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Nonconformity Assessment in Building Construction Projects: A Fuzzy Group Decision-Making Approach

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Abstract

Construction nonconformity assessment of buildings is critical to ensure the anticipated quality and living safety for their future occupants. Previous studies have paid less attention to identifying and analyzing building construction nonconformities (BCNs) in the design and construction (D&C) phases considering expert judgments, which are critiqued for human bias, uncertainty, and imprecision. In BCN assessment, previous studies also did not consider the specific time frame to detect construction nonconformities. This study aims to prioritize nonconformities in the D&C phases, addressing the limitations of expert judgment by applying the Fuzzy Group Decision-Making Approach (FGDMA). The FGDMA computes the defuzzified scores of the nonconformities to prioritize and identify critical nonconformities. The defuzzified scores are explained further by associating them with the corresponding fuzzy numbers to address the limitations involved in expert judgments. The study also identifies the detection time of BCNs and analyzes 15 different Bangladeshi project scenarios to understand their context better. The critical nonconformities identified include premature stressing on concrete, inaccurate water-cement ratios, insufficient concrete compaction, lack of full-time site supervision, and the absence of stirrups in beam-column joints. Critical nonconformities are mostly identified during construction, and residential, commercial, and multipurpose buildings, regardless of ownership (i.e., public or private) and size, have experienced poor-quality construction. This study will assist major stakeholders (owner, contractor, consultant, and regulatory authorities) to fully understand the critical nonconformities in different building projects from their preconstruction to construction phases for better quality assurance in providing a safe living and working environment for their future occupants.

Keywords: Building construction, Concrete, Construction quality, Fuzzy logic, Nonconformity

Practical Applications

The study identifies critical nonconformities and their frequency, severity, and detection times in different construction projects, including residential, commercial, and multipurpose buildings and mosques. It also studies 15 different project scenarios for analyzing the nonconformities of government and privately funded/owned buildings. The most common nonconformities are premature stressing on concrete (loading to concrete members before gaining their design strength), inaccurate water-cement ratios, insufficient concrete compaction, and the absence of stirrups in beam-column joints. These nonconformities all occur due to lack of full-time site supervision and poor workmanship during construction. The dominating detection time for identifying the critical nonconformities is “during construction”. Thus, it is possible to control many by careful supervision and improved workmanship during construction. The project scenario analysis shows that residential, commercial, and multipurpose buildings, regardless of ownership (i.e., public or private), experience poor-quality construction. These findings will assist stakeholders with different engagement levels in managing their roles in building projects to deliver a better quality of construction, and hence a sustainable and safe living and working environment.

Introduction

Construction nonconformity is a worldwide phenomenon, the severity of which can range from simple nonstructural defects to the unprecedented collapse of a massive building (Gurmu et al. 2021; Islam et al. 2021b; Sommerville and McCosh 2007). It broadly refers to a defective building product, work, or service, or simply a deviation from the stipulated quality of a work/product (Islam et al. 2021b; Sommerville and McCosh 2007). Previous studies have attempted to identify the BCNs associated with finishing works such as plumbing, electrical fittings, nonstructural materials installed in roofs or facades (Ahzahar et al. 2011; Forcada et al. 2016); handover (Jonsson and Gunnelin 2019); and post-handover and service period defects (Forcada et al. 2014; Gurmu et al. 2021). Some studies focused on identifying BCNs (that originated in the design and construction phases) in the handover or post-handover period, but did not study construction scenarios (Forcada et al. 2016; Macarulla et al. 2013; Oyewobi and Ogumsemi 2010; Sommerville and McCosh 2007; Tayeh et al. 2020; Wasfy 2010). Moreover, studies in the context of South Asian countries are lacking − but particularly significant, as the region is rife with poor construction practices; defective works; and has witnessed a series of building collapses, structural failures, and heavy loss of human lives (Islam et al. 2021b; Press 2020). It is critically important, therefore, that professionals and stakeholders involved in the building construction industry have a comprehensive grasp of potential and critical nonconformities and are provided with a tool to support their decision-making to ensure the quality, durability, and safety of a building is not compromised.

