodologies to Sopladora.

Level Difference	CTCR		EVM	
	Mean Difference	*p*-Value	Mean Difference	*p*-Value
Completion-6 month	−0.3310	0.000	−0.9212	0.000
Completion-5 month	−0.1363	0.001	−0.3891	0.000
Completion-4 month	−0.0424	0.986	−0.0000	1.000
Completion-3 month	−0.0256	1.000	0.3961	0.000
Completion-2 month	−0.0075	1.000	0.5578	0.000
Completion-1 month	−0.0051	1.000	0.1988	0.000

Table 7. Results of the Games–Howell *p*-value test for equal means when applying the CTCR and EVM methodologies to Santiago.

Level Difference	CTCR		EVM	
	Mean Difference	*p*-Value	Mean Difference	*p*-Value
Completion-6 month	−0.3262	0.000	−10.810	0.000
Completion-5 month	−0.0985	0.488	−0.4753	0.000
Completion-4 month	−0.0799	0.844	−0.1201	0.170
Completion-3 month	−0.0790	0.874	−0.1192	0.216
Completion-2 month	−0.0758	0.919	−0.0991	0.590
Completion-1 month	−0.0394	1.000	−0.0658	0.980

The consolidated results of the ANOVA analysis are shown in Table 8, where we can see that in all of the case studies, the CTCR methodology provides more efficient predictions than the EVM methodology, as it makes appropriate predictions in earlier periods than the EVM predictions, suggesting that it gives the project management a longer margin of time for making decisions.

Table 8. Effective prediction of the duration to completion of the project applying the CTCR and EVM methods.

Hydroelectric Project	Estimated Duration (Months)	Effective Prediction CTCR (Months Prior to Completion)	Effective Prediction EVM (Months Prior to Completion)
Cardenillo	75	6	5
Mazar Dudas	27	4	2
Sopladora	47	4	1
Santiago	68	5	4

5. Conclusions

The CTCR methodology for the monitoring and control of complex construction projects integrates four fundamental components for weighting the activities that make up the timeline of a project. These are the cost of the activities, durations of the activities, critical path activities, and activities with higher risk of overdue periods and/or cost overrun. CTCR is based on standards and recommendations by established institutions with considerable experience in project management at an international level, such as the USA's Project Management Institute with its EVM methodology, the International Project Management Association, and International Standard ISO 21500:2012.

Incorporating the cost, time, criticality, and risk variables means that the CTCR methodology makes estimations of physical progress and predictions of period to completion of the project that are more precise than other traditional methodologies. The results obtained illustrate this. CTCR also incorporates an adaptation of the Analytical Hierarchy Process (AHP) decision model that makes it possible to give weightings to each component—cost, time, criticality, and risks—in the project,

making it possible to achieve more effective indicators of physical–financial progress and make less subjective forecasts.

Applying the CTCR methodology to four case studies in the hydropower sector has made it possible to demonstrate probabilistically and statistically that satisfactory results can be achieved, both in estimating physical–financial progress and in predicting cost and duration at completion of the projects with reasonable ranges for making decisions when faced with potential deviations, and even improving on the performance of other methodologies used extensively at the international level such as EVM.

With regard to cost forecasts, the CTCR methodology is based on the metrics proposed by EVM owing to their efficiency, which has been proven and presented in the previous research carried out by the authors and has already been cited previously in this work, where the behavior of the probability of fit can be appreciated in the same case studies presented in the present work.

The verification and demonstration of the efficiency of the application of the CTCR methodology in the four case studies is supported by statistical analyses, where probabilistic analyses and Monte Carlo simulation were initially applied to check efficiency in predicting the durations or periods of the project between the CTCR and EVM methods. We conclude that in the four case studies, the CTCR method demonstrates that it is more efficient than EVM in all of the simulations of execution of the projects. This is summarized in Figures 2–5. In addition, an ANOVA analysis or analysis or variance was performed to test the efficiency of period predictions through hypothesis testing, which determines whether the means of the prediction periods in different periods are equal to the value of the mean period from the simulation. From the results obtained and presented in Tables 4–7, we conclude that the CTCR method makes more efficient predictions than EVM, giving reliable predictive values with sufficient time for decision making prior to the completion of the project.

In countries such as Ecuador, where the government plans the construction of new hydroelectric plants in the short term, it is essential to have new control and monitoring methodologies that are able to improve the bad historical indicators of cost and execution time obtained from this kind of project. On the contrary, the results obtained in this work show the potential of the methodology to increase efficiency in the management and control of these projects but also in any other type of complex construction project.

The proposed methodology simultaneously considers four fundamental parameters for project management, which provides greater efficiency compared to other traditional techniques. This work makes it possible to appreciate this potential through the application to four real case studies within the hydropower sector. In addition, the application of multicriteria decision techniques, specifically the Analytic Hierarchy Process, to manage the impact of some parameters during the analyses of the project development represents another aspect of great interest for further works.

In this way, the authors identify two main research lines for further works in this field. First, there is the exploration of the possibilities of multicriteria techniques in the development of methodologies for the control and monitoring of complex projects. Second, the application of methodological approaches, as the one presented in this work, in projects in other sectors is another promising research area.

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