REVISTAMATÉRIA V.30
ISSN 1517-7076 articles e20240738, 2025

Analysis and evaluation of Cost of Quality (COQ) elements on total quality costs in construction projects: design of experiments

Indhiradevi Palanisamy[1], Saravanakumar Palanichamy[2]

[1]KPR Institute of Engineering and Technology, Civil Engineering. 641407, Coimbatore, Tamilnadu, India.
[2]Government College of Engineering, Civil Engineering. 638316, Erode, Tamilnadu, India.
e-mail: drpindhiradevi@gmail.com, grpsaravanan@gmail.com

ABSTRACT
The Cost of Quality (COQ) is widely recognized in manufacturing as a critical performance metric, yet its application in the construction industry remains less established due to fundamental differences in characteristics and environments. While integrating COQ into the planning and building phases of construction projects appears straightforward in theory, practical implementation proves challenging. This study investigates the impact of COQ elements on total quality costs, analyzing 16 building projects using factorial design techniques. Internal and external failure costs emerged as significant factors affecting overall quality, with variations in prevention, appraisal, and failure costs emphasizing the critical role of preventive measures in minimizing quality-related expenses. Statistical hypothesis testing confirmed the substantial influence of failure costs on total quality costs, with Yate's algorithm and 2^4 factorial design experiments offering deeper insights into factor effects. The findings underscore the importance of strategic preventive actions, providing valuable implications for enhancing quality management practices, reducing failure costs, and improving overall project efficiency in the construction sector.

Keywords: Environment-friendly; Factorial design; Preventive measures; Quality failures; Machine learning.

1. INTRODUCTION
Most organizations today recognize the importance of prioritizing quality if they want to endure over time [1]. Others have asserted that achieving 100% quality has no economic value, even though most people think it is highly uneconomical to ignore quality [2]. It is insufficient to state that a company is attempting to improve quality or that a flashy quality policy has been implemented [3]. While making improvements is labour-intensive, doing so frequently reaps rewards for the company, its staff, and its clients. In the issue of quality, it's important to keep in mind that poor quality invariably results in bad will, loss of reputation, and fewer customers, which ultimately results in reduced market shares [4–6]. The financial condition in today's construction companies is significantly impacted by quality work. Three factors can boost a company's profitability: higher sales, lower costs, and less capital commitment due to less asset requirements [7]. Quality management has recognized the use of cost as a performance indicator; this is sometimes referred to as the Cost of Quality (COQ) [8]. It is common knowledge that understanding COQ in manufacturing is important and valuable. In the construction sector, this is not the case [9]. Due to differences in the nature, characteristics, and environments of the two industries, it is difficult to say if equivalent quality cost concepts may be applied to construction [10]. In theory, the application of the COQ concept to the planning, and building phases of a construction project appears simple. It can be challenging in practice [11].

Cost of Quality elements are collected from sixteen project sites. These sites are ongoing and handed over to the customer recently [12]. A Factorial experiment is applied to find the importance of the COQ elements on the total quality costs [13]. The collected data from the selected projects are analyzed using 2n factorial design techniques [14]. It has been observed that the impacts of external and internal failure costs are imperative compared to other costs. Findings on the collected data divulge that while quality failures can be avoided with inexpensive preventive measures, the cost of prevention is relatively low compared to the cost of its correction [15–17]. Due to the lack of attention given to quality management ideas and techniques, organizations

Corresponding Author: Indhiradevi Palanisamy Received on 27/10/2024 Accepted on 10/12/2024

DOI: https://doi.org/10.1590/1517-7076-RMAT-2024-0738

in the construction sector typically do not have an efficient organizational learning mechanism in place that can be utilized to stimulate best practice [18]. As a result, little is understood about quality cost and how it affects the effectiveness and competitiveness of a company. It is claimed that the majority of companies have come to understand that work is a crucial aspect of both their performance and that of a project [19]. It has consequently turned into a widespread issue in the construction sector. According to TSAI [18, 20], the cost of quality (CoQ) has been a major issue with quality management for years in the production industry. But quality cost is a relatively new concept in the construction industry. Interviews with construction professionals who have been actively engaged in quality assurance within the construction industry reveal a common misinterpretation of quality cost [21]. Typically, individuals perceive it narrowly as the expenses tied to maintaining a quality system, encompassing the establishment of a quality management system and the ongoing costs associated with external auditor audits [22]. Another prevalent interpretation is viewing quality cost as the price paid for a specific level of quality, emphasizing the trade-off between cost and quality [23]. Additionally, the concept of value engineering, often synonymous with cost reduction, is centered on identifying essential functions and exploring potential substitutes to achieve these activities at minimal cost [24]. However, these perspectives only scratch the surface, as the scope of quality cost extends much further [25]. It can be comprehensively defined as all expenditures incurred as a project progresses, encompassing both non-conformance-related costs and those associated with monitoring project quality [26]. For instance, unforeseen changes resulting from inadequate planning or unclear project goals impose additional expenses from the client's perspective [27]. When modifications or errors arise, designers must invest time in revising drawings or concepts. Similarly, in the event of a quality failure, the construction team expends effort on rework or, in some cases, the demolition of a portion of the structure [28]. This broader understanding emphasizes the intricate interplay of various factors contributing to quality costs throughout the construction project lifecycle [29]. ALGLAWE *et al.* [26] explored the effects of incorporating the opportunity cost (OC) into quality costing calculations to establish a common framework for the behavior of all quality cost factors throughout the supply chain (SC) [30]. The internal supply chain of an integrated aluminum manufacturing company is being investigated by PATTANAYAK *et al.* [27] to analyze the risk associated with estimating CoQ components. The outcomes have aided strategic comprehensive quality management decision-makers. A mathematical model was created in 2019 by ROSIAWAN *et al.* [28] to calculate the quality costs and financial gains of implementing a quality improvement program within a manufacturing company's business process [31]. By reaching operational performance goals, quality expenses are reduced, which results in financial gains [32]. The economic benefits will rise together with the value of the model parameters, resulting in a shorter investment return period [33]. GLOGOVAC and FILIPOVIC [34] study identified variables that have an impact on the CoQ management strategy as well as the degree of recognition of particular CoQ categories [35]. Organizational Culture (OC), according to DIMITRANTZOU *et al.* [31], is linked to the application of TQM, and both are linked to the financial element of TQM, or the Cost of Quality (CoQ) [36]. According to research by PEIMBERT-GARCIA *et al*. [32] infant mortality costs can make up more than 15% of total maintenance costs, while opportunity costs can account for more than 80% of those expenses [37]. ABDELSALAM and GAD [33] reported that the CoQ in such projects in Dubai amounts to 1.3% of the entire project civil construction cost, with 1.34% being the projected optimal CoQ value [38]. On the other side, the anticipated cost of failure was 0.7% of the total project cost. The study was carried out by TAWFEK *et al.* [35] to determine the most significant variables influencing cost of quality and to create an artificial neural network model that can assist cost estimators in reaching a more accurate conclusion for the anticipated cost of quality of any building construction project [39]. The construction industry often overlooks the true cost of errors, with many professionals unaware of the substantial expenses incurred due to 'non-quality,' a factor rarely reflected on balance sheets [40]. This ignorance perpetuates a lack of measurement and understanding of the actual price of poor quality [41]. Consequently, owners bear significantly higher costs throughout a structure's life when accepting subpar work, compared to the initial investment required for quality construction [42].

