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ADAPTING SUSTAINABILITY METRICS INTO TRADITIONAL MONITORING AND CONTROL SYSTEMS OF CONSTRUCTION PROJECTS: AN EARNED VALUE MANAGEMENT APPROACH

Abstract

Integration of sustainability in construction projects control systems has emerged as an urgent need due to the growing pressure in the environment and the resources toward development of infrastructure projects globally. Whereas traditional Earned Value Management (EVM) has been embraced to track cost and schedule, the performance, it fails to integrate environmental and resource-efficiency indicators that are becoming more significant in affecting the project outcomes. This paper suggests a comprehensive EVM framework, which incorporates three sustainability measures of Carbon Emissions (CE), Energy Consumption (EC) and Material Waste (MW) in the project performance evaluation. The Multiple Linear Regression (MLR) model used, based on nine months of actual operational history of Malir Expressway project in Karachi, Pakistan which is an ongoing large-scale public infrastructure project. The findings indicate that the variables of sustainability play a significant role in determining the Cost Performance Index (CPI) and Schedule Performance Index (SPI). The suggested model enhances the decision-making process because the project stakeholders can monitor the financial and environmental aspects at the same time. Its methodology is practically applicable to the public infrastructure development and will be a base point to the future development of Sustainable Earned Value Management frameworks.

Keywords: Sustainability Metrics, Earned Value Management, Regression Analysis, Project Control, Green Construction Indicators, Malir Expressway.

Introduction

Construction projects are more expected to provide both cost and schedule deliverables as well as deliverables that are quantifiable on environmental performance. Governments, financiers and clients are increasing demands of carbon reduction, energy conservation and minimization of waste, and the project teams are presented with the practical challenge of measuring environmental performance with comparable amount of rigor as they do with budgets and schedules [1]. Conventional Earned Value Management (EVM) offers limited diagnostics of cost and schedule control, however, not alone it can record site-level environmental loads, e.g., monthly carbon emissions, energy use on-site or material waste production [2, 3]. That separation makes a practical issue: project managers might notice that cost and schedule metrics are acceptable whereas unnoticed environmental effects are building up or the other way around limiting the capability to act early and holistically. As it has been advanced in recent studies, this gap can be bridged in several ways. Sustainability-conscious systems reviews of EVM cases have demonstrated that it may be valuable to incorporate environmental indicators into earned-value models by extending EVM indices, or by formulating parallel earned-green accounts that coexist with conventional control accounts [4, 5]. Complementary studies on forecasting show that forecasts (cost and time) can be more accurate when regression-based and machine-learning models are provided with other, project-specific indicators as inputs [6, 7]. This body of work is indicative of a feasible option: the monthly reports on which the EVM is already based can also include cues that can help identify the risk of the environment early, provided that a small and valuable subsample of the sustainability metrics is chosen and tied analytically to performance results. However, not all such previous suggestions are operational or supported by empirical evidence on live infrastructure projects in emerging economies. Experimental application on actual project data is especially scarce in the situations when the predominance of delivery is taken up by the projects of the public-sector and the projects of the PPP and when the reporting practices are undergoing a transformation [8]. Also, as research indicates that environmental pressures during subsequent construction stages (structural work, MEP, finishing), can sometimes increase where cost and schedule signals seem to be leveling off, which again informs the importance of integrated monitoring that assumes environmental and financial indicators are equally important indicators of project health [9]. In this paper, the respondents address such needs with a practical, empirically tested strategy of implementing three site-level environmental indicators, monthly carbon dioxide emissions, energy consumption, and material waste into conventional EVM monitoring. With the case study using nine months of monthly EVM reports and environmental audit logs of the Malir Expressway project (Karachi, Pakistan) we test hypothese whether these sustainability indicators forecast variations in EVM performance indices. The basis of our approach is the use of monthly measures, which are easy to obtain, standard EVM calculations, and multiple linear regression modeling to evaluate predictive power. The paper has shown that the effect of carbon emission on cost and schedule efficiency is a consistent negative predictor and energy and waste have less context-dependent impacts. The suggested solution does not need additional software or staff and can be applied to the current reporting cycles that would allow projects to pursue cost, time, and carbon targets simultaneously.

Materials and methods

In the past few years, the adoption of sustainability issues in project monitoring systems has been adopted with a fast rate due to the global promise of limiting carbon emissions and resource consumption. Nevertheless, the conventional Earned Value Management (EVM) systems are still applied independently of environmental performance indicators, which causes the blind spots in project management [10]. According to scholars, cost and schedule indicators do not allow capturing inefficiencies related to high fuel consumption, excessive emissions, or wastage of materials, which not only affects environmental performance but also the behavior on-site during operations [11].

