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Integration of Cost of Quality and Risk Analysis to Reduce Failure Costs in the KIIC Margakarya 150 KV Substation Civil Engineering Project

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Abstract

Quality failures in construction projects increase costs through failure costs, which are primarily driven by project implementation risks. Quality cost management and risk management are often conducted separately, resulting in limited integration for decision-making, particularly in civil construction projects within the electricity sector. This study aimed to identify risks contributing to failure costs, determine priority risks based on Risk Exposure and Expected Monetary Value (EMV), identify appropriate risk response strategies, and evaluate the effect of integrating risk mitigation into Cost of Quality (CoQ) management on reducing potential failure costs. This research employed a case study approach focusing on the civil works of the 150 kV KIIC Margakarya Substation Project. Data were obtained from project documents, quality reports, quality cost records, and expert judgments from eight experts. The analysis included CoQ classification using the prevention–appraisal–failure model, risk event identification based on the Risk Breakdown Structure (RBS), Risk Exposure assessment, EMV calculation, evaluation of mitigation effectiveness and costs, and calculation of residual EMV and projected post-mitigation CoQ. The total actual CoQ was IDR 259,861,400. Thirteen risk events were identified, with five priority risks categorized as high and very high, representing a total EMV of IDR 342,500,000. The selected mitigation strategies reduced the residual EMV to IDR 117,910,000, representing a 65.57% reduction. By integrating mitigation costs of IDR 72,000,000, the projected CoQ was reduced from IDR 602,361,400 to IDR 449,771,400, resulting in potential savings of IDR 152,590,000 (25.33%) and a benefit-to-cost ratio of 3.12.

INTRODUCTION

The construction industry is one of the sectors with the highest levels of complexity and uncertainty compared with other industrial sectors (Ghaleb et al., 2022; Oti-Sarpong et al., 2022). This complexity arises from the involvement of multiple stakeholders, dependence on material supply chains, dynamic site conditions, and strict quality and safety requirements. Such conditions make construction projects particularly vulnerable to delays and cost overruns. Doloi (2013) highlighted that cost overruns and construction project management failures are largely triggered by inadequate quality control and risk management, while Serrador and Turner (2015) demonstrated that project implementation efficiency is strongly correlated with overall project success. These conditions emphasize the importance of integrating quality management and risk management approaches to achieve optimal project performance.

Within the framework of quality management, Cost of Quality (CoQ) is a widely used approach for evaluating the effectiveness of a project's quality management system. CoQ classifies quality-related costs into four main components: prevention costs, appraisal costs, internal failure costs, and external failure costs (Juran, 1951; Feigenbaum, 1956; Oakland, 2003). Empirical studies have shown that failure costs often represent the largest component of CoQ in many construction projects. Khadim, Abid, and Ahmed (2023) reported that failure costs may account for more than half of total quality costs, indicating that expenses associated with correcting failures are considerably higher than investments allocated for prevention. Hwang and Aspinwall (2009) also demonstrated that quality costs in construction projects can represent a significant proportion of total project costs, primarily due to rework and quality nonconformities. These conditions reflect weaknesses in quality control practices and suboptimal allocation of prevention and appraisal costs in many construction projects.

However, the dominance of failure costs is not always explicitly reflected in actual project records. Aoieong, Tang, and Ahmed (2002) explained that some failure costs are not formally recorded in project accounting systems because they are distributed across various activities and cost accounts, causing the recorded CoQ structure to differ from actual field conditions. Unrecorded failure costs may appear in the form of project delays, reduced productivity, idle labor time, coordination disruptions, and unrealized financial losses. Cheah (2011) emphasized that hidden quality-related costs in construction projects are often greater than explicitly recorded failure costs. This condition indicates the presence of latent failure costs and unquantified risks that are not directly represented within the CoQ structure.

High failure costs are closely associated with operational risks during project implementation. Quality failures, such as rework, concrete quality deviations, inspection delays, and material rejection, are manifestations of risks occurring in the field. Doloi, Sawhney, Iyer, and Rentala (2012) identified supply chain disruptions, implementation errors, and administrative limitations as dominant risk factors affecting construction project quality, time, and cost performance. These risks not only increase failure costs but also contribute to overall project uncertainty. However, previous studies have generally examined CoQ and project risks separately, resulting in limited utilization of their relationship for managerial decision-making.

In practice, failure costs represent financial consequences of risks that have materialized. Abdollahzadeh (2015) showed that many project cost overruns originate from risk-induced costs, namely failure costs arising from unmanaged technical, operational, and managerial risks. Therefore, failure costs can serve as direct indicators of realized project risks. High failure costs not only reflect financial inefficiencies but also indicate that certain risks have not been adequately identified or effectively mitigated during project planning and execution. This condition causes quality management practices to become reactive, with costs incurred only after failures occur. Therefore, CoQ, particularly failure costs, should be viewed as quantitative indicators of realized risks that can support systematic risk identification, prioritization, and control.

