

Original Article

Evaluating Preliminary Estimation Bias and Operational Delays in Indian Public Procurement: Evidence from Infrastructure Projects and Alignment with SDGs

Papolu Pramod¹, Srikonda Ramesh², Kranti Kumar Myneni³, Faiz Ahmed Chundeli⁴

^{1,2,3,4}Department of Architecture, School of Planning and Architecture, Vijayawada, Vijayawada, India.

¹Corresponding Author : papolupramod@gmail.com

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Abstract - This study examines the empirical nexus between early-stage budgeting bias, post-award contract execution timelines, and macroeconomic sustainability within India's premier construction agency, the Central Public Works Department (CPWD). Moving away from subjective stakeholder surveys, this paper uses an unaggregated, project-specific baseline built from two large-scale historical datasets ($n = 994$ for planning; $n = 861$ for execution). A parametric paired t-test confirms a systemic pre-award overestimation trend ($t(993) = 14.83, p < .001$), with baseline preliminary estimates exceeding final expenditures by an average of ₹1,319.98 lakhs. This practice creates an artificial capital lock-up that directly undermines SDG 9. Conversely, multiple linear regression reveals that post-award schedule delays exhibit a minor but statistically significant negative partial correlation with cost overruns ($\beta = -.09, p = .012$), supporting the budgetary cushion hypothesis. Prolonged project standstills do not drive linear cost growth; instead, they cause execution halts that freeze expenditures while causing severe environmental degradation, raw material waste, and compromises on green design standards (SDG 12, SDG 13). Ultimately, this paper outlines data-driven validation filters, such as Reference Class Forecasting, to mitigate artificial resource tie-ups and optimize public funds for sustainable infrastructure networks.

Keywords - Public works, India, CPWD, Time and cost overrun, SDG, Cost estimation bias.

1. Introduction

The construction sector plays a pivotal role in India's economic development and is the second-largest contributor to the national economy after agriculture. It is a major driver of employment, industrial growth, and infrastructure creation. According to the Ministry of Statistics and Programme Implementation (MoSPI), the construction sector recorded a growth rate of 10.7% during 2023–24, continuing the positive trend observed in previous quarters, which registered growth rates of 5.7% and 8.3% in the third and fourth quarters of 2022, respectively [1].

Recognizing the importance of infrastructure in sustaining economic growth, the Government of India has consistently increased public investment in this sector. In the Union Budget 2025, capital expenditure on infrastructure was raised to INR 11.21 lakh crores from INR 11.11 lakh crores in the previous year, accounting for approximately 3.1% of the national Gross Domestic Product (GDP). This investment is intended not only to stimulate economic activity and private investment but also to generate employment and strengthen the country's resilience against global economic uncertainties [2].

The demand for infrastructure is expected to increase substantially over the coming decades as India undergoes rapid urbanisation. The country's urban population is projected to reach nearly 600 million by 2036, placing significant pressure on housing, transportation, water supply, sanitation, and other urban services. To meet these growing demands, India will require an estimated US\$840 billion in urban infrastructure investment over the next fifteen years, equivalent to approximately US\$55 billion annually [3]. Given the magnitude of this investment, improving the efficiency with which public infrastructure projects are planned and executed has become an important policy priority.

Despite sustained public investment, the delivery of infrastructure projects in India continues to be affected by persistent time and cost overruns. Delays in public projects have been reported for several decades and still remain one of the most significant challenges facing the construction industry [4]. According to the Project Management Institute [5], major public infrastructure projects in India experience an average delay of nearly 45 months. Such delays not only postpone the delivery of essential public services but also



reduce the economic returns expected from infrastructure investments. During periods of limited public resources constraints, prolonged project durations also lead to inefficient utilisation of government funds and restrict the implementation of other planned development projects [6].

Recent statistics published by MoSPI further illustrate the scale of the problem. As of March 2024, 779 of the 1,873 ongoing major infrastructure projects monitored by the Government of India were delayed with schedule overruns ranging from one month to as much as 275 months [7]. Over the last decade, the proportion of delayed projects has increased from 29.44% in 2014 to 41.59% in 2024. Interestingly, while delays have become increasingly common, the percentage of projects experiencing cost overruns has remained relatively stable at around 19%. This contrast suggests that the relationship between schedule performance and project cost may be more complex than is often assumed and warrants further investigation.

Execution and management of public works is more challenging when compared to private projects since public works are executed under the influence of a regulated atmosphere, administrative approvals, audit compliances and requirements, financial sanctions, procurement procedures, and many other institutional manuals. Therefore, technical performance with transparency, accountability, compliance, while coordinating a diverse group of stakeholders, including government agencies, consultants, regulatory authorities and contractors are involved and needs to be balanced in public works [8]. Hence, the public works are different from private works.