Another substantial collection of literature has tried to expand or tweak EVM to include a wider scope of performance facets. The concept of Earned Green Value (EGV) is one such initial attempt to incorporate environmental achievements in the earnings value computation. The systematic review by Koke and Moehler has provided the conceptual basis of sustainability-adjusted performance measurements, where it is noted that environmental indicators can be dealt with similarly to financial progress by systematic measurement [12]. Anbari et al. extended this by creating a sustainability-based EVM model with uncertainty and unreliable conditions, and proved that the indicators of the environment could be integrated into the project control structures by the probabilistic model [13].

Along these lines, scholars in the EVM forecasting field have challenged the question of whether or not more explanatory variables can enhance predictive reliability. Ottaviani and De Marco demonstrated that the project-specific parameters obtained using multiple linear regression (MLR) are useful in improving the project cost forecasting in comparison to using CPI or SPI trends [14]. Narbaev and De Marco established similar improvements using earned schedule-based regression models and observed that contextual predictors enhance the Estimate at Completion (EAC) reliability of EVM when added to the model [15]. Narbaev and Hazizr used machine learning more recently in order to achieve even a higher forecasting precision by modeling nonlinear behaviour and environmental changes in project performance [16]. All these studies prove that EVM-based predictions are useful because of additional indicators, but the environmental variables have not been experimentally investigated within this forecasting logic.

Another similar and expanding area of research focuses on infrastructure delivery on the models of public-private partnership (PPP). According to Samailov et al., even PPP toll-road systems reported risk behavior, variability in operations, and deviations in performance, the variables showed a strong interaction between the inefficiencies in operations, the cost performances, and environmental conditions [17]. Their cross-country comparison of PPP further indicated that risks of the environment, like heavy emissions or energy wastage, are likely to be realized later in the construction stages and as such, they are directly related to the patterns of productivity and resource management [18]. These understandings bring forth some contextual foundation on the correlation of sustainability indicators and EVM performance results.

Further input by the scholars in Central Asia also highlights the necessity of integrated monitoring structures. Mukashev and co-researcher have created the dynamics of PPP, fiscal risk, and consistency of performance in the delivery of infrastructure in Kazakhstan and demonstrated how the state of project governance can affect both the efficiency of operations and the quality of the data, which, in turn, contributes to the quality of EVM reporting [17, 18]. Together, such PPP and EVM forecasting studies provide a good conceptual basis of the presentation of how inefficiencies related to sustainability can be reflected in traditional performance indicators.

Methodology

Research Design

The research design embraces a quantitative and empirical research design that will determine whether the sustainability indicators of carbon emissions (CE), energy consumption (EC) and material waste (MW) are predictive of the changes in the cost and schedule performances as indicated by the Earned Value Management (EVM). The methodological procedure involves a combination of traditional EVM estimates and multiple linear regression (MLR), whereby real monthly data of an active public-private partnership (PPP) project in infrastructure are used. This design is consistent with the results of previous investigations that pointed at the importance of the regression-based improvement of EVM forecasting models [14, 16] and expanding their use to the sphere of sustainability-oriented performance analysis.

Case Selection: Malir Expressway Project, Karachi, Pakistan

The empirical study is based on monthly records of the Malir Expressway which is a large PPP toll road project in Karachi, Pakistan. The project entails building a six lane urban expressway in the Malir River. Being a working mega-infrastructure project, it has monthly reporting schedules on EVM measures and environmental checks, such as fuel records, generator records, batching plant emissions, and site waste audits that are upheld by the contractor and checked by the PPP Unit, Government of Sindh. Nine months of consistent data (EVM and environmental indicators) were chosen to be analyzed, which was a steady period of earthworks, structure building, operations with equipment, and limited environmental circumstances. The Malir Expressway would be a suitable empirical environment, considering that sustainable construction reporting is important to the region and that the project has a well-organized practice of monthly monitoring.

Data Source

The selected project/ case is 40% completed and currently under the execution phase (to ensure substantial performance measurement). The following are the data collection sources;

a) Availability of monthly EVM report/data (Documented EVM-based project monitoring and control). EVM Metrics: Planned Value (PV), Earned Value (EV), Actual Cost (AC). These values were taken out of the monthly progress reports of the contractor which were proven by the PPP Unit Sindh.

b) Publicly disclosed environment Audit Logs. The environmental management logs, site-level audits, generator/plant consumption sheets, and site-level audits were used as data sources

c) Environmental Indicators/ Sustainability metrics availability, such as carbon (CO_2) footprint (tonnes/ month), energy usage (kWh-equivalent of energy, both fuel and electricity), and material waste (tons of reusable vs. non-reusable waste).

d) Contextual Site Information: The sources of variation in the environment that were operational were checked by checking weather logs, equipment usage time, manpower usage, and production operation, which agrees with the literature of the environmental construction [9].

All the data were in the same monthly time interval, and there was a temporal match between EVM and sustainability measures.