The purpose of this project is to organize light on the notion of the cost of quality, emphasizing its importance in recognizing and mitigating faults during the building project execution. The objectives include examining the significance of quality cost, proposing a measurement system for site activities, utilizing the design of experiments to identify critical factors, and revealing post-construction costs incurred by users due to poor quality, fostering awareness within the industry. This research addresses a critical gap in understanding and quantifying the consequences of non-quality, providing valuable insights for improved decision-making in construction projects.

2. MATERIALS

A building and construction company that has received ISO 9001 certification was chosen as the study's contractor [43]. The company has created and implemented a successful program of continuous improvement that

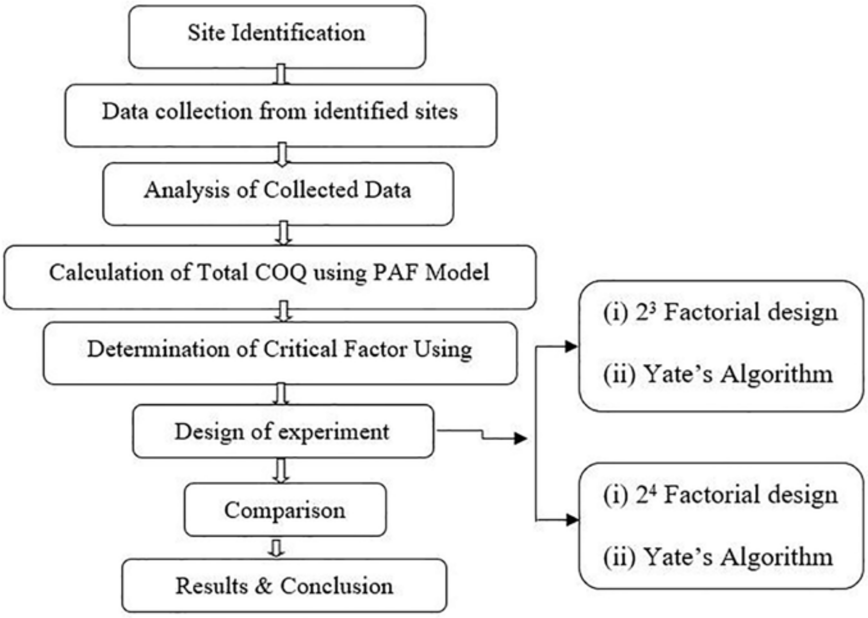

Figure 1: Research methodology.

has allowed it to lower the amount of rework experienced in its projects and strengthen its position in the market (Figure 1). The contracting organization's senior management is individually called to discuss the nature and purpose of the study, which examines the significance of quality costs and how these might be captured [44].

2.1. Data collection

Data collection is done by interviews with key staff members, as well as documentation from sources and observations [45]. The documentary sources like progress reports, non-conformance reports, test reports, variation registers, information requests, audit reports, site instructions, customer complaints register, and monthly performance reports [46]. Discussions with the project manager, site engineers, quality assurance manager, and quality system engineer provide background information about the project [47]. Interviews with subcontractors are conducted on the job site to gather more information about failure Events [23]. Data is also derived from direct observations and written sources provided by the contractor, client, subcontractor, and suppliers [48]. Three factors which are men, materials, and machines must be taken into account when assessing the costs of failure [49]. Based on how severe the failure was, materials can be predicted very simply. The bill of quantities or current market prices are used to assess the cost of the supplies required to address the quality issue [50]. The projected time required to solve the problem is used to determine man and machine costs [51].

2.2. Data analysis

The collected data from the selected building projects are converted into convenient genres for analysis purposes [52]. Based upon the collected information from the study projects, the total CoQ is calculated using PAF model which includes Prevention cost, Appraisal cost, and Failure cost for all sixteen project sites [53–55]. The percentage of the total cost of quality which includes the cost of prevention, cost of appraisal, and cost of failure (Internal and External) is given in Table 1.

2.2.1. Yate's algorithm and 2^4 factorial design techniques for construction projects

Yate's Algorithm and the 2^4 factorial design technique are invaluable tools for optimizing construction project outcomes, particularly in scenarios where multiple factors influence the result. Yate's Algorithm is designed to simplify the computation of interaction effects in factorial experiments, which is especially useful for 2^n factorial designs. This algorithm starts with a factorial design matrix, coding each factor at two levels (+1 and –1) and using a systematic sequence of additions and subtractions to compute the average effects of factors and their interactions. This approach enables the identification of how each factor, such as material type, curing time, temperature, and humidity, affects the overall response, like concrete strength. On the other hand, the 2^4 factorial design involves four factors, each at two levels, resulting in 16 experimental runs. This design

Table 1: Percentage of total cost of quality which includes cost of prevention, cost of appraisal, and cost of failure.

PROJECT	PREVENTION COST IN %	APPRAISAL COST IN %	INTERNAL FAILURE COST IN %	EXTERNAL FAILURE COST IN %	TOTAL QUALITY COST IN %
1	29.81	45.30	14.90	9.99	2.237
2	63.41	27.81	8.78	0	1.587
3	29.31	58.50	10.23	1.96	3.079
4	38.34	47.92	13.74	0	2.312
5	27.38	39.92	32.7	0	3.720
6	54.03	27.58	18.39	0	1.571
7	28.07	46.83	25.1	0	4.543
8	36.97	45.95	17.09	0	3.552
9	24.36	24.06	14.27	37.31	4.921
10	35.80	22.17	13.08	28.95	5.046
11	14.84	60.01	14.08	11.06	5.323
12	35.98	46.11	7.51	10.4	2.910
13	18.99	10.46	33.35	37.19	12.29
14	36.59	14.96	38.31	10.41	7.820
15	22.63	48.01	17.62	11.75	5.741
16	29.90	44.66	15.24	10.3	6.040

helps in understanding both the main effects and the interaction effects of the factors. For example, in a concrete curing process, one might analyze the impacts of different material proportions, curing conditions, and environmental variables on the final concrete strength [56–60]. By conducting experiments according to a design matrix and performing Analysis of Variance (ANOVA), the main and interaction effects can be quantified, revealing the significance and impact of each factor. These methods allow construction engineers to systematically optimize their processes, leading to more efficient, cost-effective, and high-quality construction outcomes [61]. Through the application of Yate's Algorithm and 2^4 factorial designs, engineers can achieve a deeper understanding of how various factors interplay, ensuring robust and durable construction projects.