Previous studies of nonconformity or building defects are mainly based on case studies of inspection/engineering reports (Gurmu et al. 2021; Islam et al. 2021b; Paton-Cole and Aibinu 2021), builders' records (Forcada et al. 2013a; b), and field observations (Silvestre and De Brito 2011). The field observations or case studies were mainly limited to similar projects from a few (even one or two) builders or contractors, which only partly represent a country's construction nonconformity scenarios. Moreover, project case-based studies depend on access to the site, or constructed property, builders', or governmental nonconformity databases. Consequently, some studies were conducted using expert judgment (interview, group discussion, and structured or semi-structured survey) to classify (Macarulla et al. 2013) and evaluate nonconformities in building projects (Jonsson and Gunnelin 2019; Milion et al. 2017). The expert-judgment-based building nonconformity studies analyzed data qualitatively, using such basic statistics as the mean, percentage, correlation, and testing hypothesis, or applying the relative importance index (RII) method (Chiel 2014; Jonsson and Gunnelin 2019; Yoon et al. 2021). The real challenge, however, is the lack of a robust methodology to address the uncertainties, vagueness, and biases associated with the expert judgment involved in ranking construction nonconformities. A fuzzy-based risk assessment model is best suited to address this issue (Elbarkouky et al. 2016; Islam et al. 2019a; Novák 2006). However, it has yet to be applied to the assessment of nonconformities of building projects. Furthermore, the literature is silent on the specific time frame at which a nonconformity is detected (hereinafter referred as the 'detection time'). The nonconformity detection time is one of the critical parameters for the early detection of quality defects in building construction projects (Ismail et al. 2015; Sommerville and McCosh 2007).

In this paper, a robust fuzzy-based nonconformity assessment model is proposed and applied to identify and prioritize critical nonconformities in the design and construction phases of building projects. It also identifies the dominating detection time of building construction nonconformities. How nonconformities arise with varying characteristics of a building project is quantitatively analyzed, including its ownership profile, building usage, and size (floor areas and story heights). The nonconformities in different construction phases are evaluated based on expert judgments, the limitations of which are handled by a fuzzy group decision-making approach (Islam et al. 2019a).

The remainder of this paper presents previous building construction nonconformity studies, the research methodology, results, and discussion of the critical nonconformities associated with various project characteristics. The concluding section summarizes the work, identifies its limitations, and makes recommendations to industry professionals controlling construction nonconformities and for further study.

Overview of Nonconformity Studies

Construction nonconformities have been studied with different terms and methods, considering varying projects in different parts of the world. For example, previous studies focus on finding construction defects, nonconformities and/or rework, their types, causation, costs, and effects on overall project performance. Thus, the present study defines all such terminologies as nonconformities, including defects and rework causes, as few studies use the term 'nonconformity' for construction quality assessment research. Accordingly, all relevant papers studied for defects, nonconformities, causes of reworks, and associated terms are considered for the identification of nonconformities in building construction projects. The following presents a brief overview of nonconformity studies contained in the literature.

Nonconformity study in Australia focuses on identifying building defects and rework causes and their cost effects (Gurmu et al. 2021; Love and Edwards 2004a; Paton-Cole and Aibinu 2021). Two recent studies have investigated defects in the service periods of low-rise residential buildings based on defect claim reports submitted to the state government (Paton-Cole and Aibinu 2021) and engineering reports of some buildings (Gurmu et al. 2021). Recently, a literature review-based study discovered causes, effects, and measures to manage construction rework (Love et al. 2022). The critical nonconformities identified in the service period of Australian building projects are severe cracks in various building elements (Gurmu et al. 2021; Paton-Cole and Aibinu 2021), slab subsidence, separation of wall plaster, etc. (Paton-Cole and Aibinu 2021). Love and Edwards (2004) identified that the root causes of building defects originated in the construction phase based on the case study of two real-life projects and concluded that poor workmanship, lack of focus on quality, and poor supervision and inspection were responsible for building defects and rework.

