Quality Failures–Based Critical Cost Impact Factors: Logistic Regression Analysis

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Abstract: Due to the various dynamic conditions of construction sites, quality failures have become part and parcel of the industry. Many studies have identified the causal factors of construction site quality failures and their cost impacts. However, limited studies have been made evaluating the domino effects of these on one another and the correlation between the cost impact and frequency of each attribute. In this study, made in the context of ongoing research into related artificial intelligence (AI)–based predictive models, a total of 2,527 nonconformance reports (NCRs) collected from 59 construction projects within the scope of a previous study were analyzed using the Delphi method and logistic regression analysis. According to the Delphi results, 25 critical cost impact factors were refined and categorized into five main groups: Materials, Design, Installation, Operation, and Process. Then, five main hypotheses were developed to test each attribute's cost impact and interaction by logistic regression. The results showed that although some attributes (from the Materials and Operation groups) have a significant impact on the cost of quality if observed in a failure report individually, others may become a critical cost-impact factor when interacting with other attributes. No significant correlation was observed between the frequency and cost impact of the attributes. Finally, a holistically based quality control system that considers the domino effects of causal factors from planning to operation was proposed for construction practitioners to reduce quality failures causing cost and time overruns. **DOI: 10.1061/(ASCE)CO.1943-7862.0002412.** © *2022 American Society of Civil Engineers.*

Author keywords: Construction quality; Quality failure cost; Nonconformance; Logistic regression; Domino effect.

Introduction

Each construction project has unique dynamics and requires a balance among project scopes, such as time, cost, and quality, to attain the required project performance. Because several factors and stakeholders are involved in a construction project during its life cycle, meeting and checking the main project objectives presents a challenge. One of the most important aims of a construction project is quality, but failures in quality are commonly observed and have adverse effects on the planned budget (Hwang et al. 2009) and schedule (Al-Hazim et al. 2017). The costs of quality problems for completed construction projects vary from less than 1% to 20% of the original contract value (Jafari and Love 2013; Josephson and Hammarlund 1999; Liu et al. 2018).

Different quality problems, such as defects, failures, and reworks, are regarded as part and parcel of the construction industry and have to be considered for each project, primarily to reduce their cost effects. In this regard, several studies (e.g., Abdelsalam and Gad 2009; Barber et al. 2000; Doloi 2012; Love et al. 2017) have emphasized that reporting quality failures and developing preventive actions during construction projects are vital in order to improve productivity and reduce construction cost and time overruns. In this context, various studies have been carried out to identify the root causes of quality issues and examine their effects on the main scopes of the construction projects (e.g., time and cost). Although most of these studies have been based on a qualitative approach, with surveys and interviews conducted with experts (e.g., Abdelsalam and Gad 2009; Heravi and Jafari 2014; Larsen et al. 2015), some have used real site observation data, such as nonconformance reports (NCRs) (Balouchi et al. 2019; Forcada et al. 2017; Love et al. 2017), final reports, the historical data of projects (Al-Hazim et al. 2017), and rework documents (Liu et al. 2018; Senouci et al. 2016).

However, such studies using site reports have primarily focused on evaluating the impact of quality issues on cost variations rather than defining causal parameters. Therefore, it is still necessary to identify and examine the critical cost impact factors in construction projects according to quality failure reports by adopting both expert opinion and site observation data from diverse perspectives. Thus, the primary purpose of this study is to investigate which and to what degree construction attributes significantly affect construction costs based on quality failure reports recorded in construction workplaces. To that end, an empirical assessment was made of the relationships among the frequencies and importance of the attributes and intersection effects of the refined factors on cost performance.

Because cost overruns and quality failures are common problems in construction projects, it is intended for construction professionals to be able to utilize the results of this study to minimize cost overruns and manage major cost impact factors occurring due to quality failures. In addition, the research methodology employed, including expert opinion and a data-driven approach, is new to the literature and will open new doors to the understanding and mitigation of project performance issues, such as time delays, cost

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overruns, and low productivity in a different and detailed way. Evaluating the correlation between frequency and cost impact factor and exploring the interaction effect of any two attributes will also contribute to the existing body of knowledge.

Literature Review

Costs of Quality in Construction

It is well-known that in order to achieve successful performance, construction projects should be delivered in a planned time frame within the estimated budget and desired quality. Low-quality construction levels, especially during the implementation phases, are the main reason for time and cost overruns (Love et al. 2017). The term quality may be defined as achieving the purposes and meeting the expectations required by the client or owner (Jafari and Love 2013). For several years, quality issues have been recognized as a primary barrier to the effective management of construction processes (Barber et al. 2000). Accordingly, additional costs have emerged due to deficiencies in quality, referred to in the literature as the cost of quality (CoQ). These have not only not been prevented but have become chronic, seemingly part of the nature of architectural, engineering, and construction (AEC) projects.

A wide range of definitions for CoQ has been provided (Abdelsalam and Gad 2009; Heravi and Jafari 2014; Jafari and Love 2013). For example, Abdelsalam and Gad (2009) identified it as a summation of the conformance cost, including activities to prevent poor quality (e.g., training, testing, monitoring, and audits) and nonconformance costs resulting from quality failures in a service or product (e.g., rework, material waste, defects, quality deviations, and repair in warranty) or client requirements (e.g., change orders). Feigenbaum (1983) classified the quality cost into three main parts, namely prevention, appraisal, and internal and external failure costs.

Generally, CoQ comes from quality-related issues that appear in construction projects. Here, CoQ is a cost impact (positive or negative) of such quality failures (Love et al. 2017). In this paper, construction cost refers to all expenditures incurred in construction projects, and the root causes of quality failures are referred to as attributes. Five categories of attributes were identified—named Materials, Design, Installation, Operation, and Process—along with 25 subattributes. Critical cost impact factor refers to the significance of the influence on construction cost of the (sub)attributes (using a 1–5 Likert-scale rating).

One of the primary aspects of CoQ is reworking, which goes under different terms, such as defects (Josephson and Hammarlund 1999), quality deviations (Larsen et al. 2015), change orders (Senouci et al. 2016), and nonconformance (Barber et al. 2000). Redoing a construction task after it has been incorrectly performed at the initial time was defined as rework by Love and Edwards (2004). Additional resources, such as labor and materials, unnecessary effort, productivity and profit loss, client dissatisfaction, and time and cost overruns are the main results of construction site reworks (Love and Irani 2002; Ye et al. 2014).

In a study carried out by Josephson and Hammarlund (1999), the causal parameters and costs of rework were explored by analyzing 2,879 defects collected from seven building projects. The findings of that study showed that 45% of the defect costs occurred on-site, and lack of knowledge and motivation were the main reasons for the defects. Love et al. (2010) attempted to identify major cost prediction factors of reworks via surveys conducted with 115 professionals working in civil infrastructure projects. Various main causes were found, including deficiencies of information technologies, ineffective work procedures, and clients changing orders. The study concluded that 10% of the total construction cost was due to reworks.

Balouchi et al. (2019) evaluated critical rework factors based on 935 NCRs filled in a single site, a mass housing construction project. They found that ineffective project management processes had the highest cost impact on this project. Yap et al. (2017) assessed the effects of reworks on total project cost and schedule via a questionnaire completed by 114 construction experts. The study concluded that building project reworks raised the total project cost by 3%–6% and extended the schedule by 5%–10%. It was also found that two main factor groups were responsible for 30% of the total rework costs: project coordination and equipment/material management. Forcada et al. (2017) investigated the contributing factors of rework costs from the perspective of cost and time variations based on 788 construction reworks in 40 construction projects. The findings of that study revealed a significant relationship between rework costs and project characteristics, notably project and contract type.