Using the factorial design technique, the internal and external failure cost are observed to be the prominent factor that affect the total cost of quality of the projects selected for the study. Victor E. Sower (2007) investigated that failure cost will be the major one in cost of quality [33]. The external cost data is selected from nine completed projects and other ongoing projects. The failures are attended during and after the defect liability period. If all are completed projects, then the impact of external failure cost will be much more. The study indicates that failure costs are high for certain failure events [62]. Problems associated with the settlement of flooring, roof and toilet leakages, water tank leakages, plastering thickness is more than the specification requirement, and blockage in the sewer line. All incurred high additional costs. For instance, poor ground conditions can be identified by adequate site and soil investigation at an initial stage, thus significantly reducing the probability of settlement in flooring. Failure to conduct an adequate site investigation caused the settlement. This can be avoided by soil investigations and suitable ground improvement techniques. In project 10, the cost is rectification of this failure is Rs.9,12,000. This can be avoided by soil investigations and suitable ground improvement techniques. The approximate cost is acquired for these activities Rs.2,00,000. The net saving is Rs.7,12,000.

The leakage of water from the toilet is detected at six places in Project 13. The rectification includes the cost of repairing and saving the defective parts, replacement of flooring components including transportation costs, and the cost associated with handling and servicing customer complaints. The total cost of failure is Rs.4,68,000. The prevention activities include the cost of various components that help to prevent the defect such as preparation of specification and work procedure for construction joint preparation, stripping time of formwork, and training of staff and labor, etc. The appraisal activities include the cost of all such activities that result in the cost of checking it is right. In this case, it includes checking the concrete-making materials against agreed specifications, inspection before placing concrete, the calibration and maintenance of equipment used for testing of concrete, and the assessment and approval of all suppliers. The total cost involved in prevention and appraisal activities is Rs.64,500. The additional cost splurged through the failure is Rs.4,03,500. Since fewer flaws occur as a result of minimizing this failure cost, there is less need for an appraisal.

Rs.4,49,500 is expended for the failure of plastering thickness more than the specification requirement in project 14. Using uniform-sized bricks for masonry, avoiding the dimensional deviations in the RCC members, and training the masons are the conformance activities. The cost of prevention measures is Rs.1,76,600. The cost of saving is Rs. 2,72,900. Similarly, the cost of saving through adequate conformance activities for the sewer line blockage is Rs.3,83,000 for Project 9. The total quality of 12.29% for project 13 is observed as the highest among all projects. The internal and external failure costs for Project 13 are Rs. 14,95,500 and Rs. 16,67,925 respectively. The cost of saving through appropriate prevention and appraisal activities is Rs.22,19,500. The total quality cost reduces to 6.21%. Internal and external failure costs fall as preventative costs rise. In the end, there is a reduction in the total cost of quality and an increase in quality compliance. The essence of the quality cost is that spending money on prevention yields a far greater return than spending money on appraisal. The construction industry's most frequent issue is poor project execution and deliverable performance. According to SHAFIEI *et al.* [23] research findings, increasing training hours and hiring seasoned workers will lower failure costs and raise preventative costs, which will lead to a decrease in the cost of quality. In 2009, ROSENFELD [36] claimed that paying less than 2% on prevention and appraisal will unquestionably result in increased failure costs while investing more than 4% is likely to have no return.

3. RESULTS AND DISCUSSION

3.1. Inferences from data analysis

Graphs depicting the cost distribution across prevention, appraisal, internal failure, and external failure, along with the overall cost of quality, provide valuable insights into the quality management of various construction projects. In Figure 2, the prevention cost is maximized for Project 2 (63.41%), contrasting with the minimum of 14.84% for Project 11. Figure 3 reveals the appraisal cost, varying from 60.01% (Project 11) to 10.46% (Project 13). Internal failure costs, showcased in Figure 4, range from the highest at 38.31% (Project 14) to the lowest at 7.51% (Project 12). Notably, Project 2 exhibits a lower internal failure cost (8.78%) due to a substantial investment in prevention (63.41%), highlighting the impact of preventive measures on reducing failure costs. Figure 5 illustrates external failure costs, with Project 13 incurring the highest at 37.19%. Figure 6 examines the total quality cost as a percentage of the project value, emphasizing the variations across projects, such as Project 13 with the highest total quality cost (12.19%) and Project 6 with the lowest (1.57%). The findings underscore the significance of preventive actions in minimizing failure costs. Project-specific analysis, like in Project 11, reveals the impact of reduced appraisal costs on increased failure costs, emphasizing the importance of preventive and appraisal measures in averting issues such as water tank leakage. The interplay of prevention, appraisal, and internal failures contributes to the overall quality cost percentages, as seen in Project 13, were high failure costs stem from low preventive and appraisal investments. These insights provide a nuanced understanding of how cost distribution influences the overall quality management and performance of construction projects, reinforcing the need for strategic preventive and appraisal measures.

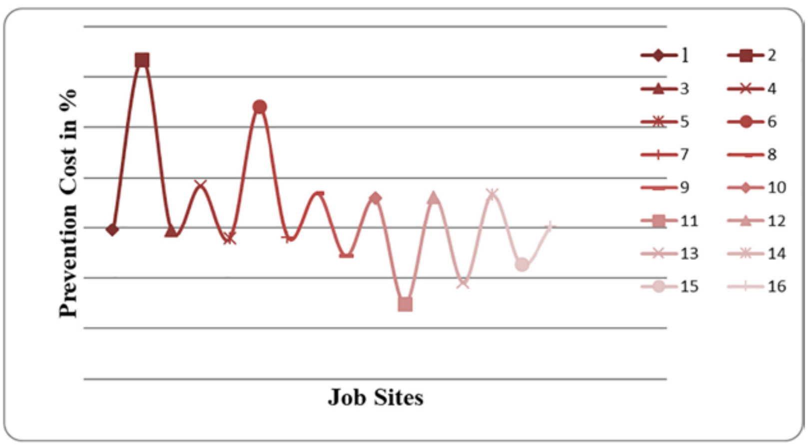

Figure 2: Prevention cost for each building project.

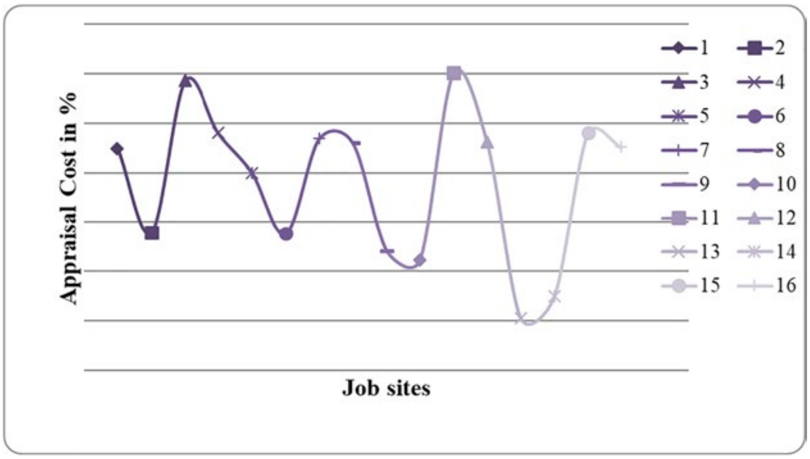

Figure 3: Appraisal cost for each building project.