Some studies have conducted research into identifying construction nonconformities encountered in such European countries as the Netherlands, Poland, Sweden, and Spain, collecting building defect data using focus group discussions, semi-structured or structured interviews (Chiel 2014; Jingmond and Ågren 2015), structured surveys (Jonsson and Gunnelin 2019), and builders' databases (Forcada et al. 2013a; b 2014). The most common construction nonconformities in Spanish buildings are the incorrect positioning of the foundation frame, errors in installation of beams, surface defects (honeycombs in concrete, bumps, dips, etc.) and functionality defects in some building elements (Forcada et al. 2013b). These nonconformities are related to poor workmanship, construction errors, and omissions (Forcada et al. 2013a). Chiel's (2014) study, on the other hand, did not identify nonconformities but developed a procedure to define nonconformities in term of risk or non-risk, and demonstrated the model in testing 100 nonconformities from two real-life projects. Jingmond and Ågren's (2015) study focused on identifying the causes of defects, which include inaccurate work performance, knowledge gap, and poor project management.

Sommerville's (2007) study found that new private house-buildings in the U.K. incur the highest rework costs due to nonconforming work, with the design phase producing almost 50% of nonconformities, followed by construction work (40%). The most frequent design-related nonconformities were the lack of detailed drawings, inadequate specifications, and noncompliance with construction legislation. This was a qualitative study based on a literature review and findings from the U.K. Building Research Establishment (BRE).

Two Nigerian studies represent the construction quality of African building projects. One was a qualitative study relying on published literature (including electronic and print media) concerning the causes of building collapses (Hamma-Adama et al. 2020), with the other conducting a structured survey to prioritize defects using the relative importance index (RII) method (Waziri 2016). The primary causes of building collapses were closely linked to such construction defects as poor quality materials used for construction, poor workmanship, faulty design, and inadequate supervision (Hamma-Adama et al. 2020;

Waziri 2016). In the Arab region, a case study of a high-rise building in Saudi Arabia found many nonconforming finishing works in electrical wiring, glasswork, plumbing, false ceiling materials, and painting (Wasfy 2010). The construction nonconformities of residential building projects in the Gaza Strip were studied using a structured questionnaire survey of 133 engineers and the factors ranked by the RII method (Tayeh et al. 2020), the most common being poor quality materials used for construction, construction equipment and lack of inspection or supervision, inadequate soil compaction, alignment of structural elements, insufficient concrete cover, etc.

There have been several studies of Asian countries. For example, Pheng and Wee (2001) and Liu (2003) applied the ISO 9000 quality management framework to investigate the causes of defects in Singapore and Hong Kong, finding the most common defects to be design faults, poor workmanship, and defective materials used for construction. Three different studies identified Korean building construction defects in different time-phases (Lee et al. 2020; Seo and Kang 2009; Yoon et al. 2021). For instance, Seo and Kang (2009) identified finishing defects in high-rise residential buildings during their service periods from the occupants' viewpoint. Yoon et al. (2021) studied household reports and expert survey data to analyze defects in the finishing work of some apartment buildings. The former study identified most of the defects as being associated with in-built furniture, electronics, painting, and masonry work, while the latter found the highest frequency of defects in the opening and closing of doors and windows, followed by furnishing, tiling, and painting. Some Malaysian studies represent construction quality and causes of nonconforming work in Southeast Asia. Ahzahar et al. (2011), for instance, investigated the causes of building failures and associated construction nonconformities through a structured interview with 40 experts (contractors and engineers), using the relative index method for ranking. Mohd-Noor et al. (2016) studied four mosques and identified 2,276 defects, and Ismail et al. (2015) inspected 72 houses based on the condition survey protocol system. The most common nonconformities found in the construction phase were honeycombing on the concrete surface, the use of corroded steel, cracks in floors and beams, and foundation failure. The nonconformities at the handover period were defects in wall skirtings, alignment of doors and windows, hollowness in wall tiles, and uneven wall painting. The defects were mostly due to poor workmanship.