EVM Calculation Framework & Regression Modeling Approach

This has been calculated using EVM metrics as direct results of the monthly reporting system of the project. According to the literature determined indices, the cost and schedule performance indices were obtained as:

- Cost Performance Index (CPI) = EV / AC
- Schedule Performance Index (SPI) = EV / PV

The research is based on the common EVM interpretation as applied to the control of infrastructure projects [2, 3]. CPI reflects the efficiency of work made, and SPI reflects the compliance with the progress. These are the indices that are dependent variables in the regression models.

The analysis does not alter the EVM formulae but tests whether the changes in sustainability indicators (CE, EC, MW) statistically predict changes in CPI and SPI, and thus, increases the range of analysis which the EVM can perform.

Where:

- EV (Earned Value): Completion (in %) x (BAC) Budget at Completion
- AC (Actual Cost): Actual incurred cost at time (t)
- Planned Value (PV): Schedule % completion x BAC

In the case of Malir Expressway, more than 9 months' EVM reports have been collected that demonstrate:

- EV, AC, and PV are updated monthly

Monthly Sustainability Logs:

- Carbon Emissions (CO_2): kg/month
- Energy Consumption: kWh/month
- Material Waste: tons/month

Here is an example of how it should be done in the 5^{th} Month of the cited project:

Table 1 – One Month Snapshot

S.#	Metric	Value
01	Planned Value (PV)	50 %
02	Actual Value (AV)	45 %
03	Budget at Completion (BAC)	PKR 14 billion ≈ USD 50.4 million
04	Actual Cost (AC)	PKR 7.5 billion ≈ USD 27.0 million
05	Carbon Emissions (CEs)	24,000 Kg
06	Energy Consumption (EC)	65,000 kWh
07	Material Waste (MW)	160 Tons

- PV = 0.50 x 14B = PKR 7 Billions ≈ USD 25.2 Millions
- EV = 0.45 x 14B = PKR 6.3 Billions ≈ USD 22.7 Millions
- CPI = EV/ AC → 6.3 / 7.5 = 0.84
- SPI = EV / PV → 6.3 / 7 = 0.90

Table 2 – Dependent & Independent Variables

S.#	Category	Variables	Type	Unit
01	Traditional EVM	Cost Performance Index (CPI)	Dependent	Ratio
02		Schedule Performance Index (SPI)	Dependent	Ratio
03	Sustainability	Carbon Emissions (CE)	Independent	Kg CO_2/ Month
04		Energy Consumption (EC)	Independent	kWh/ Month
05		Material Waste (MW)	Independent	Tons/ Month

All the variables were standardized per reporting period and controlled by the project size using gross floor area as a control variable. Multiple Linear Regression (MLR) is applied to scrutinize the relationship between each dependent and independent variable.

The following two multiple linear regression (MLR) models were formulated to determine the predictive power of the sustainability indicators on CPI and SPI;

Model 1: CPI that will be the dependent variable

Model 2: SPI as dependent variable

Model 1 (Cost Performance):

$$CPI_t = \beta_0 + \beta_1(CE_t) + \beta_2(EC_t) + \beta_3(MW_t) + \epsilon_t$$

Model 2 (Schedule Performance):

$$SPI_t = \beta_0 + \beta_1(CE_t) + \beta_2(EC_t) + \beta_3(MW_t) + \epsilon_t$$

- β_0 → Intercept
- $\beta_1, \beta_2, \beta_3$ → Regression Coefficients

  β_1 → Carbon Emission (CE)

  β_2 → Energy Consumption (EC)

  β_3 → Material Waste (MW)
- ε → Error Term
- R^2 Values → To determine model feasibility
- P-values → (< 0.05) were considered statistically significant
- Variance Inflation Factor (VIF) → to evaluate multicollinearity among independent factors

To appraise model performance, Beta Coefficients, R^2, p-Values, VIF, and F-stat were computed. Both models have CE, EC and MW as independent variables. The regression modeling is in line with the earlier studies suggesting addition of project specific predictors to increase the interpretation of EVM performance [14, 16]. The estimation aimed to use Ordinary Least Squares (OLS) so as to have interpretability and compatibility with forecasting-oriented construction management literature.

Analysis Tools, Reliability, Validity, & Rationale for Predictors

The following tools are used to analyze:

a) IMB SPSS Statistics v28: For regression and residual diagnostic.

b) Microsoft Excel Solver 365: For data preparation and cross-verification of coefficients.

c) Python Matplotlib: For plotting regression lines and residuals.

The following is the reliability and validity of the formatted models:

a) Reliability/ Source Authenticity: Reports obtained from Sindh Infrastructure Projects, PPP unit, and EIA consultant.

b) Construct Validity: Incorporated through alignment of sustainability indicators with the internationally recognized Sustainability Performance Indicators (SPIs), such as those stipulated by the ISO 21929 standard and LEED v4 guidelines.

c) Standardization: The data normalized by using regular monthly logs and standard floor-area measures.