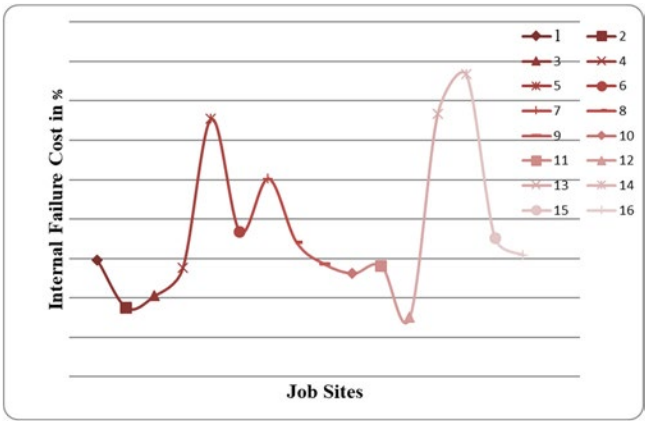

Figure 4: Internal failure cost for each building project.

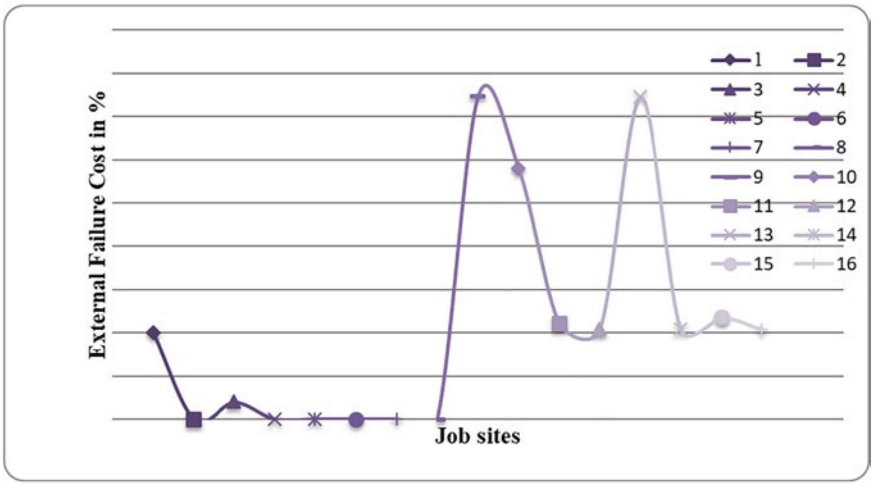

Figure 5: External failure cost for each building project.

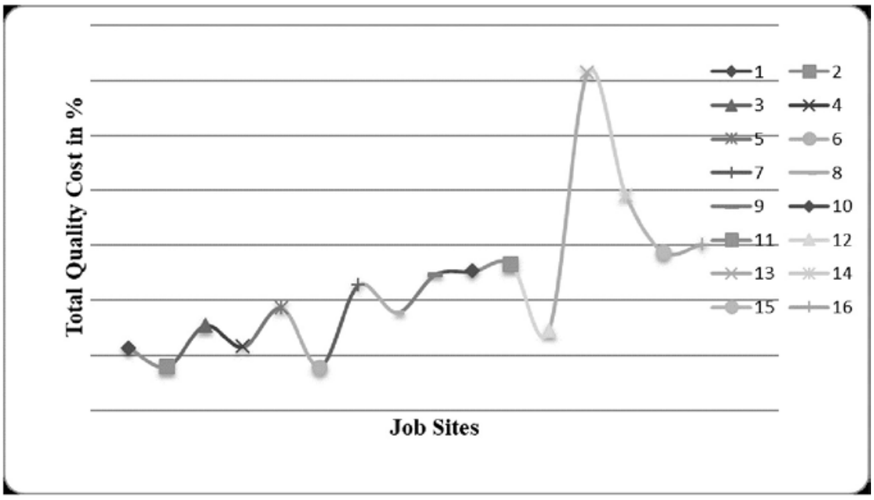

Figure 6: Total quality cost for each building project.

Project 13 has the highest failure cost (70.54%) due to excessively low preventive and appraisal costs (29.54%). The total quality cost for the same project has a higher percentage of quality cost (12.29%) compared to other sites. The additional external failure costs incurred after the defect liability period are the cause of the higher total quality cost value. In project 11, the failure costs increased to 25.14% because of the reduction in appraisal costs (14.84%). In this project, the leakage in the overhead water tank is observed as an external failure. The expended cost for the overhead water tank leakage is Rs. 2,25,500. This event can be avoided have some preventive or appraisal actions are taken. Proper work procedures for construction joint preparation, provision of water stopper, avoiding cold joints during concrete placement, cleaning the construction joints using suitable methods, application of bonding agents before concreting, and adding waterproofing admixtures in concrete are the few preventive and appraisal activities. More internal faults are discovered as a result of increased appraisal work, which raises appraisal costs. This results in higher failure costs. Fewer defects are discovered externally as more are discovered inside and found to be fixed at this level. The external failure costs are reduced as a result.

3.2. Design of experiments techniques for CoQ elements

It involves the concurrent assessment of two or more parameters (factors) for their influence on the final average or variability of a specific set of product or process attributes. The levels of the component are strategically altered to achieve this in an efficient and statistically correct manner. To identify the key variables, the desired level, and whether raising or lowering those levels might result in further advancement, The results of the particular test combinations are looked at, and the entire body of data is assessed. This experiment is often tiny with a lot of variables operating at two levels reported by MEHTA *et al.* [13].

3.2.1. 2^4 factorial designs for CoQ elements

Four major components (A, B, C, and D), sixteen distinct combinations (Low and High values), and the resultant variable (X) are needed for 2^4 factorial designs.

Where,

$$X = A + B + C + D$$

To apply this concept to COQ quality cost data for sixteen project sites are necessary with sixteen different combinations. As per MILLER and MILLER [8] report, four main effects, six two-factor interactions, four three-factor interactions, and one four-factor interaction are present in a 2^4-factorial experiment. The total quality cost is taken as the resulting variable (X).

Total quality cost (X) equals prevention cost (A) plus appraisal cost (B) plus internal failure cost (C) plus external failure cost (D).

3.2.2. Assumptions

The assessment of project sites based on the relative proportions of prevention, appraisal, internal failure, and external failure costs with the overall cost of quality (COQ) provides a valuable classification system.

A prevention cost accounting for less than 30% of the COQ value is denoted as low (–), while exceeding 30% is deemed high (+). Similarly, an appraisal cost representing less than 45% of the COQ value is labeled low (–), while surpassing 45% is considered high (+). For internal failure costs, a proportion under 15% of the COQ value is marked low (–), while exceeding 15% receives a high (+) indication. Likewise, external failure costs accounting for less than 10% of the COQ value are designated low (–), and values beyond 10% are characterized as high (+). This systematic categorization employing (+) and (–) indications facilitates a clear and concise evaluation of each project site's performance in terms of preventive measures, appraisal activities, and the incidence of internal and external failures relative to the overall cost of quality.