One approach for linking CoQ with risk management is Probability × Impact analysis to measure Risk Exposure (RE), as introduced by Hillson (2007), combined with the Expected Monetary Value (EMV) method to quantify potential financial losses from risks. Harahap, Putra, and Sari (2023) stated that EMV is an appropriate method for quantitative risk analysis, particularly in complex infrastructure projects, because it enables risks to be assessed in monetary terms and supports mitigation decision-making. Taroun and Yang (2011) emphasized that although traditional risk assessment models often involve subjectivity, the Probability × Impact approach remains effective as a screening method for identifying dominant risks before further quantification. Similarly, Dziadosz and Rejment (2015) noted that Risk Exposure is a practical risk assessment method, particularly for projects with limited historical data. However, studies that comprehensively integrate CoQ structures, Risk Exposure, and EMV analysis remain limited, especially in civil construction projects within the electricity sector.

This issue is particularly relevant in the construction of 150 kV substations, which represent critical infrastructure within electricity transmission systems. The 150 kV KIIC Margakarya Substation Project has distinctive characteristics because construction activities are performed within an energized switchyard area with limited workspace and stringent safety and quality requirements. The civil works include major components such as bored pile foundations, high-voltage equipment foundations, cable trenches, 20 kV control buildings, underground drainage systems, and access roads, as defined in the project Work Breakdown Structure (WBS). The complexity of these activities requires high technical accuracy and intensive coordination among contractors, supervision consultants, and project owners. Quality control in this project refers to the Inspection and Test Plan (ITP), which includes inspection and testing procedures such as slump tests, compressive strength tests, reinforcement inspections, formwork inspections, and measuring instrument calibration. Although the quality system has been implemented, evaluations indicate that quality failures resulting in rework, technical deviations, and approval delays continue to occur at considerable levels.

The quality management challenges in this project are further intensified by external factors, including the temporary suspension of mining operations in West Java that disrupted aggregate supply to the batching plant and directly affected structural casting schedules. This condition resulted in labor idle time, inspection delays, and increased logistics costs, which contributed to higher project failure costs. Project data indicate that the existing CoQ structure reflects not only recorded failure costs but also potential failure costs that have not been fully identified. Therefore, an integrated approach is required to identify failure sources, measure associated risk levels, and evaluate potential financial impacts comprehensively.

Several previous studies have provided important foundations for this research. Barlow (2009) demonstrated that the construction industry incurs substantial costs due to poor quality and emphasized the importance of categorizing quality costs into prevention, appraisal, internal failure, and external failure components. Basu (2015) found that CoQ in construction is often difficult to measure because organizations lack formal recording systems and concluded that increasing prevention costs can significantly reduce failure costs, indicating that prevention investment should be viewed as a strategic improvement rather than unnecessary expenditure. Maysoon (2019) applied Pareto analysis to demonstrate that major CoQ components are associated with prevention and appraisal costs, reinforcing the importance of strengthening these areas to reduce failure costs. Rosenfeld (2009) explained that increased investment in prevention and appraisal activities can reduce internal and external failure costs, with benefits potentially exceeding quality investment values. Szymański (2017) demonstrated that the Probability × Impact approach is effective for prioritizing construction risks, while Love, Edwards, and Smith (2005) identified rework as a significant contributor to failure costs that can be measured based on additional resources required for correction. Although these studies provide valuable contributions, previous research has generally analyzed CoQ and risk management separately, meaning that failure costs have not been fully utilized as quantitative indicators of realized risks in developing mitigation strategies.

The novelty of this research lies in the development of an integrative Cost of Quality–Risk Exposure–Expected Monetary Value framework used as the basis for cost-based risk mitigation decision-making through the evaluation of alternative mitigation strategies. Within this framework, failure costs are positioned as quantitative representations of realized risks, Risk Exposure is used to prioritize risks, and Expected Monetary Value (EMV) is applied to estimate potential financial losses. The resulting analysis supports the selection of the most cost-effective mitigation strategies. This research contributes to the existing literature by providing empirical evidence from a power construction project that demonstrates the applicability of an integrated framework in a context that has received limited attention in previous studies. The practical contribution of this research is to provide project managers with a systematic approach for identifying risk priorities, evaluating mitigation alternatives, and making cost-effective decisions to reduce potential failure costs.

Based on these conditions, this research was positioned as a case-based applied study focusing on managerial decision-making in quality control and risk management for construction projects. The research gap lies in the limited number of studies integrating Cost of Quality analysis, risk assessment based on Probability × Impact analysis, and financial loss quantification using Expected Monetary Value within a single decision-making framework, particularly in power construction projects. The novelty of this research lies in the development of an integrated Cost of Quality–Risk Exposure–Expected Monetary Value framework as a basis for cost-based risk mitigation decision-making through the evaluation of alternative mitigation strategies. In this framework, failure costs represent realized risks quantitatively, Risk Exposure is used to prioritize risks, and EMV is applied to estimate potential financial impacts, thereby supporting the selection of the most cost-effective mitigation strategies.

Based on this framework, this study aimed to analyze the actual condition of Cost of Quality in the civil works of the 150 kV KIIC Margakarya Substation Project, identify risks contributing to failure costs and assess their severity based on Risk Exposure, quantify expected financial losses using Expected Monetary Value, and determine effective mitigation alternatives for reducing Risk Exposure and EMV. This research is expected to contribute academically by expanding the role of Cost of Quality as a decision-making instrument in project risk management. Practically, it provides benefits for project management in establishing more cost-effective risk mitigation priorities, encouraging a shift in quality cost allocation from failure costs toward prevention and appraisal costs, and serving as a reference for applying integrated quality and risk management models in other electricity infrastructure construction projects with similar characteristics.