Change orders, a type of rework, are a major problem in AEC projects, mainly because they lead to cost growth, time delays, and disputes among stakeholders (Alnuaimi et al. 2009). Senouci et al. (2016) analyzed a total of 1,122 change orders made in 22 commercial and residential projects in Qatar to determine their primary factors and the cost impacts. The results showed that changes in scope by the owner increased the average cost of a project by 16%. Alnuaimi et al. (2009) explored the main causes and effects of change orders based on four case studies and a survey of 43 construction professionals. They found the additional works and design changes required by clients to be the most influential factor in conflicts, time delays, and cost overruns.

Another term used under CoQ, quality failure, has a broader meaning than rework, defect, and change order, as stated by Feld and Carper (1997), who defined quality failures for construction activities as nonconformity to expected design, application, or process. Quality failures include collapses or deformations and performance or process issues in construction. Several studies have looked at the underlying causal factors and cost effects of quality failures in the construction industry (e.g., Barber et al. 2000; Doloi 2012; Jafari and Love 2013; Love et al. 2017).

Based on site inspections in two road projects, Barber et al. (2000) developed a framework to estimate quality failure costs. The authors concluded that the completed project cost increases due to quality failures ranged from 3.6% to 6.6%. Love et al. (2017) empirically evaluated quality failure costs concerning construction cost variations. They received a total of 7,082 NCRs and classified them according to cost and project characteristics (project, procurement, and contract types). The findings of their study showed NCR costs as constituting 0.18% of the original contract value (OCV), with the most recorded NCR incidents being quality failures related to structural works (e.g., steel and concrete applications).

Doloi (2012) attempted to understand the relationship between quality failures and cost overruns in construction projects. For this purpose, 48 different attributes were defined based on the literature, and a questionnaire was conducted with 91 construction experts (mostly consultants, clients, and contractors). The deficiencies and failures in planning and scheduling during the construction phase were identified as the most critical factors leading to cost growth in AEC projects. Jafari and Love (2013) carried out a case study in a railway project to quantify the ratio of quality failures to OCV via site observation data. The result showed quality failures to be responsible for 0.05% of the OCV, with approximately 70% of failures being related to construction aspects (poor labor, material and equipment, improper controls, and incorrect applications).

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Research Statement

Numerous studies have focused on identifying the root causes and main effects of quality issues on construction project performance. Although most of them (e.g., Alnuaimi et al. 2009; Heravi and Jafari 2014; Larsen et al. 2015; Love and Edwards 2007; Love et al. 2010; Yap et al. 2015, 2017) have used surveys conducted with construction experts, some (e.g., Al-Hazim et al. 2017; Barber et al. 2000; Hwang et al. 2009; Josephson and Hammarlund 1999; Senouci et al. 2016) have utilized real information or historical data, such as contract values, time durations, defects, and change orders received from construction projects. A few studies (e.g., Balouchi et al. 2019; Forcada et al. 2017; Jafari and Love 2013; Love et al. 2017) have considered actual site observations or reports, including NCRs, to determine the critical factors influencing construction project performance. These NCRs were collected from only one construction site (e.g., a field study) in two studies (Balouchi et al. 2019; Jafari and Love 2013).

In other studies, Forcada et al. (2017) and Love et al. (2017) received a high number of NCRs from different projects and constructions sites but mainly focused on cost variations, such as the relationship between OCV and rework costs, to evaluate cost impact factors rather than quality failures. Although the reports were collected from construction sites, they only included direct NCR costs, type, description, type of project, contract value, procurement, contract type, and change orders; there was no information about the reason for real quality failures or defects. In fact, with no information being collected about the reasons for failure, it should be noted that the term NCR was used differently from here in those studies (Forcada et al. 2017; Love et al. 2017). In those studies, the NCR term was used as a defect or rework without giving information about the root cause formation of such failures. Similarly, Senouci et al. (2016) focused on the change orders rather than general quality failures and their impacts on the CoQ. Therefore, there is a lack of studies identifying quality failures based on critical cost impact factors from diverse perspectives utilizing actual site reports together with expert opinion.

It is in this context that the main objective of this study is to explore significant factors influencing the cost performance of construction projects according to a combination of NCRs and expert opinion. In addition, because some attributes can be observed together in failures rather than as individual factors, the domino effects of these factors on one another have not yet been examined. Thus, the interactions of each attribute on the project cost are also empirically evaluated in this study. We also assess the correlation between the frequency index (FI) and cost impact of each attribute using the NCRs and expert views.

This study has been developed and introduced as a branch of other ongoing research into artificial intelligence (AI)–based cost-impact prediction models. In that work, Doğan (2021) focused on developing a predictive model for the cost impact of nonconformity factors based on two different hybrid AI algorithms (a case-based reasoning-analytical hierarchy process and genetic algorithm). The current research is thus differentiated from that study by its assessment of the domino effect of the cost impact factors and identification of primary and subpredictive CoQ factors for the construction industry.

Research Methodology

This study combines NCRs, including diverse quality failures recorded in different construction sites, with an expert opinion approach, the Delphi technique (Fig. 1). After the data collection and identification of the most critical cost impact factors according to the literature review, we carried out the Delphi process to achieve the final attribute list and assign a weight to each attribute. By weighting each attribute, we could generate a matrix of 2,527 (cases) × 26 (25 final attributes in binary form + 1 cost impact rank, as determined by three experts). We also developed five different hypotheses to test whether each group attribute had significant effects on the construction cost. Then, we performed a logistic regression analysis to examine the CoQ effects of each attribute and of the interaction of paired subattributes.

Attribute Selection

In order to identify the critical cost impact factors and evaluate their interaction effects on the CoQ, we adopted the expert opinion approach using the Delphi method, which has been widely used in previous studies for similar purposes (Ayhan and Tokdemir 2018). Before applying the Delphi process, the wide range of CoQ attributes found in the literature were listed. In total, 79 different CoQ root causes were selected from related previous studies (Alnuaimi et al. 2009; Balouchi et al. 2019; Burati et al. 1992; Josephson and Hammarlund 1999; Love and Edwards 2004; Ye et al. 2014). Then, a total of 2,527 NCRs were collected from 59 construction projects and sent to the panelists to receive their initial ideas about attributes leading to quality failures, and an iterative process (round circulation) was implemented for more reliable results and the reduction of any thought bias among participants (Fig. 2).

The Delphi method and its results were taken from Doğan (2021). A total of 11 construction experts with at least 5 years of experience in quality management and 10 in construction were invited to participate in the Delphi process (Table 1). All these experts had taken part or had experience in these projects. Three of them, who had over 20 years' experience, also ranked the cost impact of each case in a 1–5 Likert-scale form (1 = strongly low to 5 = strongly high).

At the end of the process, a final list emerged consisting of the 25 diverse attributes categorized into five different groups (Table 2). It should be emphasized here that the primary purpose of this process was not just to extract the final attribute list but also to assign a weight to each attribute observed in quality failures. This enabled the generation of a binary form (1 or 0) for each case, indicating whether or not a related subattribute exists in an NCR.

Hypothesis Development

As stated previously, prior studies using NCRs have mainly focused on the cost variations and historical data of the construction projects (e.g., OCV, time, and cost overruns) to examine the impact of quality issues on the CoQ. However, it is also necessary to quantitatively test the cost effects of attributes based on the actual site reports, including quality failures and reworks. Previous studies applying survey methods and carrying out case studies have found diverse critical variables influencing the CoQ in construction. For instance, Ye et al. (2014) concluded from their survey results that poor quality in construction materials is one of the main reasons for the reworks in China, and Larsen et al. (2015) found that omissions or errors in materials significantly affect the project cost. Therefore, we propose Hypothesis 1:

H1: Quality failures in materials recorded in the NCRs have statistically significant effects on the CoQ.