3.2.3. Calculation of factor effects for 2^4 factorial designs

From the contrasts, a table of plus and minus signs can be created, as illustrated in the Table 2. By linking a plus with the high level and a minus with the low level, signs for the primary effects are established. The signs for the remaining columns can be derived by multiplying the appropriate preceding columns, row by row, once the signs for the primary effects have been established.

3.2.4. Yate's algorithm for 2^4 factorial designs

Table 3 shows Yate's algorithm for prevention, appraisal, and internal and external failure cost factors. From the information given in Table 3 an ANOVA table can be drawn up, and this is illustrated in Table 4. This table's square sums were obtained from Table 3. All the primary effects and interactions have one degree of freedom each because each factor is at two levels. It is usually assumed that the three and four-factor interactions are of no practical significance, and they are combined as shown in Table 4. The F values are used to test the significance of the main effect interactions by comparing them with equivalent entries in Table 4 to produce a residual or error mean square, which is equal to 10.82.

3.3. Hypothesis

In statistical hypothesis testing, the null hypothesis (H0) posits that there is no significance attributable to the elements of the Cost of Quality (COQ) on the total quality cost, while the alternative hypothesis (H1) asserts that there is a significant effect due to COQ elements on total quality cost. The calculated F-values for internal failure costs (C) and external failure costs (D) surpass the tabulated F-values, indicating statistical significance.

Table 2: Algebraic sign for calculating effects in 2^4 factorial designs.

SITES	A	B	AB	C	AC	BC	ABC	D	AD	BD	ABD	CD	ACD	BCD	ABCD
1	–	–	+	–	+	+	–	–	+	+	–	+	–	–	+
2	+	–	–	–	–	+	+	–	–	+	+	+	+	–	–
3	–	+	–	–	+	–	+	–	+	–	+	+	–	+	–
4	+	+	+	–	–	–	–	–	–	–	–	+	+	+	+
5	–	–	+	+	–	–	+	–	+	+	–	–	+	+	–
6	+	–	–	+	+	–	–	–	–	+	+	–	–	+	+
7	–	+	–	+	–	+	–	–	+	–	+	–	+	–	+
8	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–
9	–	–	+	–	+	+	–	+	–	–	+	–	+	+	–
10	+	–	–	–	–	+	+	+	+	–	–	–	–	+	+
11	–	+	–	–	+	–	+	+	–	+	–	–	+	–	+
12	+	+	+	–	–	–	–	+	+	+	+	–	–	–	–
13	–	–	+	+	–	–	+	+	–	–	+	+	–	–	+
14	+	–	–	+	+	–	–	+	+	–	–	+	+	–	–
15	–	+	–	+	–	+	–	+	–	+	–	+	–	+	–
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Table 3: Yate's algorithm for 2^4 factorial designs.

JOB SITE	A	B	C	D	X	1	2	3	4	FACTOR EFFECT	FACTOR SUM OF SQUARE	FACTOR
1	–	–	–	–	2.26	3.85	9.24	22.62	72.71	4.54	–	Mean
2	+	–	–	–	1.59	5.39	13.38	50.09	–11.03	–1.38	7.60	A
3	–	+	–	–	3.08	5.29	18.20	–4.58	–5.73	–0.72	2.05	B
4	+	+	–	–	2.31	8.09	31.89	–6.45	3.29	0.41	0.676	AB
5	–	–	+	–	3.72	9.97	–1.44	4.34	17.83	2.23	19.87	C
6	+	–	+	–	1.57	8.23	–3.14	–10.07	–3.59	–0.45	0.81	AC
7	–	+	+	–	4.54	20.11	–2.28	1.06	–5.33	–0.67	1.78	BC
8	+	+	+	–	3.55	11.78	–4.17	2.23	8.57	1.07	4.59	ABC
9	–	–	–	+	4.92	–0.67	1.54	4.14	27.47	3.43	47.16	D
10	+	–	–	+	5.05	–0.77	2.80	13.69	–1.87	–0.23	0.22	AD
11	–	+	–	+	5.32	–2.15	–1.74	–1.70	–14.41	–1.80	12.98	BD
12	+	+	–	+	2.91	–0.99	–8.33	–1.89	1.17	0.15	0.086	ABD
13	–	–	+	+	12.29	0.13	–0.10	1.26	9.55	1.19	5.70	CD
14	+	–	+	+	7.82	–2.41	1.16	–6.59	–0.19	–0.024	0.002	ACD
15	–	+	+	+	5.74	–4.47	–2.54	1.26	–7.85	–0.98	3.85	BCD
16	+	+	+	+	6.04	0.30	4.77	7.31	6.05	0.76	2.29	ABCD

Table 4: ANOVA for 2^4 factorial designs.

SOURCE	SUM OF SQUARES	DEGREE OF FREEDOM	MEAN SQUARES	F_{CALC}
A	7.60	1	7.60	3.51
B	2.05	1	2.05	0.947
C	19.87	1	19.87	9.184
D	47.16	1	47.16	21.80
AB	0.67	1	0.67	0.312
AC	0.81	1	0.81	0.374
AD	0.22	1	0.22	0.102
BC	1.78	1	1.78	0.823
BD	12.98	1	12.98	5.99
CD	5.70	1	5.70	2.63
ABC	4.59	5	2.164	
ABD	0.08			
ACD	0.0002			
BCD	10.82			
ABCD	3.85			
	2.29			
Total	898.903	15		

Level of significance α = 5% F_{table}, 0.05 = 6.61.

Table 5: 2^4 factorial design and Yate's algorithm factor effects comparison.

FACTOR	2^4 FACTORIAL EXPERIMENTS	YATE'S ALGORITHM
A	–1.38	–1.38
B	–0.72	–0.72
AB	0.41	0.41
C	2.23	2.23
AC	–0.45	–0.45
BC	–0.67	–0.67
ABC	1.07	1.07
D	**3.43**	**3.43**
AD	–0.23	–0.23
BD	–1.80	–1.80
ABD	0.15	0.15
CD	1.19	1.19
ACD	–0.024	–0.024
BCD	–0.98	–0.98
ABCD	0.76	0.76

Consequently, at a 5% level of significance, the null hypothesis is rejected. This leads to the conclusion that there exists a significant effect attributable to internal failure costs (C) and external failure costs (D) on total quality costs, when compared to other cost elements, with a confidence level of 95%. This statistical inference, supported by the findings of ALAO *et al.* [17], underscores the importance of considering internal and external failure costs as influential factors affecting the overall quality costs in a given context. The factor effects are tabulated for 2^4 Factorial designs and Yate's algorithm as shown in Table 5. The main factor and their interaction effects are the same for both methods.