Globally, cost overruns caused by weak quality control and inadequate risk management are not isolated incidents but recurring challenges across construction projects in various countries. Hwang and Low (2012) demonstrated that the economic impact of rework in construction projects can significantly affect cost and schedule performance, while Mistikoglu, Arditi, and Dikmen (2015) emphasized that combining data-based risk analysis techniques with expert judgment can improve the accuracy of identifying dominant project risks. Nguyen (2021) further highlighted that project risk management maturity is directly associated with project performance, indicating that organizations with more mature risk management capabilities tend to experience lower failure costs. These findings reinforce the argument that the relationship between quality control and risk management represents a global challenge, suggesting that integrative approaches such as the framework developed in this study have potential applicability across various construction contexts, including electricity infrastructure projects with specific technical characteristics and risk profiles.

The urgency of this research was also driven by the practical need for project managers to establish a more measurable basis for allocating quality control resources. Decisions regarding investments in prevention activities and quality inspections are often based on experience or general policies without explicitly considering project-specific risks and their potential financial impacts. By integrating CoQ, Risk Exposure, and EMV, this study provides a framework that enables project management teams to evaluate the economic benefits of mitigation alternatives transparently by comparing implementation costs with the expected reduction in potential losses. The implications of this approach extend beyond theoretical contributions, as the research findings can be applied by project managers and site managers in developing quality and risk control plans during project implementation and in similar future projects.

Other relevant studies further support the position of this research. Khodeir and Mohamed (2015) identified quality cost components in construction projects in Egypt and found that many organizations lacked structured CoQ recording systems. Similarly, Marzuki and Wisridani (2014) reported that construction contractors in Indonesia often estimated quality costs implicitly without formal documentation. Couto and Teixeira (2007) demonstrated that appropriate risk allocation between project owners and contractors significantly influenced infrastructure project performance, which is relevant to the context of 150 kV substation projects involving multiple stakeholders. Considering these findings, this study was designed to address the existing research gap by systematically linking actual CoQ structures with risk assessment and financial loss quantification to generate cost-effective mitigation recommendations.

METHOD

This study employed a case study approach focusing on the civil works of the 150 kV KIIC Margakarya Substation (Gardu Induk [GI]) Project. The scope included bored pile foundation works, high-voltage equipment foundations, cable trenches, 20 kV control buildings, underground drainage systems, and road access works as specified in the project Work Breakdown Structure (WBS). Mechanical and electrical works were excluded from the scope of this study. The analysis was conducted through four main stages: actual Cost of Quality (CoQ) analysis, failure cost-based risk identification, Risk Exposure and Expected Monetary Value (EMV) assessment, and the development and evaluation of alternative risk response strategies.

The data consisted of primary and secondary data. Secondary data were obtained from the Implementation Budget Plan, cost realization reports, Inspection and Test Plan (ITP), inspection and testing reports, Non-Conformance Reports (NCRs), rework and repair reports, and other relevant project documents. Primary data were collected through expert judgment involving eight experts with competencies in project management, construction implementation, quality control, structural engineering, and electricity construction risk management. The experts participated in validating quality cost classifications, risk events and the Risk Breakdown Structure (RBS), probability and impact assessments, and the effectiveness evaluation of alternative risk responses.

The CoQ analysis was conducted by classifying project quality costs using the Prevention–Appraisal–Failure (PAF) model, consisting of prevention costs, appraisal costs, internal failure costs, and external failure costs. Each cost item was validated through expert judgment to ensure accurate classification and prevent double counting. The CoQ calculation was limited to visible failure costs that could be identified and traced through project documents, while hidden failure costs were recognized as potential consequences but were not quantified due to limitations in the project recording system.

Risk identification was conducted through three stages: determining critical work areas based on the WBS, categorizing risk sources using the Risk Breakdown Structure into five groups (technical risks, construction and work methods, logistics and materials, work environment and safety, and managerial and administrative risks), and formulating risk events that linked work activities, causes, failure modes, and potential impacts on failure costs. Each identified risk event was validated through expert judgment to ensure completeness and avoid duplication.

Risk assessment was performed using the Risk Exposure (RE) approach, calculated as the multiplication of probability and impact scores on a scale of 1 to 5 based on the PMBOK framework (PMI, 2021). Impact assessments considered multiple dimensions, including time, cost, quality, and occupational health, safety, and environment (HSE). Probability and impact values were determined through the median aggregation of assessments from the eight experts and converted into numerical values using the class midpoint approach for Expected Monetary Value (EMV) calculations. EMV was calculated by multiplying the numerical probability value by the cost impact of each risk event categorized as High and Very High, resulting in the expected financial loss value in monetary units.

The development of risk response alternatives referred to four strategies: mitigation, avoidance, transfer, and acceptance. Each alternative was evaluated by experts based on its effectiveness in reducing probability and cost impact using a Likert scale of 1 to 5. The residual EMV for each alternative was subsequently calculated. The preferred alternative was selected based on the lowest residual EMV value, with mitigation cost used as an additional consideration when alternatives produced similar residual EMV values. The selected mitigation costs were then integrated into the projected CoQ structure and total project cost calculations before and after mitigation, enabling evaluation of the economic benefits through EMV reduction, net benefit, and benefit–cost ratio indicators.