In addition to the attributes of the materials, failures in design factors were found to be another major causal factor of the CoQ in construction. According to Alnuaimi et al. (2009), modifications in designs are the main reason for change orders and thus cost overruns in construction projects. Hence, we propose Hypothesis 2:

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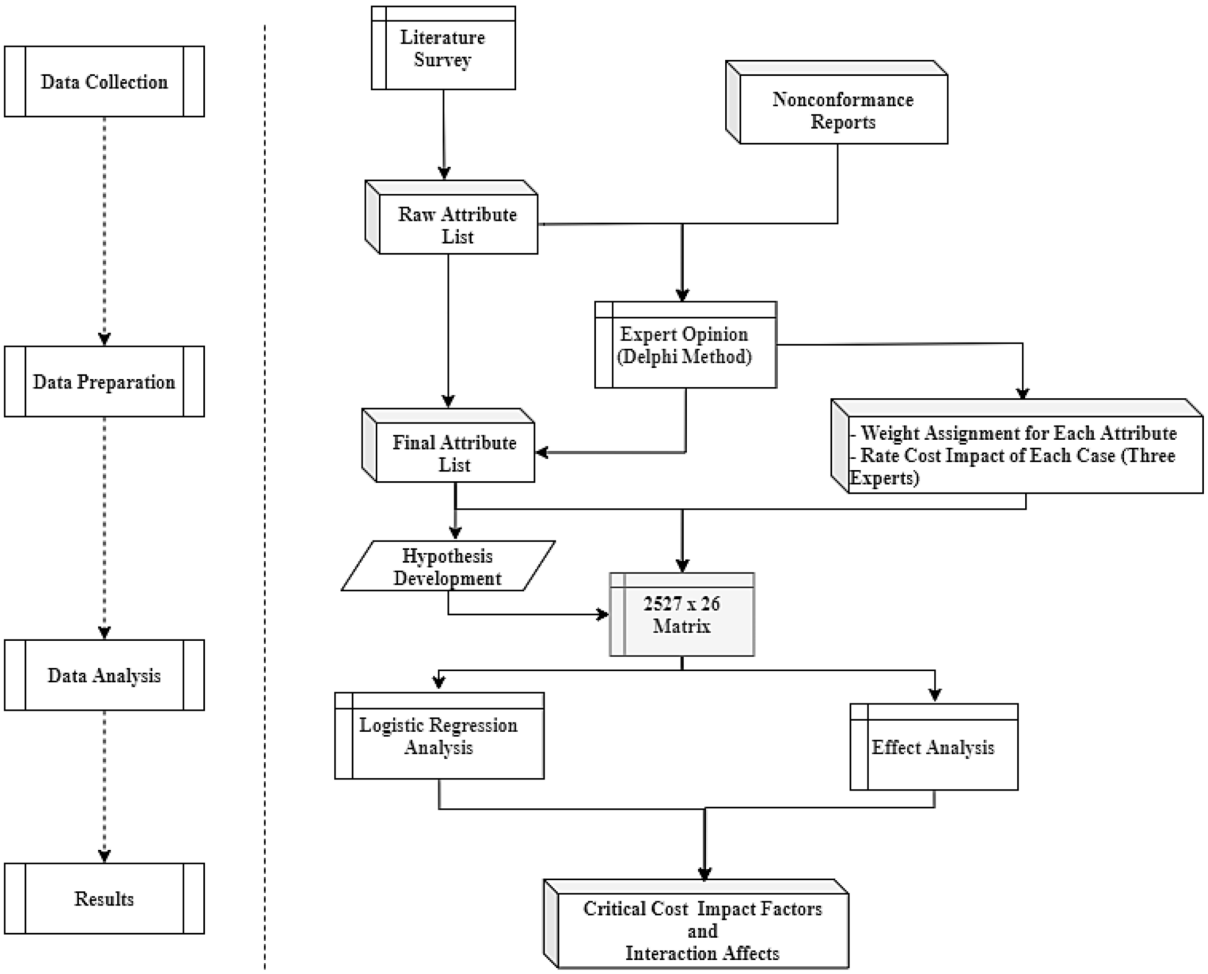

Fig. 1. Research methodology.

H2: Design changes and errors recorded in the NCRs have statistically significant effects on the CoQ.

Poor applications or installations have been identified as another primary reason for CoQ issues. The findings of a case study by Jafari and Love (2013) showed approximately 70% of nonconformances to be related to low-quality workmanship, incorrect installation, and poor equipment usage. Most of the defects observed in another case study (Josephson and Hammarlund 1999) came from poor installation. Thus, we propose Hypothesis 3:

H3: Poor applications or installations recorded in the NCRs have statistically significant effects on the CoQ.

Managerial aspects, such as operation and process issues, have also been found to be major factors of the CoQ in construction. Liu et al. (2018) highlighted that a high proportion of rework costs involve the contractor and design management. The survey results achieved by Love et al. (2010) demonstrated undefined or poor working procedures as one of the main reasons for rework costs. Yehiel (2013) found unclear tender documents to be the highest ranked reason for cost overruns in construction projects. Poor site management and controls were also a significant reason for the rework costs in the study by Balouchi et al. (2019). Therefore, we introduce failures in operation and working processes as a two-part fourth hypothesis:

H4a: Operational failures recorded in the NCRs have statistically significant effects on the CoQ.

H4b: Failures in the working process recorded in the NCRs have statistically significant effects on the CoQ.

Data Preparation and Analysis

After finalizing the attributes list, the NCRs were modeled to test the hypotheses. A total of 2,527 NCRs from the construction phases of 59 different projects were collected and categorized according to five general quality failures: reworks, defects, design modifications, warnings on managerial aspects, and nonconformances to regulations and installations. Most of the projects were located in Eastern Europe; 80% of the NCRs received were from high-rise buildings (residential and commercial), with the remainder coming from infrastructure project data collected for this study. The rest of the NCRs were collected from the construction projects carried out in Asian (Turkmenistan and Kazakhstan) countries.

Following Balouchi et al. (2019), each attribute in the NCRs was coded in binary data form. For any impact factor in the final attribute list and present in an NCR case, the related attribute was coded as 1 (observed); otherwise, 0 (unobserved) was assigned. A $2{,}527 \times 26$ matrix comprising the NCRs and the 25 final attributes plus the cost impact rate of each case was generated. Each case thus had 25 columns for each final attribute, but some cases had more than one attribute, according to the evaluation of each NCR. Also, each case had its unique cost impact mean value ranked by three experts ranging from 1 (extremely low) to 5 (extremely high), which is written at the end of each case as the 26th row in the data set. For example, three different attributes, Incorrect or Defective Material Usage (M2), Incompliance with Technical Specification (P3), and Inadequate Application Procedure (I6), were observed