In the existing literature, construction delays have received considerable attention, but research on Indian public projects remains scarce. Recent studies have identified the delay attributes using questionnaire surveys, expert literature reviews, interviews, and case studies [9-11]. Undeniably, these approaches have enhanced understanding of project management issues, however, the findings are mostly based on perceptions of different stakeholders involved and expert judgement. These methods are characteristically influenced by the experience of the respondents, organisational context, and interpretation, which are subjective. Hence, they do not precisely reflect the actual performance of completed works. Another limitation of existing literature is the lack of extensive empirical analyses based on verified project data. Historical data on completed public projects was very limited, restraining the ability of researchers to evaluate the performance of the projects using objective evidence. Because of the aforesaid circumstances, there is limited understanding of how time and cost overruns progress in public projects and if consistent patterns exist in project estimation and execution. Very few studies have observed whether the preliminary estimates systematically differ from final project costs using actual closing out data.

From the perspective of sustainable public finance, this study is very important. Green investments, innovative financing mechanisms, circular economy practices, or Industry 4.0 technologies are often discussed in sustainable infrastructure [12-16]. But comparatively little importance has been given on improving the efficacy of existing public funds. Preparing realistic cost estimates, reducing delays, and ensuring effective utilisation of allocated funds are also equally important for the government's to deliver more infrastructure with available financial resources and not only on raising additional capital.

Preliminary Estimates (PE) are the basis in the Central Public Works Department (CPWD), to obtain financial sanctions and administrative approval for public works. Preliminary estimates, which are prepared using plinth area rates and latest cost indices acts as initial financial commitment for every project. Previous studies have suggested that estimators and clients may intentionally adopt conservative estimates to minimise the professional risks associated with budget underestimation [17, 18]. While such practices may reduce financial uncertainty at the project level, systematic overestimation can result in unnecessary locking of public funds, limiting the government's ability to finance other infrastructure projects. Despite its importance for fiscal planning, this issue has received very limited empirical attention in the Indian public sector.

Against this background, an important research gap remains. Existing studies have largely relied on perception-based approaches and have rarely used verified project completion data to simultaneously examine time overruns, cost overruns, and the accuracy of preliminary estimates across a large portfolio of public works. Moreover, the relationship between project delivery performance and public financial efficiency has not been adequately explored. Consequently, there is limited empirical evidence available to support reforms in project planning and budgeting within government construction agencies.

The present work directly targets these unaddressed areas by analysing a large database of completed works executed by the Central Public Works Department (CPWD) across India. This study has evaluated the project performance using actual project records, unlike earlier studies, which are mainly relied on questionnaire surveys or expert opinions. Along with time and cost overruns, this study also investigates existence of any overestimation in the preliminary estimates. Sustainability in public works has been viewed in a new lens, combining optimal public funds utilization and project performance, extending beyond financing mechanisms.

The main objectives are accordingly derived as (i) to assess the scale and trends of schedule and cost overruns in completed CPWD works, (ii) to study the relation between time and cost overruns using actual project data, (iii) to study

the existence of overestimation of preliminary estimates if any, and (iv) to frame recommendations based on the conclusions of this study for improving public project delivery and sustainable financing strategy. It is expected that the findings of this study shall contribute to existing literature in public project delivery and for improving public works policy for achieving Sustainable Development Goals in India.

2. Previous Studies

2.1. Systemic Factors Affecting Time Overruns in Public Procurement

Even today, across the globe, the most persistent challenges influencing public projects are time and cost overruns. The delay attributes may vary from country to country, but a combination of financial, contractual, technical and administrative factors are present in the literature. Most common delay attributes identified during a study in fourteen countries like Benin, Egypt, Ethiopia, Malaysia, Pakistan, and the United Kingdom, are owner-related financial constraints, delays in contractor payments, unrealistic project timelines, regular design changes, contractor financial constraints, and inadequate planning [19]. From the above study, it can be noted that many project delivery challenges across economic and governance contexts are systemic rather than isolated to individual countries.

At the same time, the way these factors influence project performance depends largely on the institutional environment in which projects are executed. Different procurement systems, like contractual provisions, administrative procedures, and regulatory requirements, are to be balanced in public construction projects. Therefore, conclusions from a particular country or in one government cannot be applied to another similar circumstance. Hence, there is a need to study and understand delays in a country and executing agency specific context.

As highlighted by [20] in a recent review, most of the studies from the existing literature rely on stakeholder's perceptions rather than actual project records. It was also concluded that a very small fraction of the reported delay attributes were taken from the objective sources like completion reports, contractual documents, or institutional archives, and a major fraction were from interviews, questionnaire surveys, and previous literature. The review also highlighted that very few empirical studies are present from the Indian public works context when compared to global studies, and indicates that operational characteristics of government projects in India are still documented insufficiently.