RESULTS AND DISCUSSION

Analisis Cost of Quality (CoQ) Aktual

The Cost of Quality (CoQ) analysis was carried out to identify and measure the costs incurred by the project in order to prevent non-conformities, assess the suitability of work results, and deal with failures that occurred during the implementation of the GI 150 kV KIIC

Margakarya civil work. The results of the document examination show that the project does not yet have a dedicated account that records the CoQ separately, so the quality costs are still spread across several cost groups such as personnel, training, testing, inspection, equipment, rework, and repairs. Cost identification is carried out by tracing thirteen data sources, including Implementation Budget Plan, cost realization report, Inspection and Test Plan, inspection and testing report, Non-Conformance Report, rework and repair report, material use report, labor and equipment report, training and calibration document, Factory Acceptance Test document, and interview results and field observation.

Each cost item is then examined based on inclusion criteria, i.e. it has a direct relationship with quality activities, expenditure objectives can be determined, has supporting documents, cost values can be traced, can be classified into one of the components of the PAF, is within the scope of civil works, and is not double-calculated on other cost items. The results of the preliminary examination showed that the cost of measuring instrument calibration and Factory Acceptance Test was more accurately classified as an appraisal cost, while the cost of occupational safety and health training, personal protective equipment, and HSE facilities was excluded from the CoQ calculation because the main purpose was related to occupational safety, not quality control. Survey cost items, production tool inspections, and drill tool breakdowns are further validated by expert judgment before final classification is established.

Based on the classification process, cost prevention activities include quality control training, inspection and calibration of measuring instruments, inspection of work equipment readiness, location surveys and designations, factory acceptance tests, and initial topographic measurements. The cost appraisal activities include visual inspection of bored pile work, foundation of high-voltage equipment, cable trenches, 20 kV buildings, and earthworks, as well as testing of concrete slump, concrete compressive strength, steel tensile and bending of reinforcing steel. Internal failure costs were identified from two incidents, namely the improvement of the elevation of the cable trench work and the damage to the drilling machine due to the inconsistency of the implementation method, while no realization of external failure costs was found during the observation period so that the value was set at Rp0.

The results of the recapitulation of the calculation of each CoQ component are presented in Table 1.

Table 1. Actual Cost of Quality (CoQ) Component Recapitulation

CoQ Components	Value (Rp)	Percentage
Prevention Cost	172.561.400	66,40%
Appraisal Cost	48.600.000	18,70%
Internal Failure Cost	38.700.000	14,90%
External Failure Cost	0	0,00%
Current Total CoQ	**259.861.400**	**100,00%**

Based on Table 1, the total actual cost of quality of the project that can be identified and traced based on the document is IDR 259,861,400. The largest cost component is prevention cost of IDR 172,561,400 or 66.40% of the total CoQ, followed by appraisal cost of IDR

48,600,000 or 18.70%, and internal failure cost of IDR 38,700,000 or 14.90%. If prevention cost and appraisal cost are grouped as cost of control, then the project quality cost structure is dominated by control costs of 85.10%, while the visible failure cost is only 14.90%. The internal failure cost value comes from the cost of repairing the cable trench due to elevation mismatch of IDR 27,200,000 and the cost of damage to the drilling machine due to an error in the implementation method of IDR 11,500,000.

This composition shows that project expenditure is proportionally more directed to prevention and assessment activities than to handling failures that have occurred, in line with the findings of Basu (2015) and Maysoon (2019) that construction projects with good quality control tend to allocate a larger proportion of CoQ to prevention and appraisal costs. However, the dominance of control costs is not enough to state that quality management has been fully effective, because there is still an internal failure cost of Rp38,700,000 which indicates that there are prevention or assessment activities that have not been fully able to control the causes of non-conformity, especially in the control of work elevation and verification of implementation methods. The value also does not include hidden failure costs such as decreased productivity, additional coordination time, and disruption of other work as stated by Cheah (2011) and Aoieong, Tang, and Ahmed (2002), so that the overall impact of quality failure has the potential to be greater than the value of the recorded failure cost. The two actual failure events, namely the mismatch of the cable trench elevation and the damage to the drilling tool, are further used as one of the starting points in the risk identification process at the next stage, as they both show that the project failure comes not only from inappropriate work results, but also from inaccuracies in the process and method of implementation.

Failure Cost-Based Risk Identification and Assessment

Risk identification is carried out to determine events that have the potential to cause failure costs in the project, not only using the failure costs that have occurred, but also considering potential events that can cause rework, damage, delays, and other financial consequences if not controlled. The identification process begins with the determination of critical work areas based on the Work Breakdown Structure (WBS), taking into account the level of technical complexity, volume and cost weight, the relationship between activities, and the potential for rework or quality deviations. The results of the WBS evaluation show that the cable trench and reinforced concrete structure work has a high proportion of volume and complexity of implementation, while the bored pile work has a diameter of 19.10% so that it has the potential to pose a significant risk to the cost and quality of the project.

The sources of risk are further grouped using the Risk Breakdown Structure (RBS) approach into five categories, namely technical risks, construction and work method risks, logistics and material risks, environmental risks and occupational safety, and managerial and administrative risks. This grouping is in line with the categorization of construction risks put forward by Szymański (2017) and Doloi, Sawhney, Iyer, and Rentala (2012), which emphasize the importance of risk classification based on the source of the cause so that it can be traced in relation to the cost and time impact of the project. The identification results show that the categories of technical risk and construction risk are the most dominant group because they are directly related to the main civil works of the project, in particular cable trenches, bored piles, switchyard foundations, ironing, formwork, and concrete casting.