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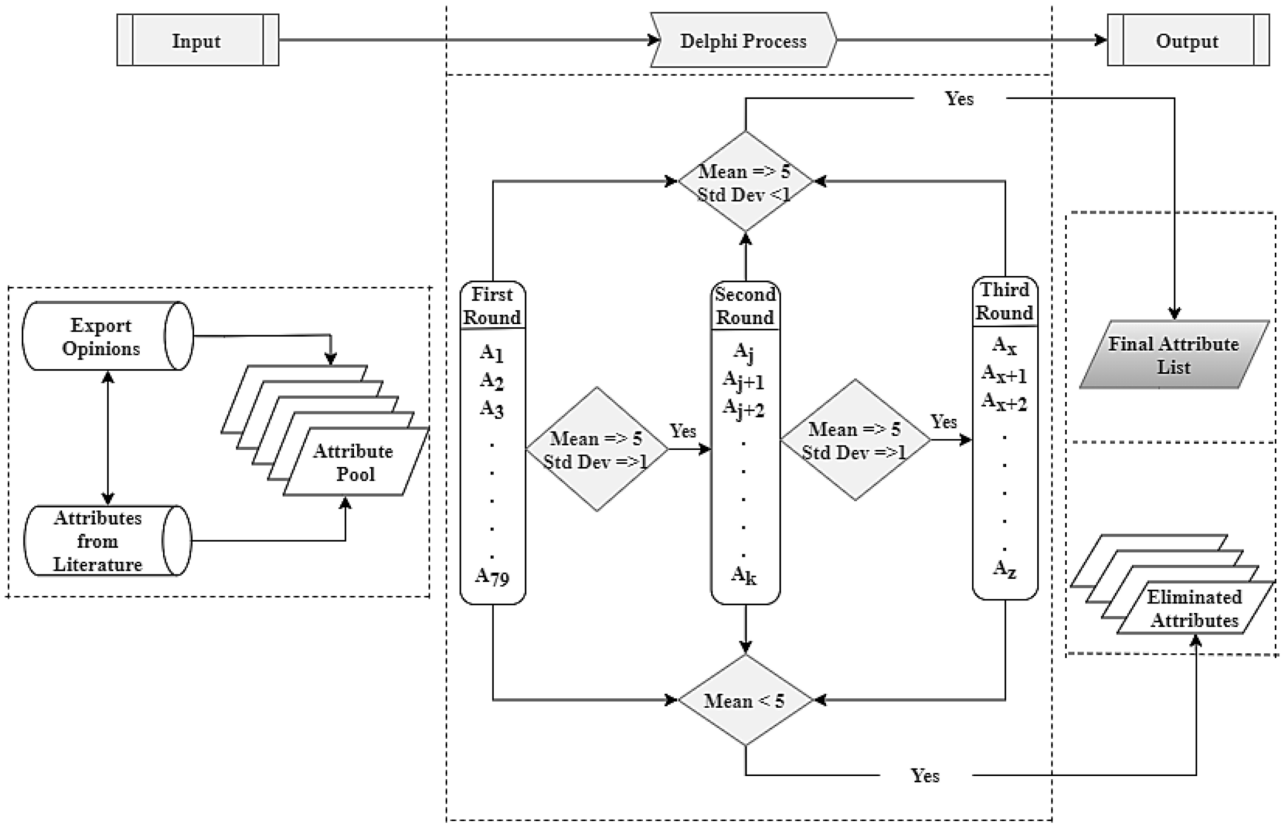

Fig. 2. Steps of the Delphi process.

Table 1. Participant information

Participant	Title	Position	Education	Experience (years)	Certification
1	Academic staff/civil engineer	Professor	Ph.D.	20–25	—
2	Mechanical engineer	Quality Control Manager	M.S.	20–25	Auditor certificate
3	Mechanical engineer	Quality Control Manager	B.S.	15–20	Auditor certificate
4	Mechanical engineer	Quality Control Manager	B.S.	15–20	Auditor certificate
5	Architect	Quality Control Manager	B.S.	10–15	Auditor certificate
6	Academic staff/architect	Associate Professor	Ph.D.	10–15	—
7	Civil engineer	Project Manager	B.S.	25–30	—
8	Architect	Project Manager	B.S.	20–25	—
9	Architect	Quality Control Supervisor	M.S.	15–20	Auditor certificate
10	Civil engineer	Quality Control Supervisor	Ph.D.	15–20	Auditor certificate
11	Architect	Site Engineer	B.S.	10–15	Auditor certificate

in NCR ID 56, and the cost impact mean of this case on the CoQ was ranked at 3.34, which was calculated by the mean of responses achieved from three experts. These experts took place in some of these projects but not all of them. They have deep experience on these kinds of projects and can rate cost impact of failures occurred in these similar project types. The projects where we collected the NCRs were carried out between 2016 and 2020. Therefore, the NCRs were collected from construction projects conducted in similar locations and in the narrow range of years.

In order to test the impact of each attribute on the construction cost, we performed a multinomial logistic regression analysis. Another type of regression analysis, stepwise multiple regression, was used in previous studies (Forcada et al. 2017; Love et al. 2010) when evaluating the rework causes and the relationships among the attributes in order to create a prediction model and ascertain the cost impacts of quality failures in the construction management field. However, because our independent variables (the 25 attributes in five groups) were coded in binary form and the dependent variable (cost impact rank of each case) was filled (by the mean value of the cost impact factors), we needed to use multinomial logistic regression (e.g., Petrucci 2009; Starkweather and Moske 2011).

A logistic regression analysis was used in this study to ascertain the attributes that significantly affected construction cost rather than to develop a prediction model or equation. The main assumption of the logistic regression analysis was only that the independent variables do not have any correlation with one another (Peng et al. 2010). We also examined the interaction effects of the five attribute groups and each subattribute on the construction cost when multiple attributes were observed in one case. Further to the cost-effectiveness analysis of each attribute, we also investigated the relationship between each attribute's frequency and cost importance. For this purpose, the FI of each attribute was calculated

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Table 2. Final attributes list

Group	Attributes	ID
Materials	Improper handling of materials and delivery	M1
	Incorrect or defective material usage	M2
	Procurement of incorrect materials	M3
	Damaging materials during transportation/loading[a]	M4
Design	Design problem/changes on construction	D1
Installation	Damaging the completed work	I1
	Work in confined space	I2
	Construction errors due to misunderstanding of design	I3
	Insufficient/improper workmanship[a]	I4
	Inadequate tools/equipment	I5
	Inadequate application procedure	I6
	Delays in construction timeline	I7
	Not following the work sequence	I8
Process	Inadequate preparation before starting the work[a]	P1
	Inadequate site cleaning after completing the work[a]	P2
	Incompliance with technical specification	P3
	Lack of documents onsite	P4
	Insufficient review of drawings[a]	P5
	Lack of drawings onsite	P6
	Insufficient number of site supervisor	P7
Operation	Problems with purchasing department	O1
	Problems with warehouse (labeling, and so on)	O2
	Sending wrong materials from warehouse	O3
	Lack of supervision[a]	O4
	Problems with documentation[a]	O5

[a]Related attribute achieved in the second or third round of the Delphi process.

Table 3. Multicollinearity analysis results

Group	Attribute	Attribute VIF	Group VIF
Materials	M1	1.384	1.031
	M2	1.171	
	M3	1.084	
	M4	1.096	
Design	D1	1.088	1.088
Installation	I1	1.528	1.119
	I2	1.005	
	I3	2.408	
	I4	1.310	
	I5	1.032	
	I6	1.546	
	I7	1.085	
	I8	1.122	
Process	P1	1.031	1.022
	P2	1.067	
	P3	1.097	
	P4	1.125	
	P5	1.282	
	P6	1.098	
	P7	1.045	
Operation	O1	1.050	1.054
	O2	1.108	
	O3	1.095	
	O4	1.239	
	O5	1.421	

according to Eq. (1), which has been commonly used in previous studies to rank the importance of independent or dependent variables (Bagaya and Song 2016)

$$\mathrm{FI} = \frac{\sum_{i=0}^{1} C_i N_i}{2 \times N} \tag{1}$$

where C_i = weighting constant value ($C_1 = 1$ for observed; $C_0 = 0$ for unobserved) in each case; N_i = frequency of each attribute; and N = total number of NCRs recorded.

Results

Before conducting a logistic regression analysis, it is necessary to test the reliability of the data set. For this purpose, the multicollinearity condition of the independent variables (each cost impact factor) was statistically checked. A multicollinearity test enables an assessment of the extent to which the independent variables are statistically correlated or unocorrelated with one another in regression models (Vatcheva et al. 2016). Each cost impact factor should be independent of the other cost impact factors to enable an evaluation of the effect of related attributes on the dependent variable (construction cost). In this regard, the variance inflation factor (VIF) of each attribute should be less than 3 for the related variable to be considered independent and usable in the regression analysis (Senaviratna and Cooray 2019).