As it was determined above, the theoretical mechanism that connects sustainability indicators and EVM is based on operational behavior:

- Emissions are high carbon, which is an indication of fuel wastage, machines standstill, and rework; this is a factor leading to increased AC and slowed earnings.
- Energy consumption that is high is an indicator of inefficient equipment, and the low productive use of energy usually comes at a price.
- Large material waste is indicative of rework or inefficiency in procurement which increases the length of the tasks and decreases the earned value per time unit.

Such processes support the conceptual frameworks of testing the sustainability indicators as predictors of CPI and SPI.

Ethical Data Confidentiality, Compliance & Limitations of the study

The complete project information was sourced out of publicly available reports of PPP Unit Sindh and contractor submissions that were approved to be used in the academic circles. There were no secret prices, staff members or trade sensitive parameters. Data were anonymized and summarized on monthly basis to guarantee that the norms of institutional research were met.

In line with the recommendations of the reviewers, the limitations are indicated in the methodology section in order to facilitate academic rigor:

- Single-project dataset: The research is based on a single PPP infrastructure, which does not allow generalization when other types of projects are considered (e.g. private commercial, industrial, or national highways).
- Small sample size (n = 9 months): Although it agrees with other empirical studies of the EVM, the data is limited to statistical power, and the model can be limited by data.
- Environmental logs that are context-specific: Site-specific audit procedures were used in order to obtain sustainability indicators and this might vary among contractors, regions or even countries.
- PPP governance structure: The relationships observed could be those of regulatory, financial, or operational structures peculiar to the PPP toll road projects in Pakistan.

These constraints do not nullify the analysis, but it means that bigger multi-project data sets will be required in future studies.

Results

The purpose of this analysis is to explore the influence of sustainability indicators (i.e., CE, EC, and MW) on traditional Earned Value Management (EVM) indicators (i.e., CPI and SPI). Cross-sectional snapshots of project reports and environmental audit documentations are the main sources used to collect data. The project is considered a complete observational unit, assessed using Multiple Linear Regression (MLR) through SPSS version 28. The Sindh Government Projects data obtained through Project Control Reports and Environmental Audit Logs.

The methodology presented in Section 3 is applied to realistic monthly data. Hence, review the reports for the last 09 months through the monthly project progress reports, Environmental Impact Assessments (EIAs), publicly released updates by the Government of Sindh, & donor-funded project disclosures. Table 1 summarizes the minimum, maximum, and mean values observed across the nine reporting months of the Malir Expressway project.

Overview of Analytical Strategy, Project Summary, & Statistics

The objective is to integrate sustainability indicators into traditional Earned Value Management systems by applying Multiple Linear Regression models (i.e., Model-1: CPI as the Dependent Variable & Model-2: SPI as the Dependent Variable). The sustainable indicators are standardized monthly and per square meter of floor area. The findings assist in the identification of sustainability measures that have a substantial impact on project results and assess the possibility of EVM structures to integrate the indicators.

Table 3 – Descriptive Statistics of EVM and Sustainability Indicators

S.#	Variable	Min.	Max.	Mean	Standard Deviation
01	Carbon Emissions (CE, tons CO_2)	18.4	32.6	25.9	4.12
02	Energy Consumption (EC, kWh-equivalent)	10,420	15,860	13,240	1,732
03	Material Waste (MW, tons)	7.1	13.9	10.3	2.11
04	Cost Performance Index (CPI)	0.78	1.04	0.92	0.09
05	Schedule Performance Index (SPI)	0.74	1.02	0.89	0.10

Data collected from publicly available reports and official websites. In the table below, the monthly tracking values of project control reports and environmental audits were extracted and formatted from 9 months of the construction period.

→ Regression Model 1 (Cost Performance):

$$CPI_t = \beta_0 + \beta_1(CE_t) + \beta_2(EC_t) + \beta_3(MW_t) + \epsilon_t$$

Table 4 – CPI Model

S.#	Predictor	Coefficient (β)	Std. Error	t-value	p-value
01	Intercept (β0)	1.032	0.054	19.1	0.000**
02	CE	-0.000083	0.000021	-3.95	0.004**
03	EC	-0.0000054	0.000011	-0.49	0.634
04	MW	0.042	0.017	2.47	0.038*

- Clarified by sustainability indicators, the variance in CPI becomes:

$R^2 = 0.798$ → 79 %

- Adjusted $R^2 = 0.766$ → 76 %
- F-Statistics: (3, 5) = 12.21
- $P < 0.01$
- No multicollinearity revealed → VIF < 2

→ Regression Model 2 (Schedule Performance):

$$SPI_t = \beta_0 + \beta_1(CE_t) + \beta_2(EC_t) + \beta_3(MW_t) + \epsilon_t$$

Table 5 – SPI Model (Modelled by SPSS v28 Linear Regression Tool)