Based on the results of WBS and RBS mapping, 13 main risk events that have the potential to affect the quality, cost, and timing of project implementation are obtained, as presented in Table 2.

Table 2. Identification of Civil Work Risk Events for the 150 kV GI KIIC Margakarya Project

Code	Category: RBS	Risk Event	Potential Impact on Failure Cost
R1	Technical & Geotechnical	Incompatibility of excavation and cable trench excavation work	Rework of excavations, additional excavations, delays in further work
R2	Technical & Geotechnical	Bored pile job incompatibility	Foundation repairs, additional boring, delays in structural work
R3	Construction & Working Methods	The quality of the concrete work is not according to specifications	Concrete repair, local dismantling, recasting, additional testing
R4	Construction & Working Methods	Ironing installation errors	Disassembly of reinforcement, inspection delays, casting delays
R5	Construction & Working Methods	Formwork and anchor bolt mismatch	Rework formwork, repair of anchor bolt position, change of structure dimensions
R6	Construction & Working Methods	Incompatibility of drainage and utility work	Re-dismantling drainage lines, inundation of work areas
R7	Materials & Logistics	Delays and material mismatches	Idle time work, material replacement
R8	Materials & Logistics	Delays in the mobilization of tools and materials	Critical work delays and decreased productivity
R9	Managerial & Administrative	Technical approval delays	Delays in advanced work and idle time
R10	Managerial & Administrative	Disruption of implementation due to field conditions and weather	Decreased productivity, work delays
R11	Construction & Working Methods	Rework due to quality mismatch	Rework, additional labor, additional material costs
R12	Managerial & Administrative	Project cost and time claims	Additional project costs and potential contract disputes
R13	Materials & Logistics	Delays and increased costs of supply of ready-mix concrete	Casting delays, idle time of labor and tools, rising concrete costs

Table 2 shows that the risks in the GI 150 kV KIIC Margakarya project are spread across all stages of civil works, from earthworks and foundations to structural work and final completion. The risks of R1 to R6 are generally related to technical aspects and methods of carrying out structural work, such as inconsistencies in excavation elevation, bored pile depth, concrete quality, iron installation, incompatibilities in formwork and anchor bolts, and drainage work. The risks of R7, R8, and R13 are related to logistical and material aspects, including delays in delivery, mobilization of equipment, and most importantly the limited supply of ready-mix concrete due to the temporary suspension of excavation operations at the C quarry mine in West Java. Meanwhile, R9, R10, and R12 risks are related to managerial and administrative aspects such as approval delays, weather disturbances, and potential project cost and time claims. These findings are consistent with Doloi (2013) who shows that administrative risks and weaknesses in project management are one of the main triggers for delays and construction cost overruns.

Each identified risk event is then assessed using the Risk Exposure (RE) approach, which is the multiplication between probability and final impact as a result of the median aggregation of eight expert judgments, with the impact dimension assessed multidimensionally including aspects of time, cost, quality, and work safety referring to PMBOK (PMI, 2021). The calculation results show that the standard deviation value and coefficient of variation between experts are in a relatively low range, which indicates adequate assessment consistency as required in a structured expert judgment procedure. The results of the Risk Exposure calculation for all risk events are presented in Table 3.

Table 3. Risk Exposure (RE) Calculation Results

Code	P Final	I Final	RE	Ranking	Category
R1	4	3,75	15,00	7	High
R2	4	4,25	17,00	2	Very High
R3	4	4,00	16,00	3	High
R4	4	4,00	16,00	3	High
R5	4	4,00	16,00	3	High
R6	3	3,00	9,00	12	Medium
R7	4	3,25	13,00	8	High
R8	4	3,25	13,00	8	High
R9	4	2,75	11,00	10	Medium
R10	4	3,25	13,00	8	High
R11	4	3,75	15,00	7	High
R12	4	4,25	17,00	2	Very High
R13	5	4,00	20,00	1	Very High

Based on Table 3, the classification of risk levels uses five categories, namely very low (RE value 1-4), low (5-8), medium (9-12), high (13-16), and very high (17-25). The classification results show that there are three risk events with a very high category, namely R13 (delay and increase in the cost of supply of ready mix concrete) with an RE of 20.00, R2 (non-conformity of bored pile work) and R12 (project cost and time claims) which each have an RE of 17.00. Seven other risk events, namely R1, R3, R4, R5, R7, R8, R10, and R11 are in the high category with RE between 13 to 16, while R6 and R9 are in the medium category. These findings are in line with Hillson (2007) and Taroun and Yang (2011) who affirmed that the Probability x Impact approach is effectively used as a screening tool to screen for dominant risks before further financial quantification using EMV. Risks with the very high and high categories are then the focus of the Expected Monetary Value analysis, while the risks of the medium category such as R6 and R9 are still controlled through routine monitoring because of their relatively small level of influence on the project.