The use of Yate's Algorithm and the 2^4 factorial design technique in construction projects is crucial for optimizing processes and improving outcomes. These models enable the analysis of multiple factors simultaneously, leading to efficient resource utilization and cost savings. They help in constructing higher quality and longer-lasting structures. The structured experimentation approach reduces guesswork, providing reliable results and supporting data-driven decision-making. Ultimately, these techniques foster continuous innovation and improvement, enhancing efficiency, quality, and cost-effectiveness in construction projects.

4. CONCLUSIONS

Sixteen projects are selected for the study. They are selected on pragmatic considerations, namely their availability. A minimum of sixteen projects are required to apply the design of the experiment technique. These projects are ongoing and handed over to the clients recently. The concept of design of experiments is applied to quality costs collected from the selected building projects. The collected quality cost data from the selected projects are analyzed using 2^4 factorial design experiments. The analysis reveals that the cost of internal and external failure is the prominent factor that affects the total quality cost of the projects.

The study has drawn several important results, including the following:

1. If certain preventive or appraisal measures had been adopted, the failed events might have been prevented. For instance, the tile process of checking and re-checking the concreting, waterproofing works, and construction joint preparation during construction, thus significantly reducing the probability of "roof and toilet leakage".
2. More labour on the appraisal process results in higher appraisal costs, but more internal faults are found, which lowers internal failure costs. Less flaws are discovered externally as more are discovered internally. External failure costs are reduced as a result.
3. Both internal and external failure diminish as preventative costs rise. The overall improvement in quality may also result in lower appraisal costs. An increase in quality conformity and a decrease in the overall cost of quality are the results. Increased productivity and profitability result from lower quality costs. This

is the essence of the quality cost: that spending on prevention yields a far higher return than spending on appraisal. This research proves the pre-eminence of prevention rather than the amelioration from appraisal.

4. This study has several limitations regarding the application of Yate's Algorithm and the 2^4-factorial design in construction projects. The primary limitation is the controlled experimental setup, which may not fully capture the complexities and variabilities encountered in real-world construction environments. Additionally, the study focused on a limited number of factors, and interactions among these factors might differ in more complex scenarios. Future research should aim to incorporate a broader range of variables and consider more diverse project conditions to enhance the robustness and applicability of the findings. Furthermore, the scalability of these statistical techniques in large-scale construction projects needs further investigation. Expanding the scope to include long-term impacts and cost-benefit analyses will provide deeper insights and improve the practical implementation of these models in construction project management.

5. ACKNOWLEDGMENTS

The authors express their gratitude to the Department of Civil Engineering, KPR Institute of Engineering and Technology, Tiruchengode, Tamil Nadu, for the facilities and support provided during the research work.

6. BIBLIOGRAPHY

[1] HERAVI, G., JAFARI, A., "Cost of quality evaluation in mass-housing projects in developing countries", *Journal of Construction Engineering and Management*, v. 140, n. 5, pp. 04014004, 2014. doi: http://doi.org/10.1061/(ASCE)CO.1943-7862.000083.

[2] SHARMA, N., LAISHRAM, B., "Understanding the relevance and impact of the cost of quality in the construction industry: a systematic literature review using PRISMA", *Construction Innovation*, 2024. In press. doi: http://doi.org/10.1108/CI-08-2023-0197.

[3] ANDERSON-COOK, C., MYERS, R.H., MONTGOMERY, D.C., *Response surface methodology: process and product optimization using design of experiment*, 3 ed., Newark, John Wiley & Sons, 2009.

[4] PATEL, M.T., DESAI, A.D., "An exploratory study on status of cost of quality in different industries", *International Journal of Engineering Development and Research*, v. 8, n. 4, pp. 193–308, 2020.

[5] ERIKSSON, B., *Using cost of poor quality to identify areas for quality improvements*, Wollongong, University of Wollongong, 2016.

[6] KULABI, A.K.A., LEBBAN, M.F.A., "Identifying and analyzing failure factors of public construction projects: a case study", *AIP Conference Proceedings*, v. 2775, n. 1, pp. 020021, Jul. 2023. doi: http://doi.org/10.1063/5.0140817.

[7] ZHANG, P., ZHANG, Z.J., GONG, D.Q., "An improved failure mode and effect analysis method for group decision-making in utility tunnels construction project risk evaluation", *Reliability Engineering & System Safety*, v. 244, pp. 109943, 2024. doi: http://doi.org/10.1016/j.ress.2024.109943.

[8] MILLER, J.C., MILLER, J.C., *Statistics and chemometrics for analytical chemistry*, London, Pearson Education, 2018.

[9] JIANG, Z., CHEN, D., XIE, S., "Failure analysis and innovative pressure load-off control technology of deep coal roadway both ribs: a case study", *Engineering Failure Analysis*, v. 158, pp. 107976, 2024. doi: http://doi.org/10.1016/j.engfailanal.2024.107976.

[10] RAVIKUMAR, K., PALANICHAMY, S., SINGARAM, C.J., *et al.*, "Crushing performance of pultruded GFRP angle section with various connections and joints on lattice towers", *Matéria*, v. 28, n. 1, e20230003, 2023. doi: http://doi.org/10.1590/1517-7076-rmat-2023-0003.

[11] MAKHANYA, B.B.S., H., PRETORIUS, J.H.C., "Costs of quality management in global and south african manufacturing companies: similarities and differences", In: *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management*, Singapore, 2021. doi: http://doi.org/10.1109/IEEM50564.2021.9672809.

[12] ANTONIOU, F., TSIOULPA, A.V., "Assessing the delay, cost, and quality risks of claims on construction contract performance", *Buildings*, v. 14, n. 2, pp. 333, 2024. doi: http://doi.org/10.3390/buildings14020333.

[13] MEHTA, B.V., GHULMAN, H., GERTH, R., "A new methodology of using design of experiments as a precursor to neural networks for material processing: extrusion die design", In: *Proceedings of the 2nd International Conference on Intelligent Processing and Manufacturing of Materials*, Honolulu, HI, USA, 1999.

[14] KOC, K., BUDAYAN, C., EKMEKCIOĞLU, Ö., *et al.*, "Predicting cost impacts of nonconformances in construction projects using interpretable machine learning", *Journal of Construction Engineering and Management*, v. 150, n. 1, pp. 04023143, 2024. doi: http://doi.org/10.1061/JCEMD4.COENG-13857.

[15] AL-FADHALI, N., "An AMOS-SEM approach to evaluating stakeholders' influence on construction project delivery performance", *Engineering, Construction, and Architectural Management*, v. 31, n. 2, pp. 638–661, 2024. doi: http://doi.org/10.1108/ECAM-09-2021-0780.

[16] TEMBO, C.K., MULEYA, F., KANYEMBA, A., "An appraisal of cost management techniques used in the construction industry", *International Journal of Construction Management*, v. 24, n. 1, pp. 10–18, 2024. doi: http://doi.org/10.1080/15623599.2022.2132355.

[17] ALAO, A.A., SADIQ, O., MOSHOOD, H.A., OLAYINKA, L., "Nigerian tax system and policy defectiveness: how relevant is Warren buffett theory", *Research Journal of Finance and Accounting*, v. 6, n. 20, pp. 63–75, 2015.