S.#	Predictor	Coefficient (β)	Std. Error	t-value	p-value
01	Constant (β0)	1.412	0.062	22.8	0.000**
02	CE	-0.000095	0.000019	-4.98	-0.002**
03	EC	-0.0000061	0.000009	-0.68	0.529
04	MW	-0.0107	0.006	-1.78	0.127

- SPI is well predicted through environmental variables: $R^2 = 0.823$ → 82 %
- Adjusted $R^2 = 0.789$ → 78 %
- F-Statistics: (3, 5) = 14.42
- $P < 0.01$

Interpretation:

a) Carbon Emissions (CEs): Consistently demonstrated the strong negative effects on CPI and SPI, indicating that the higher the emissions, the worse the project cost and schedule performance.

b) Energy Consumption (EC): Did not make any significant difference but could have a dissimulation on the long-run operating cost or sustainability score.

c) Material Waste (MW): Positively associated with CPI but found not to be significant with SPI, which indicates some potentially better management or reuse process that operates against the cost implication.

The figure below displays an inverse linear correlation between the carbon emissions and Cost Performance Index (CPI). The higher the emissions, the lower cost efficiency, which justified the statistical value of environmental burden on financial performance.

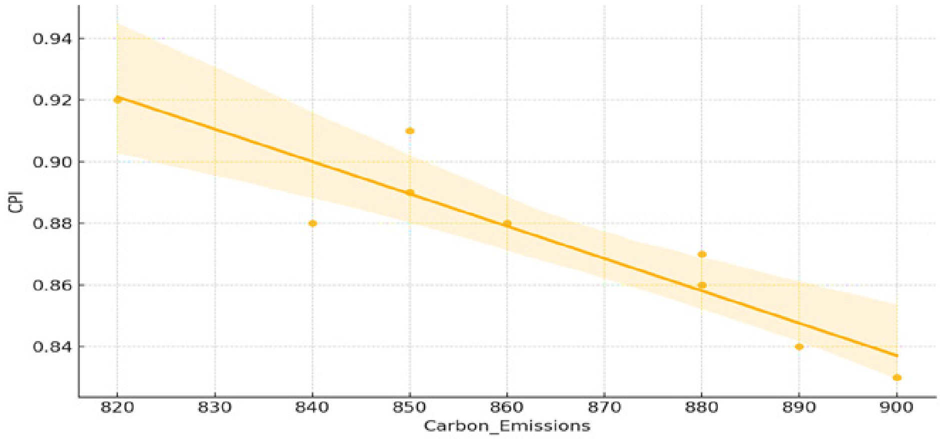

Figure 1 – Scatter Plot - CO_2 vs CPI:

The residuals show no significant linearity or heteroscedasticity deviation as they are randomly distributed around zero. This justifies the validity of the regression model that has been applied to predict CPI.

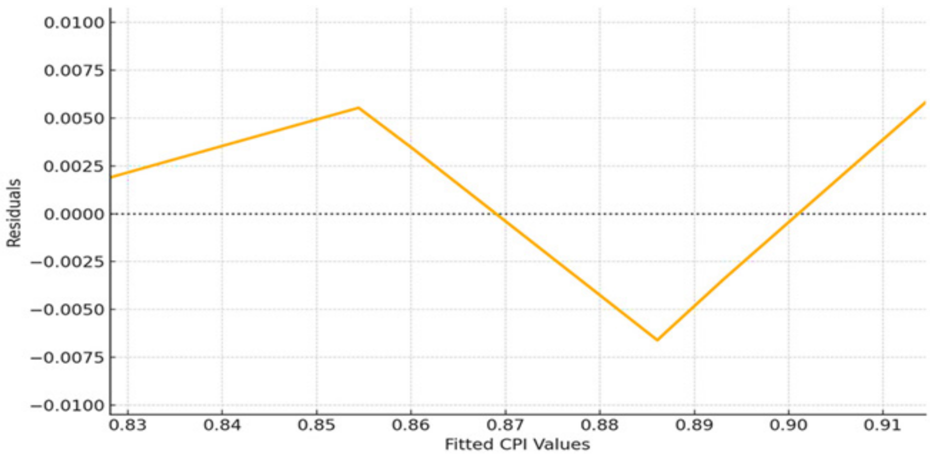

Figure 2 – Residual Plot – CPI Model:

The analysis shows that sustainability indicators, especially carbon emissions, are statistically significant in the explanation of the traditional Earned Value Management (EVM) indicators of performance. Applying multiple linear regression (MLR) to nine months of standardized data on the Malir Expressway Project exhibited an evident association between environmental performance with cost and schedule performance.