Across the construction management literature, majority of the studies kept its focus on perception-based research. [21], observed that majority of the studies adopted questionnaire surveys, with the Relative Importance Index (RII) as most common tool, and many stakeholders believe

that the contribution from these studies identified various delay factors which influence project performance. However, their findings inevitably depend on respondents' experience, organisational background, and professional judgement. Different stakeholders often perceive the same project differently, making it difficult to determine how individual factors actually affect project outcomes [11, 22].

For this reason, there is growing recognition that perception-based studies should be complemented with analyses based on verified project data. Historical project records provide an opportunity to examine what actually occurred during project execution rather than what participants remember or perceive after project completion. Such datasets also allow researchers to investigate the statistical relationships between project characteristics, schedule performance, and cost outcomes using objective evidence. As larger project databases become increasingly available, data-driven approaches are expected to play a greater role in improving the understanding of project performance and supporting evidence-based decision-making in public infrastructure management [23].

2.2. Methodological Divergences in Project Scale and Cost Overrun Analysis

Project size has a considerable influence on time and cost overruns, as per the empirical studies conducted on recorded project data. Central Public Works Department (CPWD) projects were studied, and it was concluded that time overruns increased with project cost, ranging from an average of 229 days for projects costing less than INR 1 crore to 459 days for projects exceeding INR 50 crores. A consistent cost overrun was observed across all the project categories, with an average cost overrun of 46%. Delay attributes were also not the same across various project sizes. Scope changes, design revisions, administrative approvals and delays in the issue of structural drawings were frequent hurdles for large projects. While lack of funds, rainfall and delay in approvals are consistent in medium-sized projects, whereas delay in handing over of site and work in occupied building facilities are affected factors in small projects [20]. It can be suggested that the delay mitigation strategies are to be planned different for various project characteristics instead of a common approach.

The trends were also similar for the major infrastructure public projects, which were being monitored by the Ministry of Statistics and Programme Implementation (MoSPI). Across various sectors, transportation sector recorded the highest levels of time and cost overruns, crossing 265% and 249%, respectively [11]. Regulatory approvals, land acquisition, environmental approvals, and cost escalation of materials are the main delay attributes in India and other countries [11, 24].

Planning of projects has also got importance in project performance. Due to the greater stakeholder focus, stronger monitoring and realistic scheduling large sized projects in

terms of duration are often reporting lower percentage schedule overruns [11]. In view of large and complex project datasets, investigators have increasingly adopted advanced analytical techniques, such as random forest regression, to capture the non-linear relationships between project characteristics and performance more effectively than conventional regression models [24].

2.3. Preliminary Cost Estimation and Systemic Overestimation Bias

The fundamental focal point for any project to be delivered successfully is the accurate cost estimation at the planning stage. Comparing the accuracy of the estimate has got its own importance, and traditionally it was compared with the accepted tender price for assessment [17]. Even though this method is conventional in many procurement settings, the budget performance of public works cannot be imagined since the accepted tender cost will not always be the same as final project cost, while operating contractual provisions, design modifications, price escalation, and other adjustments that occur during project execution. Comparing final completion costs with preliminary estimates was also discussed by various scholars in the recent past for a more realistic assessment [25, 26].

Trusted project records and discrepancies in project documentation was always a constraint due to its limited access from the past to use the final project costs in estimation research [27, 28].

The influence of organisational and behavioural factors on cost estimation was also highlighted in the earlier studies. Conservative estimates were adopted by quantity surveyors and public clients to reduce the risks associated with budget shortfalls, contract variations, or funding constraints [17, 18]. One advantage of this system is that it improves financial security, but it also leads to overestimation.

The focus of the majority of researchers was on cost underestimation and cost overruns, particularly in relation to forecasting accuracy, earned value management, and project risk [18, 29]. But the overestimation was understudied, particularly in public works in India. Overestimation is very vital for public projects where the capital sanctions are dependent on the preliminary estimates. The ability to finance other infrastructure projects gets decreased if the excess overestimated funds are locked up in individual projects for long periods. Very few studies were available in the literature relating to overestimation in public works.

2.4. Interface of Infrastructure Finance, Digital Innovation, and SDGs

Long-term financial sustainability, resource efficiency and environmental performance are the extended arms of sustainable infrastructure research expanding beyond project delivery. The effect of climate change on construction

schedules was studied in recent investigations [30, 31], carbon emissions during project execution [32, 33], and the influence of the latest digital technologies, such as Building Information Modelling (BIM), Project Management Information Systems (PMIS), and real-time monitoring tools, in improving project performance [34]. Similarly, green investments, innovative funding systems, circular economy models are gaining popularity to achieve Sustainable Development Goals (SDGs) [12, 15, 16]. However, the focus is limited to financial sources but very minimal on the efficient utilisation of already allocated public funds.

In public works, time and cost overruns, overestimation will reduce efficiency in terms of prolonged project durations, locking up financial resources which would get utilized in other investments. Despite its importance, the topic remains underexplored. Addressing this gap is essential for improving fiscal efficiency and promoting more sustainable infrastructure development.