Analisis Expected Monetary Value (EMV)

The Expected Monetary Value (EMV) analysis is carried out to estimate the potential loss of project costs based on a combination of probability and impact of risk costs, so that the EMV value does not represent the actual cost of project failure, but the potential for an increase in future failure cost if a risk occurs. The EMV analysis was focused on eleven risk events in the High and Very High categories as a result of Risk Exposure analysis, namely R1, R2, R3, R4, R5, R7, R8, R10, R11, R12, and R13, while R6 and R9 were not analyzed because they were in the medium category. The probability value is converted from the ordinal scale of 1-5 of the expert judgment result to a numerical value of 0-1 using the interval middle value approach, so that the median probability of the scale of 4 is equivalent to the numerical probability of 0.70 and the median of the scale of 5 is equivalent to 0.90. The cost impact of each risk is determined based on the volume of work affected, unit price, additional labor and equipment, and late costs traced from Cost of Quality data, Implementation Budget Plan, and project confirmation. The results of the EMV calculation for all risk events analyzed are presented in Table 4.

Table 4. Expected Monetary Value (EMV) Calculation Results

Code	Probability	Cost Impact (Rp)	EMV (Rp)
R1	0,70	35.000.000	24.500.000
R2	0,70	95.000.000	66.500.000
R3	0,70	80.000.000	56.000.000
R4	0,70	65.000.000	45.500.000
R5	0,70	70.000.000	49.000.000
R7	0,70	45.000.000	31.500.000
R8	0,70	40.000.000	28.000.000
R10	0,70	38.000.000	26.600.000
R11	0,70	60.000.000	42.000.000
R12	0,70	90.000.000	63.000.000
R13	0,90	120.000.000	108.000.000

Code	Probability	Cost Impact (Rp)	EMV (Rp)
Total			**540.600.000**

Based on Table 4, the total cumulative Expected Monetary Value of the eleven risk events analyzed is IDR 540,600,000. This value illustrates the potential expected project cost loss that can be caused by all identified dominant risk events. The comparison between the actual internal failure cost value of IDR 38,700,000 in the CoQ analysis and the total EMV of IDR 540,600,000 shows a fundamental difference between the realized failure cost and the potential loss that is still possible. Harahap, Putra, and Sari (2023) emphasized that this difference is important to understand so that there is no double calculation between the actual failure cost and the expected value of risk loss in the mitigation decision-making process.

Based on the combination of Risk Exposure and EMV values, five priority risks were determined that were the main focus of the preparation of alternative risk responses, namely R13 with EMV of IDR 108,000,000, R2 of IDR 66,500,000, R12 of IDR 63,000,000, R3 of IDR 56,000,000, and R5 of IDR 49,000,000, with a total of five EMV priority risks of IDR 342,500,000. R13 is the risk with the highest expected potential loss because concrete work is the main part of the substation civil work. So that the disruption of concrete supply can delay casting, cause idle time for labor and equipment, and cause an increase in material costs. R2 has a high EMV value because the inconsistencies of bored pile work can affect the function of the foundation and hinder subsequent structural work, while R12 deals with potential cost and time claims whose impacts can include indirect costs and extended use of project facilities. R3 and R5 are directly related to the dismatch in the quality of structural work which can lead to rework and delay of further work if not controlled. The selection of the five risks did not rule out other risks that remained in the high category, which still required operational control and regular monitoring, but the development of detailed response alternatives focused on the risks with the greatest EMV value so that mitigation resources could be efficiently directed.

Evaluation of Risk Response Alternatives and Integration to CoQ

The preparation of alternative risk responses is carried out against five priority risks by referring to four mitigation strategies, namely mitigation, avoidance, transfer, and acceptance, in accordance with the construction project risk management framework. Each risk was given three alternative actions which were then assessed by the expert judgment on the reduction of probability and cost impact using a Likert scale of 1-5, before calculating the residual value of EMV using the equation REMV = P'xC', with P' and C' respectively being the probability and cost impact after the implementation of the response. For R13 risk, the alternative is to add a reserve ready mix supplier (R13-A) and a fixed-price contract with the supplier (R13-B) resulting in the same residual EMV of Rp38,880,000, so R13-A was chosen because it requires a lower cost, which is Rp18,000,000. A similar pattern also occurs in R2, where the addition of bored pile drilling supervision (R2-A) and PDA Test (R2-B) results in the same residual EMV of Rp23,940,000. So R2-A was chosen because the cost was lower by IDR 15,000,000. In R12, the strengthening of approval of work changes and project documentation (R12-A) was chosen with a residual EMV of IDR 22,680,000 and a cost of IDR 10,000,000, while in R3, the improvement of quality control of concrete work (R3-A) was chosen with a residual EMV of IDR 20,160,000 and a cost of IDR 14,000,000. In contrast to the other four risks, in R5 the alternative implementation of hold point approval before casting (R5-C) resulted in a The lowest residual EMV was IDR 12,250,000 even though it was classified as an avoidance strategy at a cost of IDR 15,000,000, lower than the increase in ordinary formwork inspections which only lowered the EMV to IDR 17,640,000.

A recapitulation of the selected risk response alternatives for the five priority risks is presented in Table 5.