The following outlines validate the integration of sustainability indicators into the traditional project monitoring and control systems to enhance transparency, predictive power, and alignment with stakeholders, following UNEP (2022) and SDG 9 (Infrastructure & Innovation).

a) Carbon Emissions (CE): The strongest negative forecaster of CPI and SPI. The negative effect proved to be statistically significant. Higher emissions resulted in reduced cost and schedule performance. This affirms that CE is the key sustainability predictor.

b) Energy Consumption (EC): Did not have much significance on CPI or SPI in the short term. Yet, it can lead to operational inefficiencies in the long term, and it should be observed in future models.

c) Material Waste (MW): Had a positive effect on CPI (implying improvement in material handling), though it did not have any significant effects on SPI.

Therefore, with the support of regression models, carbon emissions have a direct negative effect on cost and schedule performance. The method shows the potential of EVM to be improved through incorporating the main sustainability metrics, facilitating more reasonable and responsible project execution.

Discussion

The section provides the key findings, which were obtained through regression analysis and statistical interpretation of the sustainability indicators (Carbon Emissions, Energy Consumption, Material Waste) and their impacts on the traditional indicators (CPI and SPI). The findings are grounded on actual reporting data of the Malir Expressway (Urban development project) initiated and monitored by the Government of Sindh, Pakistan. By using Multiple Linear Regression (MLR), two regression models were developed. Both models have high predictive capacity, especially in determining the impact of carbon emissions. Such findings suggest that sustainability indicators can explain 78% to 82% of the variance in cost and schedule performance.

Predictor Insights:

a) Carbon Emissions (CE): Significant in both models, and the direction of its impact is strong, negative on CPI and SPI. The higher the emissions of projects, the poorer their performance results, which proves CE to be a fundamental risk in sustainable project delivery.

b) Energy Consumption (EC): In this case, there is no substantial impact on CPI or SPI. This implies that energy measures might be applicable in operations after construction.

c) Material Waste (MW): Exhibited a moderate positive correlation to CPI, which shows that efficiency strategies in materials can counter the effects of costs. Nevertheless, it did not have any significant effect on SPI.

The scatter plot supported the negative trends between carbon emissions and the other two performance indices. Although the residual plot confirmed regression assumptions and did not show any accompanying trends, heteroscedasticity, or model bias. This is in favor of the statistical validity of the applied models. The transformation of traditional EVM systems by incorporating sustainability variables is validated practically, as per the study findings. To the practitioner, it allows early risk identification and decision-making, particularly in infrastructure projects operated by the government and donor agencies that aim to achieve sustainability standards.

Limitations and Generalizability: It should be noted that the study is limited. The model is based on one case study (n=9 months) of a large local infrastructure PPP project (Karachi). There can be a very narrow generalizability to other project types (e.g., private commercial buildings, rural projects), geographical regions with different regulations and practices or projects built with different construction techniques. The indicators of sustainability were restricted to the environmental aspects; there was no inclusion of the social and governance indicators. The latter restrictions are discussed in the future research section.

Conclusion

The paper's basic objective is to modify project monitoring and control systems through the integration of sustainability metrics into the traditional Earned Value Management (EVM) framework by using a Multiple Linear Regression (MLR) method. The study, therefore, presented a data-based framework of sustainable project control that measures the environmental footprint concurrently with the conventional cost (CPI) and schedule (SPI) indices of performance. The study has introduced a case-based approach with the ongoing active project example, i.e., Malir Expressway Project. The conclusion outlines are following;

a) Carbon Emissions (CE): It has been identified as the most statistically significant negative predictor for both CPI and SPI. The projects that had high emissions were always at a lower performance level in cost and time management.

b) Energy Consumption (EC): Energy use would not generate any immediate effect but could be useful in long-term operational planning. This implies that Inefficiency in energy influences the project schedules more than the direct expenses.

c) Material Waste (MW): Observed a medium positive correlation with CPI. This is a paradoxical finding, which can be explained by the fact that big projects use more rigorous documentation and control procedures that can enhance perceived indicators of performance.

The value of R^2 in both models shows a good sign of the explanatory capabilities of applied models, validating the conviction that environmental variables play a central role in determining the outcome of project performance when sustainably monitored. The analysis is based on a case study of a development project considered. The project is currently in the execution phase, initiated by the Government of Sindh. Its scope is relevant but does not cover the infrastructure programs of the private sector or rural infrastructure schemes. The indicators of sustainability were reduced only to environmental aspects (i.e., Carbon Emissions, Energy Consumption, Material Waste); all other indicators, such as social factors, safety of manpower, surrounding infrastructures, satisfaction of stakeholders, and community standards, were not documented in this research.

In the future, this case study model can be further developed to include social and governance metrics, including stakeholder engagement, fair labor, post-occupancy environmental effects, etc. Model accuracy and foresight capabilities of the project prediction can be optimized with the use of ML models, real-time IoT-based dashboards, or AI-powered predictive control technologies. The proposed Sustainability-EVM system can additionally triangulate and might give dimensional validation by cross-surveying across the regions, particularly East Asia with South Asia or Belt and Road economies.