[18] TSAI, W., HSU, W., "A novel hybrid model based on DEMATEL and ANP for selecting cost of quality model development", *Total Quality Management & Business Excellence*, v. 21, n. 4, pp. 439–456, 2010. doi: http://doi.org/10.1080/14783361003606852.

[19] PSOMAS, E., DIMITRANTZOU, C., VOUZAS, F., BOURANTA, N., "Cost of quality measurement in food manufacturing companies: the Greek case", *International Journal of Productivity and Performance Management*, v. 67, n. 9, pp. 1882–1900, 2018. doi: http://doi.org/10.1108/IJPPM-12-2017-0325.

[20] KHATAIE, A.H., BULGAK, A.A., "A cost of quality decision support model for lean manufacturing: activity-based costing application", *International Journal of Quality & Reliability Management*, v. 30, n. 7, pp. 751–764, 2013. doi: http://doi.org/10.1108/IJQRM-Jan-2011-0016.

[21] SCHIFFAUEROVA, A., THOMSON, V.J., "Managing cost of quality: insight into industry practice", *The TQM Magazine*, v. 18, n. 5, pp. 1–10, 2006. doi: http://doi.org/10.1108/09544780610685502.

[22] DEMIRORS, O., YILDIZ, O., SELCUK GUCEGLIOGLU, A., "Using cost of software quality for a process improvement initiative", In: *Proceedings of the 26th Euromicro Conference. EUROMICRO 2000. Informatics: Inventing the Future*, Maastricht, Netherlands, 2000. doi: http://doi.org/10.1109/EURMIC.2000.874440.

[23] SHAFIEI, I., ESHTEHARDIAN, E., NASIRZADEH, F., *et al.*, "Dynamic modeling to reduce the cost of quality in construction projects", *International Journal of Construction Management*, v. 23, n. 1, pp. 24–37, 2023. doi: http://doi.org/10.1080/15623599.2020.1845425.

[24] SHARMA, U., SADAM, R., "How far does the predictive decision impact the software project? The cost, service time, and failure analysis from a cross-project defect prediction model", *Journal of Systems and Software*, v. 195, pp. 111522, 2023. doi: http://doi.org/10.1016/j.jss.2022.111522.

[25] PSOMAS, E., DIMITRANTZOU, C., VOUZAS, F., "Practical implications of cost of quality: a systematic literature review", *International Journal of Productivity and Performance Management*, v. 71, n. 8, pp. 3581–3605, 2021.

[26] ALGLAWE, A., SCHIFFAUEROVA, A., KUZGUNKAYA, O., "Analysing the cost of quality within a supply chain using system dynamics approach", *Total Quality Management & Business Excellence*, pp. 1–24, 2019.

[27] PATTANAYAK, A.K., PRAKASH, A., MOHANTY, R.P., "Risk analysis of estimates for cost of quality in supply chain: a case study", *Production Planning and Control*, v. 30, n. 4, pp. 299–314, 2019. doi: http://doi.org/10.1080/09537287.2018.1541488.

[28] ROSIAWAN, M., LAKSONO SINGGIH, M., WIDODO, E., "Model of quality costs and economic benefits of a business process of manufacturing companies", *Cogent Engineering*, v. 6, n. 1, pp. 1678228, 2019. doi: http://doi.org/10.1080/23311916.2019.1678228.

[29] INDHIRA DEVI, P., CHITRA, G., "Cost of quality in construction industry", *Journal of Rural and Industrial Development*, v. 1, n. 1, pp. 1, 2013.

[30] SOWER, V.E., QUARLES, R., BROUSSARD, E., "Cost of quality usage and its relationship to quality system maturity", *International Journal of Quality & Reliability Management*, v. 24, n. 2, pp. 121–140, 2007. doi: http://doi.org/10.1108/02656710710722257.

[31] DIMITRANTZOU, C., PSOMAS, E., BOURANTA, N., *et al.*, "The role of organisational culture in total quality management adoption and cost of quality", *Total Quality Management & Business Excellence*, v. 33, n. 8, pp. 1–19, 2021.

[32] PEIMBERT-GARCIA, R.E., LIMON-ROBLES, J., BERUVIDES, M.G., "Cost of quality modeling for maintenance employing opportunity and infant mortality costs: an analysis of an electric utility", *The Engineering Economist*, v. 61, n. 2, pp. 112–127, 2016. doi: http://doi.org/10.1080/0013791X.2016.1152619.

[33] ABDELSALAM, H.M.E., GAD, M.M., "Cost of quality in Dubai: an analytical case study of residential construction projects", *International Journal of Project Management*, v. 27, n. 5, pp. 501–511, 2009. doi: http://doi.org/10.1016/j.ijproman.2008.07.006.

[34] GLOGOVAC, M., FILIPOVIC, J., "Quality costs in practice and an analysis of the factors affecting quality cost management", *Total Quality Management & Business Excellence*, v. 29, n. 13–14, pp. 13–14, 2018. doi: http://doi.org/10.1080/14783363.2016.1273105.

[35] TAWFEK, H.S., MOHAMMED, H., ABDEL RAZEK, M.E., "Assessment of the expected cost of quality (COQ) in construction projects in Egypt using artificial neural network model", *HBRC Journal*, v. 8, n. 2, pp. 132–143, 2012. doi: http://doi.org/10.1016/j.hbrcj.2012.09.009.

[36] ROSENFELD, Y., "Cost of quality versus cost of non-quality in construction: the crucial balance", *Construction Management and Economics*, v. 27, n. 2, pp. 107–117, 2009. doi: http://doi.org/ 10.1080/01446190802651744.

[37] KRISHNAIAH, K., SHAHABUDEEN, P., *Applied design of experiments and Taguchi methods*, New Delhi, PHI Learning Private Ltd., 2012.

[38] SAWAN, R., LOW, J.F., SCHIFFAUEROVA, A., "Quality cost of material procurement in construction projects", *Engineering, Construction and Architectural Management*, v. 25, n. 8, pp. 974–988, 2018. doi: http://doi.org/10.1108/ECAM-04-2017-0068.

[39] RAVIKUMAR, K., SINGARAM, C.J., PALANICHAMY, S., *et al.*, "Testing and evaluation of buckling and tensile performance of glass fiber–reinforced polymer angle section with different joints/connections", *Journal of Testing and Evaluation*, v. 52, n. 1, pp. 621–638, 2024. doi: http://doi.org/10.1520/JTE20230010.

[40] PATTUSAMY, L., RAJENDRAN, M., SHANMUGAMOORTHY, S., *et al.*, "Confinement effectiveness of 2900psi concrete using the extract of Euphorbia tortilis cactus as a natural additive", *Matéria*, v. 28, n. 1, e20220233, 2023. doi: http://doi.org/10.1590/1517-7076-rmat-2022-0233.