Table 5. Recapitulation of Selected Risk Response Alternatives

Code	Initial EMV (Rp)	Selected Mitigations	Mitigation Fee (Rp)	Residual EMV (Rp)	EMV Decline (Rp)
R13	108.000.000	Adding a backup ready mix supplier	18.000.000	38.880.000	69.120.000
R2	66.500.000	Addition of bored pile drilling supervision	15.000.000	23.940.000	42.560.000
R12	63.000.000	Strengthening change approval and documentation	10.000.000	22.680.000	40.320.000
R3	56.000.000	Improved quality control of concrete work	14.000.000	20.160.000	35.840.000
R5	49.000.000	Implementation of hold point approval	15.000.000	12.250.000	36.750.000
Total	**342.500.000**		**72.000.000**	**117.910.000**	**224.590.000**

Based on Table 5, the total EMV of the five priority risks decreased from IDR 342,500,000 to residual EMV of IDR 117,910,000 after the implementation of the selected mitigation, with a total mitigation cost of IDR 72,000,000. The resulting reduction in potential losses amounted to IDR 224,590,000, or equivalent to 65.57% of the initial EMV of the five priority risks. This value shows that mitigation alternatives selected based on the lowest EMV residual criteria are able to significantly reduce potential risk losses, in line with the findings of Rosenfeld (2009) that the benefits of quality investments in the form of reduced failure costs can exceed the value of the investment itself, as well as Basu (2015) who shows a direct relationship between increased prevention costs and reduced failure costs.

The selected mitigation cost of Rp72,000,000 was then integrated into the Cost of Quality structure, with Rp43,000,000 categorized as additional prevention cost (from R13-A, R12-A, and R5-C alternatives) and Rp29,000,000 as additional appraisal costs (from R2-A and R3-A alternatives). This integration resulted in a CoQ structure in the mitigation scenario with the prevention cost increasing to IDR 215,561,400 and the appraisal cost increasing to IDR 77,600,000, while the actual internal failure cost was maintained at IDR 38,700,000 because the cost had already occurred and could not be eliminated by the mitigation applied afterwards.

The evaluation of the economic benefits of mitigation was carried out by comparing the projected total costs without mitigation and after mitigation. The unmitigated projection was calculated from the sum of the actual CoQ of IDR 259,861,400 and the initial EMV of five priority risks of IDR 342,500,000, resulting in a projected total cost of IDR 602,361,400. In contrast, the post-mitigation projection was calculated from the sum of the actual CoQ, the mitigation cost of IDR 72,000,000, and the total residual EMV of IDR 117,910,000, resulting in a projected total cost of IDR 449,771,400. A comparison of the two scenarios is presented in Table 6.

Table 6. Comparison of Total Cost Projections Without Mitigation and After Mitigation

Components	No Mitigation (Rp)	After Mitigation (Rp)	Changes
Actual CoQ of the project	259.861.400	259.861.400	Fixed
Mitigation costs	0	72.000.000	Up IDR 72,000,000
Potensi future failure cost	342.500.000	117.910.000	Down IDR 224,590,000
Projected total costs	**602.361.400**	**449.771.400**	**Down IDR 152,590,000 (25.33%)**

Based on Table 6, the implementation of mitigation resulted in a decrease in the projected total cost of Rp152,590,000, or 25.33% compared to the projection without mitigation. This percentage value is different from the EMV decrease of 65.57% because it uses a different comparative basis, namely 65.57% is a decrease in EMV of priority risk alone, while 25.33% is a decrease in the projected total cost that has taken into account the actual CoQ and mitigation costs simultaneously. The effectiveness of mitigation integration on CoQ was also evaluated through a benefit-cost ratio, calculated from the comparison of EMV reduction to mitigation costs, resulting in a BCR value of 3.12. This value shows that every Rp1 mitigation cost incurred has the potential to result in a reduction in expected losses of Rp3.12, with a net benefit of Rp152,590,000.

These results strengthen the arguments of Khadim, Abid, and Ahmed (2023) and Hwang and Aspinwall (2009) that increased investment in prevention and appraisal costs is not a waste, but a control mechanism that can economically reduce potential failure costs in a much larger proportion than the value of the investment. From a managerial perspective, these findings show that risk mitigation decisions in electricity construction projects should be based not only on qualitative risk perception, but also on quantitative evaluation of economic benefits as developed in the integrative framework of CoQ-Risk Exposure-EMV in this study. The framework allows project managers and site managers to determine the most cost-rational mitigation priorities, while encouraging a shift in quality cost allocation from failure costs to prevention and appraisal costs in a more measurable and data-driven manner, in line with the view of Dziadosz and Rejment (2015) that Risk Exposure-based approaches and financial quantification are able to produce more accurate risk priority mapping than risk assessments qualitative.

Synthesis and Implications of Research Results

Overall, the results of this study show a clear relationship between the actual Cost of Quality structure, Risk Exposure level, and Expected Monetary Value value in the 150 kV KIIC Margakarya Substation civil project. The dominance of prevention cost and appraisal cost of 85.10% of the total actual CoQ indicates that the project management has allocated considerable resources for prevention and quality assessment, but it was still found that an internal failure cost of Rp38,700,000 came from two failure events, namely the mismatch of the cable trench elevation and the damage to the drilling tool. When the two events were further traced through the Risk Breakdown Structure approach, it was found that they were related to broader risks in the technical and construction categories, as indicated by the Risk Exposure value R2 (bored pile mismatch) which reached the very high category. This pattern reinforces the view of Abdollahzadeh (2015) that failure cost is a direct indicator of the risk that has been realized, so that CoQ analysis alone without being linked to a risk assessment is not enough to provide a comprehensive picture of potential project losses in the future.