According to the multicollinearity test results here, the VIF values of all the attributes were less than 3, thus enabling their employment in the regression analysis. The VIF value of all the five attributes group was close to 1 (Materials = 1.031; Design = 1.088; Installation = 1.119; Operation = 1.022; and Process = 1.054), which shows that the cost impact groups were highly independent of one another (Table 3).

After validating the data set, we conducted the multinomial logistic regression analysis to test the five main hypotheses. According to the results (Table 4), Materials had a significant impact on the construction cost ($\chi^2 = 29.286$ and $p < 0.001$), which allowed us to accept Hypothesis 1. Although three cost impact factors related to materials—namely Improper Handling of Materials and Delivery (M1) ($\chi^2 = 9.567$ and $p = 0.048$), Incorrect or Defective Material Usage (M2) ($\chi^2 = 9.554$ and $p = 0.049$), and Damaging Materials During Transportation/Loading (M4) ($\chi^2 = 12.724$ and $p = 0.013$)—were found to play significant role in construction cost, one—Procurement of Incorrect Materials (M3) ($\chi^2 = 5.670$ and $p = 0.225$)—was found not to be a significant factor.

Design-related quality failures were seen to be another critical factor influencing CoQ in construction ($\chi^2 = 25.180$ and $p < 0.001$), which allowed us to accept Hypothesis 2. On the other hand, the attribute group Installation did not significantly affect the quality failure costs ($\chi^2 = 4.660$ and $p = 0.324$), so Hypothesis 3 was rejected. However, two impact factors under the Installation group—namely Damaging the Completed Work (I1) ($\chi^2 = 21.263$ and $p < 0.001$) and Delays in Construction Timeline (I7) ($\chi^2 = 10.238$ and $p = 0.037$)—did make significant contributions to cost growth.

The attribute group Operation did not significantly impact the quality failures based on the cost in construction ($\chi^2 = 8.970$ and $p = 0.062$), so we rejected Hypothesis 4a. Under the Operation group, however, it was found that Problems with Documentation (O5) significantly changed the CoQ in construction projects ($\chi^2 = 18.472$ and $p < 0.001$). The Process attribute group was also not found to be a significant factor for the CoQ in construction ($\chi^2 = 3.973$ and $p = 0.410$), so we rejected Hypothesis 4b. Only one attribute assigned to the Process groups—Insufficient Number

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Table 4. Hypothesis test results

Group	Attribute	Chi-square, χ^2 (attribute)	Effect significance (attribute)	Chi-square, χ^2 (group)	Effect significance (group)	Hypothesis
Materials	M1	9.567	0.048[a]	29.286	0.000[a]	Accepted
	M2	9.554	0.049[a]			
	M3	5.670	0.225			
	M4	12.724	0.013[a]			
Design	D1	25.180	0.000[a]	25.180	0.000[a]	Accepted
Installation	I1	21.263	0.000[a]	4.660	0.324	Rejected
	I2	—	—			
	I3	4.747	0.314			
	I4	13.913	0.084			
	I5	3.803	0.433			
	I6	8.107	0.088			
	I7	10.238	0.037[a]			
	I8	6.425	0.170			
Process	P1	2.570	0.632	3.973	0.410	Rejected
	P2	1.897	0.755			
	P3	1.610	0.807			
	P4	2.667	0.615			
	P5	4.985	0.289			
	P6	0.099	0.999			
	P7	15.755	0.003[a]			
Operation	O1	3.403	0.493	8.970	0.062[a]	Rejected
	O2	7.269	0.122			
	O3	—	—			
	O4	2.930	0.570			
	O5	18.472	0.001[a]			

[a]The related attribute and group has significant effect on the CoQ.

of Site Supervisors (P7) ($\chi^2 = 15.755$ and $p = 0.003$)—was shown to be an underlying factor for construction cost performance. The significance value of two attributes—Work in Confined Space (O3) and Sending Wrong Materials from Warehouse (I2)—could not be calculated due to their rare occurrence in the NCRs (Table 4).

As well as testing the significance of attributes on the cost performance, we explored the interaction effects of the main groups on the CoQ in two dimensions (as Attribute X versus Attribute Y). This revealed that some group attributes observed together in quality failure-based cases could have a significant impact on the cost overruns; these were Materials versus Installation, $p = 0.018$; Materials versus Operation, $p = 0.006$; Materials versus Process, $p = 0.036$; Design versus Installation, $p = 0.021$; and Design versus Operation, $p < 0.001$ (Table 5).

In addition to main group effects, the interaction effects of each critical cost impact factor were similarly evaluated. Here, the interaction effect term means the impact of any two attributes on the CoQ when they are observed together in a case. The results revealed seven attributes that had a crucial impact on the CoQ when occurring together with another critical cost impact factor. These were Procurement of Incorrect Materials (M3), Inadequate Tools/Equipment, I6 Inadequate Application Procedure (I5), Delays in Construction Timeline (I7), Lack of Documents Onsite (P4), Insufficient number of Site Supervisors (P7), and Problems with Documentation (O5). Conversely, five attributes did not have a significant impact on construction cost when interacting with any other attribute in any case, namely, Insufficient Review of Drawings (P5), Lack of Drawings Onsite (P6), Problems with Purchasing Department (O1), Problems with Warehouse (Labeling, and so on) (O2), and Sending Wrong Materials from Warehouse (O3). Some interaction effect values could not be computed because the attributes were not adequately observed together in any one case (Table 6).

Table 5. Test results of group interaction effects

Group attributes	Design (significance)	Installation (significance)	Operation (significance)	Process (significance)
Materials	0.159	0.018[a]	0.006[a]	0.036[a]
Design	—	—	—	0.095
Installation	—	0.021[a]	0.000[a]	0.257
Operation	—	—	0.102	0.795

[a]The related two groups have interaction effect on the CoQ.

According to the FI results (Table 7), the attributes Construction Errors Due to Misunderstanding of Design (I3) (FI = 0.339) and Insufficient/Improper Workmanship (I4) (FI = 0.238) had the highest FI and were ranked the highest of the critical cost impact factors. Conversely, Sending Wrong Materials from Warehouse (O3) (FI < 0.001) and Work in Confined Space (I2) (FI = 0.001) had the lowest FI and rank, meaning that those attributes were rarely observed in the NCRs.

Discussion

Various studies have focused on identifying the root causes of quality failure cost in construction. Here, we explored the causal factors of the quality failures and the interaction effects of different attributes on the CoQ, and we assessed the relationship between the frequency and cost impact significance of each attribute. We also addressed a gap in the literature by evaluating these aspects according to both expert opinion and NCRs. For this purpose, we initially defined our attributes based on the expert opinions by implementing the Delphi method and developed five main hypotheses.