[41] JAMALUDIN, S.Z.H.S., MOHAMMAD, M.F., AHMAD, K., "Enhancing the quality of construction environment by minimizing the cost variance", *Procedia: Social and Behavioral Sciences*, v. 153, pp. 70–78, 2014. doi: http://doi.org/10.1016/j.sbspro.2014.10.042.

[42] DHARIWAL, J., BANERJEE, R., "An approach for building design optimization using design of experiments", *Building Simulation*, v. 10, n. 3, pp. 323–336, 2017. doi: http://doi.org/10.1007/s12273-016-0334-z.

[43] ABBASNEJAD, B., *Poor quality cost in construction: literature review*, Sweden, Chalmers University of Technology Gothenburg, 2013.

[44] SAYED, M., ABDEL-HAMID, M., EL-DASH, K., "Improving cost estimation in construction projects", *International Journal of Construction Management*, v. 23, n. 1, pp. 135–143, 2023. doi: http://doi.org/10.1080/15623599.2020.1853657.

[45] OCAKCI, E., NIEMANN, J., LUMINOSU, C., *et al*., "Quality cost and economic analysis: a synthesis in the manufacturing systems", *Matec Web of Conferences*, v. 343, pp. 05008, 2021. doi: http://doi.org/10.1051/matecconf/202134305008.

[46] DAUNORIENE, A., KATILIUTE, E., "The quality costs assessment in the aspect of value-added chain", *Quality Innovation Prosperity*, v. 20, n. 2, pp. 119–144, 2016. doi: http://doi.org/10.12776/qip.v20i2.746.

[47] MOHANRAJ, R., SENTHILKUMAR, S., GOEL, P., *et al*., "A state-of-the-art review of Euphorbia Tortilis cactus as a bio-additive for sustainable construction materials", *Materials Today: Proceedings*, 2023. In press. doi: http://dx.doi.org/10.1016/j.matpr.2023.03.762.

[48] ALTAF, M., ALALOUL, W.S., MUSARAT, M.A., *et al.*, "Life cycle cost analysis (LCCA) of construction projects: sustainability perspective", *Environment, Development and Sustainability*, v. 25, n. 11, pp. 12071–12118, 2023. doi: http://doi.org/10.1007/s10668-022-02579-x.

[49] KHADIM, N., THAHEEM, M.J., ULLAH, F., *et al.*, "Quantifying the cost of quality in construction projects: an insight into the base of the iceberg", *Quality & Quantity*, v. 57, n. 6, pp. 5403–5429, 2023. doi: http://doi.org/10.1007/s11135-022-01574-8.

[50] SHRESTHA, K., SHRESTHA, P.P., LOHOUD, M., "Critical factors affecting the bid cost of building construction projects", *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, v. 15, n. 3, pp. 04523018, 2023. doi: http://doi.org/10.1061/JLADAH.LADR-960.

[51] AMINI, S., REZVANI, A., TABASSI, M., *et al.*, "Causes of cost overruns in building construction projects in Asian countries, Iran as a case study", *Engineering, Construction, and Architectural Management*, v. 30, n. 7, pp. 2739–2766, 2023. doi: http://doi.org/10.1108/ECAM-05-2021-0445.

[52] KRISHNASAMY, R., JOHNSON, S.C., KUMAR, P.S., *et al.*, "Experimental Investigation of Lateral Load Test on Diagonal Braced 3M Glass Fiber Reinforced Polymer Transmission Tower", *Power Research - A Journal of CPRI*, v. 19, n. 2, pp.225–231, 2023. doi: https://doi.org/10.33686/pwj.v19i2.1150.

[53] LOGANATHAN, P., MOHANRAJ, R., SENTHILKUMAR, S., *et al.*, "Mechanical performance of ETC RC beam with U-framed AFRP laminates under a static load condition", *Revista de la Construcción. Journal of Construction*, v. 21, n. 3, pp. 678–691, 2022. doi: https://doi.org/10.7764/RDLC.21.3.678.

[54] SHOAR, S., YIU, T.W., PAYAN, S., *et al.*, "Modeling cost overrun in building construction projects using the interpretive structural modeling approach: a developing country perspective", *Engineering, Construction, and Architectural Management*, v. 30, n. 2, pp. 365–392, 2023. doi: http://doi.org/10.1108/ECAM-08-2021-0732.

[55] KRISHNARAJA, A.R., ANANDAKUMAR, S., JEGAN, M., *et al.*, "Study on impact of fiber hybridization in material properties of engineered cementitious composites", *Matéria*, v. 24, n. 2, e12347, 2019. doi: http://doi.org/10.1590/s1517-707620190002.0662.

[56] JOHNSON, B.G.C., RAMASAMY, M., NARAYANAN, A., "Experimental study and assessment of the structural performance of laced reinforced concrete beams against reverse cyclic loading", *Matéria*, v. 29, n. 1, e20240001, 2024. doi: http://doi.org/10.1590/1517-7076-rmat-2024-0001.

[57] PRASANTHNI, P., PRIYA, B., PALANISAMY, T., *et al.*, "Enhancing PVCC beam performance through PVA fiber and basalt fabric in sustainable construction: ductility, strength, and energy absorption improvements", *Matéria*, v. 29, n. 1, e20230299, 2024. doi: http://doi.org/10.1590/1517-7076-rmat-2023-0299.

[58] MOHANRAJ, R., KRISHNASAMY, R., "Enhancing Concrete Flexural Behaviour with Euphorbia Tortilis Cactus: Sustainable Additive for Improved Load-Carrying Capacity and Ductility", *Indian Journal of Engineering & Materials Sciences*, v. 31, n. 3, pp. 388–396, 2024. doi: https://doi.org/10.56042/ijems.v31i3.6667.

[59] RAJESH, A.A., SENTHILKUMAR, S., SARGUNAN, K., *et al*., "Interpolation and extrapolation of flexural strength of rubber crumbs and coal ash with graphene oxide concrete", *Matéria (Rio de Janeiro)*, v. 28, n. 4, pp. e20230179, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2023-0179.

[60] SHANMUGASUNDARAM, S., MOHANRAJ, R., SENTHILKUMAR, S., *et al*., "Torsional performance of reinforced concrete beam with carbon fiber and aramid fiber laminates", *Revista de la Construcción Journal of Construction*, v. 21, n. 2, pp. 329–337, 2022. doi: http://dx.doi.org/10.7764/RDLC.21.2.329.

[61] VÁSQUEZ-HERNÁNDEZ, A., ALARCÓN, L.F., PELLICER, E., *et al*., "Construction Industrialization: A Mosaic of Definitions", *Journal of Construction Engineering and Management,* v. 151, n. 3, 2025. doi: https://doi.org/10.1061/JCEMD4.COENG-15181.

[62] RAJESH, A.A., SENTHILKUMAR, S., SAMSON, S., "Optimal proportional combinations of rubber crumbs and steel slag for enhanced concrete split tensile strength", *Matéria (Rio de Janeiro)*, v. 28, n. 4, pp. e20230206, 2023. doi: http://dx.doi.org/10.1590/1517-7076-rmat-2023-0206.