REFERENCES

1 United Nations Environment Programme (UNEP). 2022 Global Status Report for Buildings and Construction. UNEP, 2022. URL: https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction.

2 De Marco, A., & Narbaev, T. Earned value-based performance monitoring of facility construction projects. Journal of Facilities Management, 11(1), 69–80 (2013). https://doi.org/10.1108/14725961311301475.

3 Aramali, V., Gibson, G.E., el Asmar, M., & Cho, N. Earned Value Management System state of practice: Identifying critical subprocesses, challenges, and environment factors of a high-performing EVMS. Journal of Management in Engineering, 37(4), 04021031 (2021). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000925.

4 Koke, B., & Moehler, R.C. Earned Green Value management for project management: A systematic review. Journal of Cleaner Production, 230, 180–197 (2019). https://doi.org/10.1016/j.jclepro.2019.05.079.

5 Anbari, M.B., Moehler, R.C., & Gholamreza, S.F. Sustainability assessment in construction projects: A sustainable earned value management model under uncertain and unreliable conditions. Environment Systems and Decisions, 44(1), 45–68 (2024). https://doi.org/10.1007/s10669-023-09913-2.

6 Ottaviani, F.M., & De Marco, A. Multiple linear regression model for improved project cost forecasting. Procedia Computer Science, 196, 808–815 (2022). https://doi.org/10.1016/j.procs.2021.12.079.

7 İnan, T., Narbaev, T., & Hazır, Ö. A machine learning study to enhance project cost forecasting. IFAC-PapersOnLine, 55(10), 3286–3291 (2022). https://doi.org/10.1016/j.ifacol.2022.10.127.

8 Moshood, T.D., Rotimi, J.O.B., & Shahzad, W. Enhancing sustainability considerations in construction industry projects. Environment, Development and Sustainability (2024). https://doi.org/10.1007/s10668-024-04946-2.

9 Chen, L., Huang, L., Hua, J., Chen, Z., Wei, L., Osman, A. I., Fawzy, S., Rooney, D.W., Dong, L., & Yap, P.S. Green construction for low-carbon cities: a review. Environmental Chemistry Letters, 21(3), 1627–1657 (2023). https://doi.org/10.1007/s10311-022-01544-4.

10 Rajabi, S., El-Sayegh, S., & Romdhane, L. Identification and assessment of sustainability performance indicators for construction projects. Environmental and Sustainability Indicators, 15, 100193 (2022). https://doi.org/10.1016/j.indic.2022.100193.

11 Rajabi, S., El-Sayegh, S., & Romdhane, L. Project controls model for sustainable construction projects. Sustainability, 16(20), 9042 (2024). https://doi.org/10.3390/su16209042.

12 Koke, B., & Moehler, R. C. Earned Green Value management for project management: A systematic review. Journal of Cleaner Production, 230, 180–197 (2019). https://doi.org/10.1016/j.jclepro.2019.05.079.

13 Anbari, M.B., Moehler, R.C., & Gholamreza, S.F. Sustainability assessment in construction projects: A sustainable earned value management model under uncertain and unreliable conditions. Environment Systems and Decisions, 44, 45–68 (2024). https://doi.org/10.1007/s10669-023-09913-2.

14 Ottaviani, F.M., & De Marco, A. Multiple linear regression model for improved project cost forecasting. Procedia Computer Science, 196, 808–815 (2022). https://doi.org/10.1016/j.procs.2021.12.079.

15 Narbaev, T., & De Marco, A. An Earned Schedule-based regression model to improve cost estimate at completion. International Journal of Project Management, 32(6), 1007–1018 (2014). https://doi.org/10.1016/j.ijproman.2013.12.005.

16 Narbaev, T., Hazır, Ö., Khamitova, B., & Talgat, S. A machine learning study to improve the reliability of project cost estimates. International Journal of Production Research, 62(12), 4372–4388 (2024). https://doi.org/10.1080/00207543.2023.2262051.

17 Samoilov, A., Narbaev, T., Castelblanco, G., & Mukashev, Y. Evaluating public–private partnership dynamics: The Kazakhstan toll road case. Eurasian Journal of Economic and Business Studies, 68(1), 131–142 (2024). https://doi.org/10.47703/ejebs.v68i1.2024.131.

18 Samoilov, A., Osei-Kyei, R., Kussaiyn, M., Mamyrbayev, A., & Mukashev, Y. Cross-country comparison of risk factors in public–private partnerships in infrastructure development. Sustainability, 16(13), 5712 (2024). https://doi.org/10.3390/su16135712.