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Table 6. Interaction effect of any two attributes

Attributes	M1	M2	M3	M4	D1	I1	I2	I3	I4	I5	I6	I7	I8	P1	P2	P3	P4	P5	P6	P7	O1	O2	O3	O4
M2	0.088	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
M3	0.426	0.449	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
M4	0.089	0.125	0.142	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
D1	0.000[a]	—	0.000[a]	0.003[a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I1	0.40	0.004[a]	0.003[a]	0.000[a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I2	0.189	—	—	—	—	0.008[a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I3	0.431	0.124	0.053[a]	0.813	0.988	—	0.456	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I4	—	0.269	0.052[a]	0.004	—	—	0.075	0.076	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I5	0.997	0.890	0.292	0.237	0.238	0.000[a]	0.700	0.005[a]	0.398	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I6	0.000[a]	0.000[a]	0.000[a]	—	—	—	0.000[a]	0.003[a]	0.000[a]	0.000[a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I7	0.079	0.236	0.017[a]	0.015[a]	0.017[a]	—	0.023[a]	0.074	0.090	0.017[a]	0.020[a]	—	—	—	—	—	—	—	—	—	—	—	—	—
I8	0.682	0.864	0.699	0.604	0.679	—	0.894	0.373	0.946	0.852	—	0.055[a]	—	—	—	—	—	—	—	—	—	—	—	—
P1	0.906	0.334	0.426	0.467	0.608	0.274	0.443	0.707	0.774	0.407	0.286	0.453	0.842	—	—	—	—	—	—	—	—	—	—	—
P2	0.999	0.343	0.770	0.778	0.828	0.748	0.774	0.923	0.767	0.801	0.904	0.903	0.838	0.965	—	—	—	—	—	—	—	—	—	—
P3	0.715	0.727	0.940	0.562	0.000[a]	0.622	0.617	0.709	0.000[a]	0.728	0.787	0.902	0.491	0.128	0.199	—	—	—	—	—	—	—	—	—
P4	0.463	0.038[a]	0.179	0.056[a]	0.139	0.333	0.053[a]	0.102	0.264	0.051[a]	0.133	0.066	0.230	0.052[a]	0.050[a]	0.236	—	—	—	—	—	—	—	—
P5	0.415	0.965	0.518	0.520	—	0.559	0.596	0.298	—	0.688	0.040	0.539	0.740	0.889	0.386	0.035	0.512	—	—	—	—	—	—	—
P6	0.986	0.977	0.980	0.972	0.982	0.975	0.975	0.870	0.994	0.976	0.277	0.236	0.972	0.977	0.973	0.975	0.989	0.704	—	—	—	—	—	—
P7	0.303	0.014[a]	0.018[a]	0.016[a]	0.033[a]	0.014[a]	0.018[a]	0.071	0.124	0.032[a]	0.052[a]	0.100	0.017[a]	0.019[a]	0.022[a]	0.011[a]	0.007[a]	0.108	0.144	—	—	—	—	—
O1	0.875	0.930	0.815	0.872	0.866	0.915	0.911	0.956	0.975	0.839	0.841	0.916	0.995	0.907	0.911	0.856	0.900	0.902	0.994	0.309	—	—	—	—
O2	0.242	0.167	0.128	0.127	0.105	0.208	0.142	0.519	0.303	0.366	0.240	0.140	0.141	0.145	0.144	0.124	0.151	0.128	0.143	0.136	—	—	—	—
O3	0.205	0.894	0.534	0.607	0.431	0.380	—	0.909	—	0.388	—	—	—	—	0.970	—	—	—	0.992	—	—	0.289	—	—
O4	0.061	0.330	0.254	0.093	—	—	0.099	0.004[a]	0.034[a]	0.005[a]	0.019[a]	0.943	0.880	0.271	0.288	0.251	0.042[a]	0.007[a]	0.467	0.81	0.413	0.216	0.257	—
O5	0.000[a]	0.001[a]	0.002[a]	0.000[a]	—	0.232	0.004[a]	0.000[a]	0.004[a]	0.000[a]	0.002[a]	0.000[a]	0.013[a]	0.000	0.005[a]	0.002[a]	0.008[a]	0.001[a]	0.002[a]	0.000[a]	0.152	0.000[a]	0.000[a]	0.006[a]

[a]The related two attributes have interaction effects on the CoQ.

Table 7. Frequency index (FI) of each attribute

Group	Attribute	Frequency index	Rank
Materials	M1	0.030	9
	M2	0.106	5
	M3	0.009	15
	M4	0.008	17
Design	D1	0.007	18
Installation	I1	0.059	8
	I2	0.001	24
	I3	0.339	1
	I4	0.238	2
	I5	0.008	16
	I6	0.203	4
	I7	0.004	20
	I8	0.020	11
Process	P1	0.015	12
	P2	0.010	14
	P3	0.081	7
	P4	0.012	13
	P5	0.087	6
	P6	0.005	19
	P7	0.002	23
Operation	O1	0.003	21
	O2	0.002	22
	O3	<0.001	25
	O4	0.235	3
	O5	0.027	10

According to the logistic regression analysis, Hypothesis 1 was accepted, showing that quality failures in materials significantly impacted project cost increases. Similar results regarding quality failures due to materials were also found in a previous study (Larsen et al. 2015). Because the main contributing factors under the Materials group were Improper Handling of Materials and Delivery (M1), Incorrect or Defective Material Usage (M2), and Damaging Materials during Transportation/Loading (M4), we concluded that quality level in the application process of the materials was more important than the procurement process of the materials [Procurement of Incorrect Materials (M3)]. Although incorrect materials procurement can be compensated for by following the correct timing strategy, quality failures in materials application routinely cause rework or defects, which increases the CoQ in construction (Josephson and Hammarlund 1999).

The second hypothesis, suggesting that design issues make significant contributions to the CoQ, was also statistically accepted in this study. Specifically, design modifications requested by clients, named change orders in the literature, are the main reason for cost overruns in construction projects (Alnuaimi et al. 2009; Senouci et al. 2016). In the case of change orders, it can become difficult to manage the time, cost, and quality of the construction because such changes are generally decided or ordered during the construction phases of the projects.

Hypothesis 3, that poor applications or installations recorded in the NCRs have statistically significant effects on the construction cost, was rejected in the current study. This was unexpected because several studies (Hwang et al. 2009; Love and Edwards 2004, 2007) have indicated that quality failures in implementations considerably increase construction cost and are the primary reason for reworks. It is well-known that poor quality in construction applications can cause considerable cost and time variations because of the need to redo the same work. However, only two attributes—Damaging the Completed Work (I1) and Delays in Construction Timeline (I7)—were found to play a significant role in the CoQ here. Damaging completed work inevitably requires new application processes, time, and budgets and is widely observed in construction sites (Hwang et al. 2009). The other six attributes (I2–I6 and I8) weaken the importance of the Installation group of attributes in terms of influencing the CoQ. The cost impact of the Work in Confined Space (I2) attribute was not calculated because this was only observed three times in total.

Developed under the managerial aspect, Hypothesis 4a, regarding operational failures, was rejected. However, Problems with Documentation (O5), under the Operation attribute, was found to be a significant factor of increased construction costs. Quality issues in the documentation have also been identified as a critical cost impact factor elsewhere (Yehiel 2013). Some documents explain how and where construction tasks should be applied and provide detailed instructions to be followed as required steps. A lack of detailed information may lead to incorrect applications; sometimes, tasks are implemented at the wrong locations. Thus, documentation issues can create rework in construction sites, which is the primary reason for the cost overruns.

Hypothesis 4b, also developed under the managerial aspect but concerning working process failures, was similarly rejected. Unlike previous studies (Balouchi et al. 2019; Love et al. 2017; Ye et al. 2014; Yehiel 2013), we found that quality failures in the construction process do not significantly impact the CoQ. Only Insufficient Number of Site Supervisors (P7) was found to have a significant impact on construction overruns. A lack of supervisors and inadequate control procedures in construction sites were highlighted by Love et al. (2017) as one of the main reasons for the reworks and, therefore, for high CoQ. From this, one can conclude that site control and direction processes are important to prevent quality failures in construction workplaces.

Diverse cost impact factors have been found in previous studies and in the current study. The critical cost impact factors identified here were located from combining a literature review with expert opinions on the NCRs. Accordingly, we attempted to combine different cost impact factors and provide a wide range of attributes. Although the findings for two of the group factors applied here (Design and Materials) were similar to previous studies with respect to the cost impacts of quality failures, the other three (Process, Installation, and Operation) have been newly classified in this study. Moreover, exploring the interaction effect of two simultaneous subgroup attributes on the CoQ offers a new approach for construction practitioners during planning and construction phases.