2.5. Articulation of the Research Gap

Delays in Public projects were well studied in the literature, the institutional and contractual implication, its impact and causes need further focus, particularly in Central Public Works Department (CPWD), which is India oldest central public works department. Secondly, the financial sustainability needs to be investigated in a new lens in terms of overestimation of preliminary estimates. Third, most previous studies rely on questionnaire surveys and perception-based ranking methods, with relatively few using verified project completion records to examine actual project performance. A large dataset was utilized from CPWD archival data, providing empirical evidence on time and cost performance, and preliminary estimate bias using objective project records.

3. Data and Methods

3.1. Institutional Context and Empirical Sampling

The Central Public Works Department (CPWD) is one of the premier public works executing agency in India. This department works under the administrative control of Ministry of Housing and Urban Affairs, Government of India. The data utilized for this study was retrieved from the construction works portal and customized reports system openly available in the official website of CPWD. Time and cost overruns were studied for the project completed during the years 2016-17 and 2017-18, utilizing the first data set. This data includes project cost, planned, actual start and completion dates, and final project expenditure. Before analyzing the completeness and consistency, the data consists of 1,979 project records. To investigate the preliminary cost estimation bias, a second long-term dataset was utilized. The data of completed projects spanning from 2009 to 2024. A total of 19302 completed projects were extracted, and 18,308 projects were excluded in view of the non-availability of expenditure detail.

3.2. Variables and Operational Definitions

The performance of the projects for the dataset between 2016-18 are worked out using three basic metrics. Let M represent the planned project duration (in days), N represent delay (in days), and the final financial deviation by O (in INR lakhs). The project duration (M) is the stipulated time allowed for completion of work as per the original contract agreement of the work. Schedule delay (N) is the difference between the actual completion date and the stipulated completion date. A positive value in delay indicates a project slippage, whereas a negative value represents an early completion. Cost overrun (O) is the absolute financial variance between the expenditure after completion of work and the initial contract value in lakhs. A negative value reflects a net structural saving post-execution.

3.3. Data Cleaning and Functional Filtration

The assumptions of Ordinary Least Squares (OLS) regression were satisfied to ensure that the 2016–2018 time-cost dataset accurately reflects true field execution patterns. 1,979 raw project details were subjected to multiple deterministic filtering process. During the first stage, incomplete data entries, rescinded works, contracts which were not executed, and administrative data entry errors were pruned. Certain projects with missing timelines ($n = 81$) were systematically excluded. Petty works with project durations of less than 7 days ($M < 7$, $n = 36$) and very low-value projects with an agreement value below INR 11akh ($L < 1$, $n = 13$) were excluded to maintain focus on substantial public infrastructure projects. A substantial number of projects ($n = 745$) without final actual expenditures in the dataset were also removed, as the calculation of cost overrun (O) requires this metric. To isolate valid contract execution behaviors, works exhibiting early completions exceeding 50% of the planned duration ($N < -0.5 \times M$, $n = 26$) were filtered out. Further works with abnormal recorded savings exceeded 70% of the original agreement amount ($O < -0.7 \times L$, $n = 217$) were also removed because these may represent premature agreement termination or administrative abandonment instead of true operational efficiency. Following these deterministic filters, a refined baseline of 861 fully executed public works projects was established, removing a total of 1,118 non-viable records.

3.4. Outlier Treatment via Winsorization

Further examination of the balance 861 projects exposed substantial right-skewness and extreme variance. The maximum time overruns were observed upto 2,507 days, while the cost overruns peaked at INR 4,228.64 lakhs. Keeping these extreme values may excessively alter the OLS regression parameters due to the minimizing of squared residuals, while also violating the normality constraints of model residuals.

A two side winsorization was adopted and implemented with boundaries derived from the Interquartile Range (IQR) method to mitigate the outliers and to retain the sample size.

The escaping values of the upper and lower fences ($Q3 + 1.5 \times IQR$ and $Q1 - 1.5 \times IQR$) were replaced with the respective fence values. An upper statistical fence of 806 days was placed for the Schedule Delays (N). Accordingly, 39 projects with delays exceeding this threshold were capped at exactly 806 days using the minimizing function.

Further, for the Cost Overruns (O), the upper financial fence was determined to be INR 44 lakhs. A total of 111 projects exceeding this limit were capped at INR 44 lakhs. For Cost Savings (O), the lower financial fence for structural savings was fixed at INR -48.33 lakhs. A total of 109 projects falling below this boundary were brought up to INR -48.33 lakhs. This combined treatment stabilized the error variance across the dataset while preserving the full sample size of 861 projects for subsequent empirical modeling.