The finding that the risk with the highest EMV value (R13) comes from external factors, namely the limited supply of ready-mix concrete due to the temporary suspension of mine operations at Mine C, suggests that quality control of electricity construction projects cannot be fully controlled through internal process improvements alone. This condition is in line with the findings of Doloi, Sawhney, Iyer, and Rentala (2012) that supply chain disruptions are one of the dominant risk factors affecting the cost and time performance of construction projects, while emphasizing the importance of anticipatory mitigation strategies, such as the addition of backup suppliers, rather than relying solely on improvements at the implementation stage. With an EMV value of IDR 108,000,000, this risk is also proof that the financial impact of external risks can exceed the impact of internal technical risks such as bored pile or concrete quality mismatches, so project mitigation strategies need to take into account risks that are beyond the contractor's direct control.

The results of integrating risk mitigation into the CoQ structure also provide empirical evidence on the trade-off between quality control investment and the reduction of potential losses, as conceptualized by Oakland (2003) in the Prevention-Appraisal-Failure model. The addition of mitigation costs of IDR 72,000,000, which is equivalent to an increase of around 27.71% from the actual CoQ, was able to reduce the potential future failure cost of IDR 224,590,000 in the five priority risks, or result in a reduction in the projected total project cost by 25.33%. A benefit-to-cost ratio of 3.12 indicates that the additional quality control investment is economically more profitable than leaving the risk unmitigated, reinforcing the argument of Rosenfeld (2009) and Hwang and Aspinwall (2009) that increasing prevention and appraisal costs is an investment, not a waste, as long as it is directed to the risk that has the highest expected value of loss.

Compared to previous research, the main contribution of this study lies in the provision of an analytical framework that connects three elements at once, namely the actual CoQ structure, the severity of the risk through Risk Exposure, and financial quantification through EMV, in a single mitigation decision-making flow. Research by Barlow (2009) and Basu (2015) has shown the importance of separating CoQ components and their relationship to failure cost, but has not explicitly linked the cost structure to the Risk Exposure level and EMV value of each risk event. Similarly, the research of Szymański (2017) and Taroun and Yang

(2011) provides a methodological foundation for Probability x Impact-based risk assessment, but has not yet integrated it with the actual quality cost structure of the project to generate cost projections after mitigation. Thus, the integrative approach of CoQ-Risk Exposure-EMV developed in this study provides methodological added value in the form of the ability to evaluate the economic benefits of each mitigation alternative transparently, namely by comparing the control costs incurred to the reduction in the expected losses produced.

From a managerial perspective, the results of this study provide practical implications for the management of the 150 kV KIIC Margakarya Substation Project and similar electricity construction projects. First, periodic CoQ evaluations need to be conducted not only to monitor the amount of quality costs, but also to trace the actual occurrence of failures as a starting point for broader risk identification. Second, mitigation priorities should be directed at the risks with the highest EMV values, as the five priority risks in this study, which only cover a fraction of the 13 risk events identified, contributed to more than 63% of the total EMV of the eleven risk events analyzed. Third, the selection of mitigation alternatives needs to consider both the effectiveness of the risk reduction and the cost of its implementation, as shown in the case of R13 and R2 where two alternatives with different effectiveness produce the same residual EMV, so that the lower-cost alternative becomes a more economically rational option.

However, this study has limitations that need to be considered in interpreting the results. The probability and impact value of the risk used is sourced from the expert judgment of eight experts on one project, so that the results of the analysis are specific to the context of the 150 kV KIIC Margakarya Substation Project and require adjustments when replicated in projects with different risk characteristics. In addition, the CoQ calculation in this study is limited to visible failure costs that can be traced through project documents, while hidden failure costs such as decreased productivity and coordination disorders are not quantified due to the limitations of the recording system, so that the total financial impact of project quality failures in real terms has the potential to be greater than the value reported in this study.

CONCLUSION

This study demonstrated that the integration of Cost of Quality (CoQ) and risk management could serve as an effective approach for identifying sources of failure costs, determining risk priorities, developing appropriate mitigation strategies, and reducing potential failure costs in the civil construction works of the 150 kV KIIC Margakarya Substation Project. The CoQ analysis results showed a total actual quality cost of IDR 259,861,400, dominated by prevention and appraisal costs, which accounted for 85.10% of total CoQ. Meanwhile, internal failure costs accounted for 14.90% and served as the basis for risk identification, resulting in 13 identified risk events. Among these, five priority risks were categorized as high and very high, with a total EMV of IDR 342,500,000. The implementation of selected risk response strategies with mitigation costs of IDR 72,000,000 reduced the residual EMV to IDR 117,910,000, representing a 65.57% reduction. Consequently, the projected total project cost decreased from IDR 602,361,400 to IDR 449,771,400, resulting in potential savings of IDR 152,590,000 (25.33%) and a benefit-to-cost ratio of 3.12. These findings demonstrated that increased investment in prevention and appraisal activities, when appropriately directed toward priority risks, could generate significant economic benefits compared with allowing risks to remain unmanaged.

The integrated CoQ–Risk Exposure–EMV analysis model developed in this study can be applied to other electricity construction projects by adjusting risk characteristics, cost impact values, and project-specific quality cost structures. Further research is recommended to develop models using multi-project historical data to improve generalizability, explore more data-driven approaches for risk probability quantification, such as Bayesian methods, and develop quality cost optimization models to determine the optimal allocation of prevention and appraisal costs that minimize failure costs while achieving the most efficient overall project cost.

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