Along with identifying the critical cost impact factors, we assessed the interaction effect of the attributes in two dimensions. It is well known that quality failures in construction do not come alone. One causal factor tends to lead to another, referred to as a domino effect (Wang et al. 2021; Yang et al. 2018). Therefore, a holistic approach should be adopted to understand the cost of impact factors rather than focusing on individual reasons. According to the results of interaction effects investigated in this study, although the Installation main attribute alone did not significantly impact the CoQ, it did significantly increase quality costs when combined with the Materials factor. Also, the interaction effect of failures related to Installation and Design was significant. Thus, we concluded that quality failures in Installation triggered by quality-related Materials or Design issues could return critical cost factors.

It has previously been noted that the majority of installation failures are related to materials and design misunderstandings (Josephson and Hammarlund 1999; Larsen et al. 2015). Quality failures in the Process and Operation attributes alone were found not to have a significant cost impact here; in combination with

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Materials, however, they were significant. Similar conditions were also observed for different critical cost impact factors assigned under the main attributes. Clearly, it can be concluded that impact factors should also be evaluated together. The domino effects of causal parameters should be considered for a detailed understanding of the main reasons for quality failures.

We also examined the correlation between each attribute's frequency and cost importance. This was the main reason for using FI in the present study. High frequency in some quality failures (I3 and I4) did not mean that related attributes significantly impacted the CoQ. On the other hand, some attributes (M1, M2, P7, and O5) that did not have high FI could significantly affect the CoQ. We concluded that there was no significant overall correlation between the cost significance and frequency of the causal attributes. Hence, these aspects are different and should be quantified separately.

Regarding the limitations of this study, it should be noted that more NCRs could be included and analyzed to include further causal factors and diverse perspectives. Also, this study can be extended by developing a predictive model that provides a proactive system for quality failures. Further, different critical cost impact factors could be derived according to the literature review. Because the NCRs were mainly collected in building and infrastructure projects carried out in Eurasian countries, the results may not be generalizable for all construction industries and types of projects worldwide. Therefore, similar studies can be carried out in different regions and on special projects (e.g., industrial) and the results compared. This should reveal whether quality failures and their cost impacts are similar for each and all project types or not. Also, the Analytical Hierarchy Process (AHP) can be used to finalize the attribute list based on the expert opinions rather than Delphi Process. These limitations can be addressed in the future.

Quality failures are commonly observed in construction sites because of the dynamic process of construction activities. Such failures inevitably influence the cost performance of construction projects, their CoQ. Although many studies have identified causal factors and evaluated the impact level of the quality failures on construction cost, adopting a range of approaches for this, such as survey and quantitative methods, we have investigated the causal factors of the quality failures and the interaction effect of these attributes. Using results from another ongoing research program, we conducted the Delphi process for expert opinions and used this to define critical cost impact factors causing quality failures during the different construction phases. The employment of expert opinion, as well as the factors of cost, time overruns, and the historical data of construction projects when evaluating NCRs, is a major contribution of this study to the literature. Only examining NCRs or employing expert opinion may not be enough to appreciate the full picture of causal factors in quality failures. These approaches should be merged and evaluated together to provide a more comprehensive view of the CoQ in construction.

The findings presented here can be used by construction practitioners (e.g., site and planning engineers, control teams) during the planning and ongoing construction stages, suggesting the direct practical contribution of this study. Particularly, site and control engineers should consider these critical impact factors and how such quality failures influence each other during construction projects. Accordingly, it will be possible to better manage quality failure risks and considerably reduce their adverse impacts on the CoQ.

In most cases, NCRs are created as soon as the problem occurs and followed up diligently. The top priority is to solve the issue and get rid of the problem during ongoing construction processes. As NCRs accumulate, quality management staff work with the site staff to identify the root cause of the problem and make sure not to face a similar problem. Many organizations do not have capabilities or data collection system to include cost impact of the NCRs when they occur. The data collected in this study did not have cost impact value included in the recorded NCR data. Therefore, the authors worked with three construction experts to assign the cost impact and eventually create a system that embeds cost attribute into NCRs as the data collected. We believe that the methodology followed here could help many organizations that have missing quality failures–based cost links in their quality management system.

This study developed five main hypotheses and tested them by performing multinomial logistic regression analysis. Two attributes (Materials and Design) were found to have a significant impact on the CoQ when observed alone in failure cases, whereas the three others (Process, Operation, and Installation) did not, but the latter did affect cost performance when observed together with another main attribute. A similar pattern was also recorded for different subattributes assigned under the main attributes. Therefore, critical cost impact factors resulting from quality failures should be considered with other factors rather than treated just as individual parameters.

Because most quality issues have more than one reason, the combination of these may result in domino effects. The attributes and subattributes considered in this study were variously interrelated, leading to such effects. These can be eliminated. An appreciation of the domino effect of one attribute on another in terms of cost overrun should be considered in detail because this can help the development of good practice for all potential cost impact factors.

The relationship between each attribute's frequency and cost impact degree was also investigated but found not to be significant. Thus, this study has shown that a high number of observations alone of any attribute does not necessarily translate to a significant cost impact. This represents another contribution of the work here to the literature and also needs to be considered when assessing the effects of quality failure.

In this context also, it should be emphasized that although process factors might not influence the CoQ in the short term, the adverse effects of failures are likely to emerge in the ongoing process. This will inevitably be seen after completion and during the operation of the construction assets. Therefore, we can conclude that making failure inspections only during the construction process is likely to be insufficient to prevent the adverse cost influences of quality failures in the long term. Investments in quality controls should be made for the construction process itself and during all stages of a project, from planning to operation, and improving the construction process management to preventing the adverse cost effects of quality failures in the long term.

Because the root causes and results of each quality failure were provided in the collected NCRs with all details, any construction expert who has deep experience in similar kinds of project types can evaluate and predict the cost impact of the quality failures reliably. Besides, the data were collected from the construction projects conducted in similar regions and in a narrow range of years. We believe that these properties of the collected NCRs make it more reliable to generate and discuss the results.

Contribution to Body of Knowledge

This research is important for those who are responsible for construction quality management. It contributes to the body of knowledge in three main ways:

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- The theoretical contribution of this study is to provide an understanding of critical cost impact factors that emerged due to quality failures by combining NCRs and expert opinion in different ways (the interaction effects of paired attributes observed in each case and the relationship between frequency and the importance of each attribute); the Delphi method and rating cost impact of each NCR on the construction cost were utilized together.
- As a practical contribution, the results can lead construction practitioners to better manage critical cost impact factors and quality failures, reducing cost overruns in construction projects.
- This research also provides a basis for further research by (1) using the data by applying Machine Learning algorithms, (2) changing the evaluation model to evaluate the interaction effects of contributing factors on the cost of quality, (3) changing the number or categorization of labels to be tested, and (4) opening a new door to predicting the CoQ due to quality failures.

Conclusion

Identifying the critical impact factors based on quality failures may help construction professionals develop a more comprehensive approach to potential failure risks due to issues with materials, design, installation, and management, making it possible to put timely, proactive steps into action when a failure occurs. Reducing quality problems with cost overruns and time delays stimulates productivity and increases the efficiency of the construction management process. The findings of this study can thus be beneficial for the construction industry by indicating approaches to the development of new quality control systems. Such systems should be used regularly to reduce cost overruns and unscheduled delays in construction projects.

This study has indicated the utility of a quality control system that considers all site issues together for all project phases of construction projects and includes expert opinion to reduce quality failures that would otherwise result in cost and time overruns. Identifying the critical cost impact factors or cost impact degree of attributes alone and considering them separately and in the short-term does not maximize the potential for CoQ reduction. Instead, a holistic approach to reducing quality failures should be integrated into construction project management and control systems. We have to emphasize that data collection is essential in construction management one more time. When valid data are collected and analyzed, most problems can be predicted and avoided. As we enter the age of data management, if contractors invest in data collection systems and, much more importantly, AI-based project management systems, it is possible to minimize unnecessary cost increases and manage more effectively in the future.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Abdelsalam, H. M. E., and M. M. Gad. 2009. "Cost of quality in Dubai: An analytical case study of residential construction projects." *Int. J. Project Manage.* 27 (5): 501–511. https://doi.org/10.1016/j.ijproman.2008.07.006.