3.5. Analytical Modeling of Time-Cost Interdependencies

Methodologically, project-level correlation and regression models were applied to assess relationship between time and cost overruns without the distortions inherent in data aggregation. Previous study relied on analyzing combined group averages, and a positive correlation coefficient was obtained, and time overruns clarified 58.73% of the variance in project costs with minimal residual autocorrelation [20]. This statistical analysis on aggregated data values would largely decrease statistical power, conceals localized project-scale heterogeneity, then introduces a risk of ecological fallacy, and artificially overstate trend linearity by smoothing out operational noise and project-level outliers.

Accordingly, project-level data has been utilized in this study to address the aforesaid errors in the analysis. Ordinary Least Squares (OLS) linear regression and multiple linear regression was adopted utilizing the 861 number of project level data set, which was previously adopted in the literature to study project performance. [11, 24]. To verify the model's validity, residual diagnostics and coefficients of determination are subsequently evaluated on an unaggregated basis.

3.6. Evaluation of Early-Stage Planning and Estimation Bias

The statistical significance of deviations between the approved preliminary estimates and actual close-out expenditures from the 2009–2024 project records ($n = 994$) is determined using a paired t-test. This parametric technique evaluates whether the observed variances reflect random estimation noise or systemic institutional overestimation by comparing the paired difference between the initial planning parameters and final commitments.

This verification is paired with descriptive statistics, visualization, and savings calculations to quantify the volume of public funds unnecessarily tied up during the planning phase, directly measuring the impact of estimation patterns on institutional capital efficiency.

4. Findings and Results

4.1. Trends of Preliminary Estimates in CPWD and Paired T-Test

Out of 994 projects sorted, the actual expenditure for 142 projects exceeded the approved preliminary estimates with an average cost of INR 656 lakhs. For 852 projects, the preliminary estimates are higher than the actual expenditure, with an average overestimation of INR 1649 lakhs. The total savings of the works for the 15 years of data (2009- 2024) is calculated using the following formula:

$$TS = \sum_{i=1}^n (PE_i - AE_i) \quad (1)$$

Where:

TS represents the Total Savings in INR lakhs.

PE_i represents Preliminary Estimate in INR lakhs an individual project i .

AE_i represents Actual Expenditure in INR lakhs after work completion an individual project i .

n represents the total number of fully reconciled project contracts within the active analytical sample.

Using equation (1), the total savings of the works is calculated:

Table 1. Statistics and t-test for Paired Samples

	n	Mean	Std. Deviation	Std. Error Mean	
Preliminary Estimate in INR lakhs	994	3858.01	5568.81	176.63	
Actual expenditure incurred in INR lakhs	994	2538.03	4513.06	143.15	
Correlation					
	n	Correlation	p		
Preliminary Estimate in INR lakhs - Actual Expenditure incurred in INR lakhs	994	0.87	<.001		
t-test for paired samples					
	t	df	p	Cohen's d	
Preliminary Estimate in INR lakhs - Actual Expenditure incurred in INR lakhs	14.83	993	<.001	0.47	
95% Confidence Interval of the Difference					
	Mean	Std. Deviation	Std. Error Mean	Lower limit	Upper limit
Preliminary Estimate in INR lakhs - Actual Expenditure incurred in INR lakhs	1319.98	2806.89	89.03	1145.29	1494.67

Table 2. Hypotheses

Null hypothesis	Alternative hypothesis
There is no difference in the mean value between the variables Preliminary Estimate in INR lakhs and Actual Expenditure incurred in INR lakhs.	There is a difference in the mean value between the variables Preliminary Estimate in INR lakhs and Actual Expenditure incurred in INR lakhs.

Total Savings (TS) = 3834860 – 2522799 = 1312070

Average savings per year in Crores: INR 87471 lakhs.

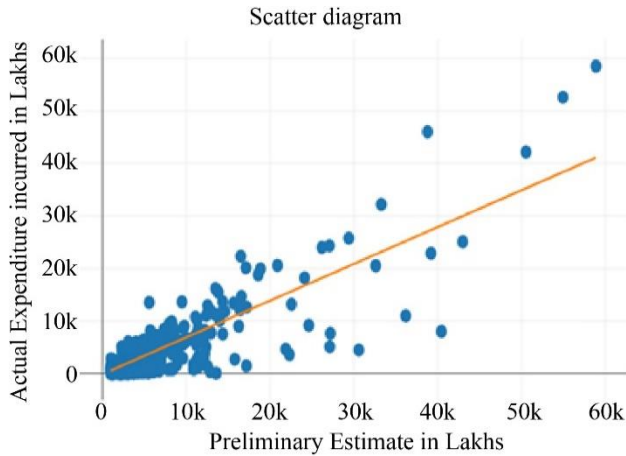


Fig. 1 Scatter plot of preliminary estimate and actual expenditure

From Table 1, it can be observed that the average preliminary estimate for the projects (INR 3858.01 lakhs) was higher than the actual expenditure (INR 2538.03 lakhs). A paired sample t-test confirmed that this difference is statistically significant, with $t(993) = 14.83$, $p < .001$, and a 95% confidence interval between INR 1145.29 and INR 1494.67 lakhs. Since the p-value is well below the standard threshold of 0.05, we can confidently say this result is not due to chance. The null hypothesis in Table 2 (that there is no difference) is rejected, suggesting that the preliminary estimates and actual expenditures likely come from different distributions. The scatter plot between preliminary estimate and the actual expenditure is depicted in Figure 1.