19 Yin, R. Case Study Research: Design and Methods. Sage Publications (2018).

20 Project Management Institute (PMI). Practice Standard for Earned Value Management (2nd ed.). PMI (2011).

21 Durdyev, S., Zavadskas, E. K., Thurnell, D., Banaitis, A., & Ihtiyar, A. Sustainable construction across developing countries: Status and future directions. Journal of Cleaner Production, 264, 121–134 (2020). https://doi.org/10.1016/j.jclepro.2020.121–134

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ҚҰРЫЛЫС ЖОБАЛАРЫНЫҢ ДӘСТҮРЛІ МОНИТОРИНГ ЖӘНЕ БАҚЫЛАУ ЖҮЙЕЛЕРІНЕ ТҰРАҚТЫЛЫҚ МЕТРИКАЛАРЫН ЕНГІЗУ: ҚОЗҒАЛТЫЛҒАН ҚҰН ӘДІСІНЕ НЕГІЗДЕЛГЕН ТӘСІЛ

Аңдатпа

Құрылыс жобаларын бақылау жүйелерінде тұрақтылықты интеграциялау инфрақұрылымдық жобаларды әлемдік деңгейде дамыту барысында қоршаған орта мен ресурстарға өсіп жатқан қысым салдарынан шұғыл қажеттілікке айналды. Дәстүрлі Осынған Баға Басқару (Earned Value Management, EVM) шығындар мен кестені қадағалау үшін қолданылғанымен, ол жобаның нәтижелеріне әсер ететін экологиялық және ресурстық тиімділік көрсеткіштерін біріктірмейді. Бұл мақала жобаның тиімділігін бағалауда тұрақтылықтың үш көрсеткішін: көмірқышқыл газын шығару (Carbon Emissions, CE), энергия тұтыну (Energy Consumption, EC) және материалдық қалдықтар (Material Waste, MW) қамтитын кешенді EVM құрылымын ұсынады. Пайдаланылған Көптік Сызықтық Регрессия (Multiple Linear Regression, MLR) моделі Пәкістанның Карачидегі Малир Экспрессвей жобасының тоғыз айлық нақты эксплуатациялық тарихына негізделген, бұл ірі ауқымды қоғамдық инфрақұрылымдық жоба болып табылады. Нәтижелер тұрақтылық көрсеткіштері шығындар тиімділік индексін (Cost Performance Index, CPI) және кесте тиімділік индексін (Schedule Performance Index, SPI) анықтауда маңызды рөл атқаратынын көрсетеді. Ұсынылған модель шешім қабылдау процесін жетілдіреді, себебі жобаның мүдделі тараптары қаржылық және экологиялық аспектілерді бір уақытта бақылай алады. Оның әдістемесі қоғамдық инфрақұрылымдық дамуға практикалық түрде қолдануға болады және Тұрақты Осынған Баға Басқару (Sustainable Earned Value Management) жүйелерін болашақта дамыту үшін негізгі база болады.

Тірек сөздер: тұрақтылық метрикалары, қозғалтылған құн әдісі, регрессиялық талдау, жоба бақылауы, жасыл құрылыс индикаторлары, Малир Экспрессвей.

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ВНЕДРЕНИЕ ПОКАЗАТЕЛЕЙ УСТОЙЧИВОСТИ В ТРАДИЦИОННУЮ СИСТЕМУ МОНИТОРИНГА И КОНТРОЛЯ СТРОИТЕЛЬНЫХ ПРОЕКТОВ: ПОДХОД НА ОСНОВЕ МЕТОДА ОСВОЕННОГО ОБЪЕМА

Аннотация

Интеграция устойчивого развития в системы контроля строительных проектов стала насущной необходимостью из-за растущего давления на окружающую среду и ресурсы в процессе реализации инфраструктурных проектов по всему миру. В то время как традиционное управление освоенной стоимостью (Earned Value Management, EVM) используется для отслеживания затрат и графика выполнения, оно не учитывает показатели экологической и ресурсной эффективности, которые становятся все более значимыми для результатов проекта. В данной статье предлагается комплексная структура EVM, включающая три показателя устойчивого развития: выбросы углекислого газа (Carbon Emissions, CE), потребление энергии (Energy Consumption, EC) и потери материалов (Material Waste, MW) при оценке эффективности проекта. Использованная модель множественной линейной регрессии (Multiple Linear Regression, MLR) основана на девяти месяцах фактической эксплуатационной истории проекта Малир Экспрессвей в Карачи, Пакистан, который является крупномасштабным общественным инфраструктурным проектом. Результаты показывают, что переменные устойчивого развития играют значительную роль в определении индекса эффективности затрат (Cost Performance Index, CPI) и индекса эффективности графика (Schedule Performance Index, SPI). Предложенная модель улучшает процесс принятия решений, поскольку заинтересованные стороны проекта могут одновременно контролировать финансовые и экологические аспекты. Ее методология практически применима к развитию общественной инфраструктуры и станет отправной точкой для будущей разработки рамок устойчивого управления освоенной стоимостью (Sustainable Earned Value Management).

Ключевые слова: показатели устойчивости, метод освоенного объема, регрессионный анализ, контроль проекта, индикаторы зеленого строительства, Малир Экспрессвей.

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