Al-Hazim, N., Z. A. Salem, and H. Ahmad. 2017. "Delay and cost overrun in infrastructure projects in Jordan." *Procedia Eng.* 2017 (Mar): 18–24. https://doi.org/10.1016/j.proeng.2017.03.105.

Alnuaimi, A. S., R. A. Taha, M. Al Mohsin, and A. S. Al-Harthi. 2009. "Causes, effects, benefits, and remedies of change orders on public construction projects in Oman." *J. Constr. Eng. Manage.* 136 (5): 615–622. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000154.

Ayhan, B. U., and O. B. Tokdemir. 2018. "Predicting the outcome of construction incidents." *Saf. Sci.* 113 (Nov): 91–104. https://doi.org/10.1016/j.ssci.2018.11.001.

Bagaya, O., and J. Song. 2016. "Empirical study of factors influencing schedule delays of public construction projects in Burkina Faso." *J. Manage. Eng.* 32 (5): 05016014. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000443.

Balouchi, M., M. Gholhaki, and A. Niousha. 2019. "Reworks causes and related costs in construction: Case of Parand mass housing project in Iran." *Int. J. Quality Reliab. Manage.* 36 (8): 1392–1408. https://doi.org/10.1108/IJQRM-06-2018-0155.

Barber, P., A. Graves, M. Hall, D. Sheath, and C. Tomkins. 2000. "Quality failure costs in civil engineering projects." *Int. J. Quality Reliab. Manage.* 17 (4): 479–492. https://doi.org/10.1108/02656710010298544.

Burati, J. L., J. J. Farrington, and W. B. Ledbetter. 1992. "Causes of quality deviations in design and construction." *J. Constr. Eng. Manage.* 118 (1): 34–49. https://doi.org/10.1061/(ASCE)0733-9364(1992)118:1(34).

Doğan, N. B. 2021. *Predicting the cost impacts of construction nonconformities using CBR-AHP and CBR-GA models*. Ankara, Turkey: Middle East Technical Univ.

Doloi, H. 2012. "Cost overruns and failure in project management: Understanding the roles of key stakeholders in construction projects." *J. Constr. Eng. Manage.* 139 (3): 267–279. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000621.

Feigenbaum, A. V. 1983. *Total quality control*, 3rd ed. New York: McGraw-Hill.

Feld, J., and K. Carper. 1997. *Construction failure*. Vol. 78 of *Wiley Series of Practical Construction Guides*. New York: John Wiley & Sons.

Forcada, N., M. Gangolells, M. Casals, and M. Macarulla. 2017. "Factors affecting rework costs in construction." *J. Constr. Eng. Manage.* 143 (8): 04017032. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001324.

Heravi, G., and A. Jafari. 2014. "Cost of quality evaluation in mass-housing projects in developing countries." *J. Constr. Eng. Manage.* 140 (5): 04014004. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000837.

Hwang, B.-G., S. R. Thomas, C. T. Haas, and C. H. Caldas. 2009. "Measuring the impact of rework on construction cost performance." *J. Constr. Eng. Manage.* 135 (3): 187–198. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:3(187).

Jafari, A., and P. E. D. Love. 2013. "Quality costs in construction: Case of Qom monorail project in Iran." *J. Constr. Eng. Manage.* 139 (9): 1244–1249. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000704.

Josephson, P. E., and Y. Hammarlund. 1999. "Causes and costs of defects in construction: A study of seven building projects." *Autom. Constr.* 8 (6): 681–687. https://doi.org/10.1016/S0926-5805(98)00114-9.

Larsen, J. K., G. Q. Shen, S. M. Lindhard, and T. D. Brunoe. 2015. "Factors affecting schedule delay, cost overrun, and quality level in public construction projects." *J. Manage. Eng.* 32 (1): 04015032. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000391.

Liu, Q., G. Ye, Y. Feng, C. Wang, and Y. Peng. 2018. "Case-based insights into rework costs of residential building projects in China." *Int. J. Constr. Manage.* 20 (4): 347–355. https://doi.org/10.1080/15623599.2018.1484856.

Love, P., and D. J. Edwards. 2007. "Forensic project management: The underlying causes of rework in construction projects." *Civ. Eng. Environ. Syst.* 21 (3): 207–228. https://doi.org/10.1080/10286600412331295955.

Love, P. E. D., and D. J. Edwards. 2004. *Determinants of rework in building construction projects*. Bingley, UK: Emerald Group Publishing.

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Love, P. E. D., D. J. Edwards, H. Watson, and P. Davis. 2010. "Rework in civil infrastructure projects: Determination of cost predictors." *J. Constr. Eng. Manage.* 136 (3): 275–282. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000136.

Love, P. E. D., and Z. Irani. 2002. "A project management quality cost information system for the construction industry." *Inf. Manage.* 40 (7): 649–661. https://doi.org/10.1016/S0378-7206(02)00094-0.

Love, P. E. D., P. Teo, and J. Morrison. 2017. "Revisiting quality failure costs in construction." *J. Constr. Eng. Manage.* 144 (2): 05017020. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001427.

Peng, C. Y. J., K. L. Lee, and G. M. Ingersoll. 2010. "An introduction to logistic regression analysis and reporting." *J. Educ. Res.* 96 (1): 3–14. https://doi.org/10.1080/00220670209598786.

Petrucci, C. J. 2009. "A primer for social worker researchers on how to conduct a multinomial logistic regression." *J. Soc. Service Res.* 35 (2): 193–205. https://doi.org/10.1080/01488370802678983.

Senaviratna, N. A. M. R., and T. M. J. A. Cooray. 2019. "Diagnosing multicollinearity of logistic regression model." *Asian J. Probab. Stat.* 5 (2): 1–9.

Senouci, A., A. Alsarraj, M. Gunduz, and N. Eldin. 2016. "Analysis of change orders in Qatari construction projects." *Int. J. Constr. Manage.* 17 (4): 280–292. https://doi.org/10.1080/15623599.2016.1211973.

Starkweather, J., and A. K. Moske. 2011. "Multinomial logistic regression." Accessed August 1, 2011. https://it.unt.edu/sites/default/files/mlr_jds_aug2011.pdf.

Vatcheva, P., M. Lee, J. B. McCormick, and M. H. Rahbar. 2016. "Multicollinearity in regression analyses conducted in epidemiologic studies." *Epidemiol. Open Access (Sunnyvale)* 6 (2): 16.

Wang, L., R. Huang, W. Shi, and C. Zhang. 2021. "Domino effect in marine accidents: Evidence from temporal association rules." *Transp. Policy* 103 (5): 236–244. https://doi.org/10.1016/j.tranpol.2021.02.006.

Yang, Y., G. Chen, and P. Chen. 2018. "The probability prediction method of domino effect triggered by lightning in chemical tank farm." *Process Saf. Environ. Prot.* 116 (Feb): 106–114. https://doi.org/10.1016/j.psep.2018.01.019.

Yap, J. B. H., P. L. Low, and C. Wang. 2017. "Rework in Malaysian building construction: Impacts, causes and potential solutions." *J. Eng. Des. Technol.* 15 (5): 591–618. https://doi.org/10.1108/JEDT-01-2017-0002.

Ye, G., Z. Jin, B. Xia, and M. Skitmore. 2014. "Analyzing causes for reworks in construction projects in China." *J. Manage. Eng.* 31 (6): 04014097. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000347.

Yehiel, R. 2013. "Root-cause analysis of construction-cost overruns." *J. Constr. Eng. Manage.* 140 (Jan): 04013039. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000789.

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