4.2. Bivariate Correlation Analysis

A Pearson correlation analysis examined the linear relationship between Delay in days and Cost Overrun (INR lakhs). The analysis revealed a negligible negative correlation, $r(859) = -.07$, $p = .033$. The 95% confidence interval for the population correlation ranged from -0.14 to -0.01. Although the result was statistically significant at $\alpha = .05$, the effect size was exceptionally small. Normality assumptions were violated for both variables (Shapiro-Wilk $p < .001$), which may affect the validity of the p-value, though the large sample size ($N = 861$) provides robust sampling distributions.

4.3. Simple Linear Regression Modeling

A simple linear regression was conducted to predict Cost Overrun (INR lakhs) from Delay in Days. The model included 861 valid cases and explained a statistically significant but minute proportion of the variance, $R^2 = .01$, adjusted $R^2 = .00$, $F(1, 859) = 4.56$, $p = .033$. The standard error of the estimate was 26.93. The intercept was not statistically significant, $B = 0.85$, $SE = 1.36$, $t = 0.63$, $p = .531$, 95% CI [-1.82, 3.53]. Delay in Days emerged as a significant negative predictor, $B = -.01$, $SE < .01$, $\beta = -.07$, $t = -2.13$, $p = .033$, 95% CI [-0.02, 0.00].

Assumption diagnostics indicated violations of residual normality (Shapiro-Wilk $W = 0.93$, $p < .001$; Anderson-

Darling $A^2 = 22.17$, $p < .001$) and severe positive autocorrelation (Durbin-Watson = 0.00, $p < .001$). Standardized residuals ranged from -1.84 to 1.87, with no values exceeding the ± 3 threshold for outliers. Multicollinearity diagnostics were not applicable for the single-predictor model.

4.4. Multiple Linear Regression Modeling

A multiple linear regression was conducted to predict Cost Overrun (INR lakhs) simultaneously from Agreement Amount, Project Duration in Days, and Delay in days. The model was estimated using $n = 861$ valid complete cases. The overall model was statistically significant, $F(3, 857) = 4.11$, $p = .007$, and explained a small proportion of the variance in the dependent variable ($R^2 = .01$, adjusted $R^2 = .01$). The standard error of the estimate was 26.84.

Regarding individual predictors, Delay in days remained a statistically significant negative predictor ($B = -0.01$, $SE < .01$, $\beta = -.09$, $t = -2.52$, $p = .012$, 95% CI [-0.02, 0.00]). Conversely, baseline contract metrics were not statistically significant: Agreement Amount ($B = 0.00$, $SE < .01$, $\beta = .06$, $t = 1.46$, $p = .145$, 95% CI [0.00, 0.00]) and Project Duration ($B = 0.01$, $SE < .01$, $\beta = .06$, $t = 1.53$, $p = .126$, 95% CI [0.00, 0.01]). The intercept was not significant ($B = -0.76$, $SE = 1.55$, $t = -0.49$, $p = .624$, 95% CI [-3.81, 2.29]).

Residual normality was violated according to both the Shapiro-Wilk ($W = 0.94$, $p < .001$) and Anderson-Darling ($A^2 = 20.43$, $p < .001$) tests. The Durbin-Watson statistic ($DW = 0.00$, $p < .001$) suggested strong positive autocorrelation. Multicollinearity was completely absent, as all tolerance values were safely above 0.10 and Variance Inflation Factors (VIF) were well below the standard threshold of 10 (Agreement Amount: $VIF = 1.25$; Project Duration: $VIF = 1.23$; Delay in Days: $VIF = 1.03$). The standardized residuals have not exceeded the threshold of ± 3 , without any extreme outliers. Upon visual inspection of residual plots and empirical scatter plots, homoscedasticity and linearity were verified.

5. Discussion of Results

5.1. Pre-Award Budgeting and Institutional Estimation Bias

The parametric paired t-test evaluation demonstrates that the mean preliminary estimate ($M = \text{INR } 3,858.01$ lakhs, $SD = 5,568.81$) was significantly higher than the actual project expenditure incurred ($M = \text{INR } 2,538.03$ lakhs, $SD = 4,513.06$), resulting in a highly significant financial gap ($t(993) = 14.83$, $p < .001$, 95% CI [INR 1,145.29 lakhs, INR 1,494.67 lakhs]). The result indicated a systematic overestimation trend in the preliminary estimates, as zero is not present in the confidence interval, and the null hypothesis is rejected. A conservative estimating pattern is reflected to create financial buffers to mitigate future risks of the project. Due to this pattern of overestimation, public funds shall be allocated inefficiently, capitals is locked up which could have

been utilised for other sustainable projects in need, and this pattern will also create administrative barriers that prolong initial project approval timelines.

5.2. Post-Award Execution and the Budgetary Cushion Hypothesis

The operational dynamics of the project gets shifted once the project gets started. Standard infrastructure risk literature generally documents schedule delays and budget expansions as coupled variables that follow a consistent, positive trajectory. For example, [11] used project-level cross-plots across 30 Indian mega-projects to identify a positive trend where protracted delays drove up final costs due to prolonged overheads. In a study across 138 South Asian projects adopting regression and machine learning techniques, it was concluded that time overruns compound non-linearly due to continuous resource commitments [24].

By comparison, the unaggregated CPWD asset dataset ($N = 861$) exhibits a different structural distribution. The isolated bivariate correlation ($r = -.07$, $p = .033$) shows that schedule delays account for a negligible 1% ($R^2 = .01$) of cost variance, indicating that a predictable linear trajectory is not present. Further, the multiple linear regression model identified a statistically significant, negative partial regression coefficient for schedule delays ($\beta = -.09$, $t = -2.52$, $p = .012$), where every additional day of schedule deviation is associated with a reduced average cost overrun of INR 0.01 lakhs. Conversely, initial contract scale (Agreement Amount: $p = .145$) and planned timelines (Project Duration: $p = .126$) were statistically insignificant.

The budgetary cushion hypothesis was supported by this inverse relationship, highlighting an operational variance. Since the preliminary estimates are overestimated, they carry a financial cushion with an average of INR 1,145 lakhs, and the individual projects shall run within an integrated financial cushion from inception, accommodating all the schedule delays. Further, these delays do not accumulate cost overruns daily, but may reflect other operational standstills or resource halts which are consequential to administrative, land acquisition, or legal bottlenecks. And because of these halts in the works, the site expenditures shall drop to minimal or zero, and the unspent budget remains frozen. Financial growth is therefore insulated from continuous temporal expansion, manifesting instead as sudden, episodic shocks driven by post-award scope modifications or material price adjustments made when operations resume.

5.3. Sustainability Implications and Data Diagnostics

Although prolonged standstills do not drive linear financial growth, they introduce critical environmental compromises that directly impact project sustainability. As a result of these delays, there will be an increase in energy consumption, water and raw materials in terms of the extended maintenance of temporary site infrastructure facilities,

increasing carbon emissions from non-renewable energy sources and exposing stockpiled materials to weather-induced degradation, which increases landfill waste. The said delays may also lead to decisions from administration to compromise on green building factors and frequent design changes to minimise the delays and cost overruns. Further, opportunities shall also be lost due to these delays in terms of green financing which has strict deadlines, reducing the budget available for integrating sustainable technologies and weakening public confidence in the green credentials of public infrastructure.

To ensure academic transparency, the severe positive autocorrelation ($DW = 0.00$, $p < .001$) and non-normal residual distributions ($p < .001$) must be recognized as common structural traits in heavy-tailed public procurement datasets. The structural dependency ($DW = 0.00$) indicates that contract files are administratively clustered—likely by geographic division, contractor portfolios, or the specific fiscal year of funding approval. This clustering compresses standard errors, meaning that while the directional negative effect ($\beta = -.09$) is institutionally accurate, individual contract variations are governed by episodic operational shocks rather than standard temporal or baseline contract metrics, offering a more precise explanation of cost overruns than traditional aggregated studies.

5.4. Scale-Dependent Execution Dynamics: A Comparative Evaluation of Global and Localized Delay Paradigms

From a global comparative study, late payments, unrealistic timelines, financial hurdles of the owner, frequent changes in design, instability of the contractor and improper planning are the identified delay triggers from the literature relating to public infrastructure projects [19]. The delay attributes identified within CPWD [20], suggest that the risks are nonuniform and are heavily dependent on contract scale. The CPWD data aligns with these global trends regarding design fluidity in high-value mega-projects (INR 50 Crores), where disruptions are almost entirely driven by administrative variations like client-directed modifications to approved drawings and scope adjustments, as well as funding gaps in mid-to-low tier portfolios (INR 5 to 50 Crores and < INR 1Crore), where a lack of funds ranks as a dominant bottleneck ($F=42$ and $F=51$, respectively where F denotes frequency of delay factor occurrence). However, the CPWD framework diverges significantly from the global public works baselines documented by [19], by isolating a highly specific institutional practice in minor works (<INR 1Crore), where pre-construction site handover delays and partial site availability stand out as the single most critical disruption across the entire study ($F=68$). This localized bottleneck indicates that smaller contracts are frequently awarded before legal or physical possession is secured, forcing projects into immediate operational standstills that freeze spending and validate the negative regression coefficient ($\beta = -.09$) established in the present execution analysis. Furthermore, the CPWD dataset

departs from global trends by showing notable insulation from contractor-side performance instability, which appears minor across all tiers, while revealing that environmental variable like seasonal rainfall act as an unmitigated, recurrent disruptor ($F=21$) across all lower financial portfolios due to a lack of flexible scheduling contingencies in standard contract templates.

6. Conclusion

This study evaluated the operational and financial dynamics of public infrastructure delivery within the CPWD framework across pre-award planning and post-award contract execution lifecycle phases. By utilizing an unaggregated project-level approach across a substantial contract dataset, a clear distinction between initial budgeting assumptions and real-world field performance was established.

A consistent pattern of overestimation was identified in the preliminary estimation stage of the CPWD projects upon conducting the parametric paired t-test on the dataset. The preliminary estimates are on observed to be the higher side when compared to the final project expenditures ($t(993) = 14.83$, $p < .001$). This systematic overestimation locks up public funds that could otherwise fund parallel infrastructure assets, slows down initial administrative approval pipelines, and reduces the precision of public expenditure forecasting tools.

Once contracts entered the active execution stage, the multiple linear regression model demonstrated that baseline contract dimensions—specifically initial Agreement Amount ($p = .145$) and planned Project Duration ($p = .126$)—exerted no linear predictive influence over final budget expansions. More significantly, the model identified a statistically significant, negative partial regression coefficient for schedule delays ($\beta = -.09$, $p = .012$). Every additional day of schedule deviation was associated with an average cost overrun reduction of INR 0.01 lakhs. This inverse relationship points to a distinct institutional process within standard public works execution: because individual contracts operate within an artificially inflated financial boundary from inception, the routine daily overhead costs generated by schedule deviations are absorbed by the initial buffer. Long delays typically indicate operational freezes or project standstills driven by administrative, land acquisition, or legal bottlenecks. During these prolonged pauses, active expenditure drops to zero, and cost overruns manifest later as sudden, episodic shocks driven by post-award scope revisions or material price adjustments made when active work finally resumes. Long delays typically indicate operational freezes or project standstills driven by administrative, land acquisition, or legal bottlenecks. Furthermore, these delay dynamics are highly dependent on contract scale, with high-value mega-projects disrupted by upstream design fluidity and client scope revisions, whereas minor contracts face operational freezes due to immediate pre-

construction site handover delays and partial site availability. During these prolonged pauses, active expenditure drops to zero, and cost overruns manifest later as sudden, episodic shocks driven by post-award scope revisions or material price adjustments made when active work finally resumes.

Although these prolonged standstills do not trigger a steady, linear accumulation of daily financial costs, they impose critical compromises on project sustainability and directly impact the United Nations Sustainable Development Goals (SDGs). At the planning stage, the capital lock-up driven by overestimation bias actively undermines SDG 9 (Industry, Innovation, and Infrastructure) by keeping scarce public resources idle within inflated accounts, thereby stalling parallel regional network expansions and weakening the state's capacity to build resilient public assets. Once in the execution phase, extended timelines lead to increased consumption of energy, water, and raw materials due to the continuous maintenance of temporary site infrastructure, directly undermining sustainable consumption targets (SDG 12) and increasing carbon emissions (SDG 13). Furthermore, execution delays frequently lead to late-stage design modifications where green engineering elements are sacrificed to meet delayed deadlines or cut costs. These timeline slippages also increase the risk of missing strict deadlines for green financing or government grants, which limits the budget available for integrating sustainable technologies and weakens public confidence in the environmental credentials of public infrastructure.

To resolve these interconnected inefficiencies across both the planning and execution stages, a systemic refinement of the public procurement framework is recommended. Policymakers should implement an 'Outside View' protocol that enforces multi-stage validation filters for preliminary budgets, legally mandating the use of Reference Class Forecasting (RCF) during the conceptual phase to apply programmatic downward adjustments against a centralized cost ledger, while integrating Simple Linear Regression Analysis (SLRA) and Radial Basis Function (RBF) Neural Networks at post-design milestones to correct structurally inflated unit schedules. Transitioning to these advanced data-driven techniques, alongside adopting fast-track administrative approval mechanisms, will shorten project standstills, prevent the artificial capital lock-up that undermines SDG 9, protect environmental baselines, and optimize public fund allocations. While the contract sample analyzed in this study represents a small fraction of the total public works portfolio, this localized assessment establishes an empirical foundation and provides a clear methodological reference for future, comprehensive infrastructure lifecycle studies utilizing complete national datasets.

Conflicts of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

All data that support the findings of this study are

available from the corresponding author upon reasonable request. These data were derived from the following resources available in the public domain at.

1. <https://cpwdpms.gov.in/pmspublicdomain.aspx>
2. <https://cpwdpms.gov.in/ProjectReport.aspx>

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