However, only Islam et al.'s (2021) study of Bangladeshi building projects represents the South Asian construction industry. Based on focus group discussions followed by three qualitative case studies, the most common construction of nonconformities were found to be inadequate soil investigation, substandard material quality, poor concrete quality, structural misalignments, insufficient concrete cover, insufficient concrete curing, imperfect formwork, and premature formwork removal.

In summary, the most common causes of building construction nonconformities found in previous studies are poor workmanship, inadequate inspection or poor site management, and poor-quality materials used for construction identified in the construction period, handover, and service period of a building. Few studies investigated nonconformities in the preconstruction and construction phases, and the majority studied the handover period, finding nonconformities in finishing works but originating in the construction phase. None paid attention to nonconformity detection time, which can be defined as a specific time frame in which particular nonconformity was noticed, as the studies were conducted after the construction phase ended. The above discussion also pinpoints the research gap as the lack of a quantitative assessment of critical construction nonconformities in the densely populated South Asian developing countries, where poor workmanship, quality of materials, severe lack of the construction workers' knowledge and skills, and inadequate supervision and inspection (Islam et al. 2021b) are potential causes of recent building collapses (Omondi 2019). A few studies collected data using questionnaire surveys or interviews and analyzed by descriptive statistics or the RII method (Tayeh et al. 2020; Waziri 2016; Yoon et al. 2021). Since expert-judgment-based data is subject to uncertainty, vagueness, and bias (Elbarkouky et al. 2016; Islam et al. 2019a; Novák 2006), a fuzzy-logic-based model such as the fuzzy group decision-making approach (FGDMA) can be potentially used to rank and analyze the critical nonconformities in building construction projects (Islam et al. 2019a).

Research Method

The research method consisted of a literature review to find the research gaps, listing potential nonconformities in the project planning to construction phases, selecting a suitable data collection tool and a method for data analysis following Islam et al. (2019a) and Li and Wang (2016). A panel of experts was convened, and semi-structured interviews were conducted, to finalize the nonconformities relevant to Bangladeshi building construction projects. Based on the final list of nonconformities, a structured questionnaire was developed, and experts' judgements elicited in evaluating building construction nonconformities. The fuzzy group decision-making approach (Islam et al. 2019a) was adopted for analyzing these and identifying the critical building construction nonconformities. The importance of nonconformities and their variations for different project variables are also analyzed, justifying their relationships in varying project scenarios. The following subsections present the background of selecting FGDMA, its step-by-step procedure, and details of the expert judgment elicitation.

Fuzzy group decision-making approach

Assessing the critical nonconformities of any project depends mostly on expert judgment, where there is a lack of data records, poor accuracy, or limited access to datasets. Moreover, handling the expert evaluations of nonconformities and associated subjective biases and the suitability of the chosen model/method is also critical. Previous expert-judgment-based nonconformity studies mostly used a simple discrete Likert type scale (0, 1, 2, ….) for the nonconformities assessment, and analyzed data using the averaging technique or the most frequently used relative importance index (RII) method (Heravi and Jafari 2014; Tayeh et al. 2020). Those methods have limitations in addressing the uncertainty, subjectivity, and biases involved. Instead, the fuzzy method evaluates a risk (nonconformity in this paper) linguistically and transfers it to a fuzzy triangular or trapezoidal number or range instead of a crisp value (Islam et al. 2019a; Nguyen and Robinson Fayek 2022). The decision maker's risk attitude (seeker, neutral, or averse) and corresponding project contexts, along with the fuzzy risk assessment result, assists them to take an informed decision in handling those risks. However, conventional fuzzy logic has a limitation in aggregating expert judgments for risk ranking (Novák 2006; Xu et al. 2010). Moreover, the use of its *if-then* rules for analyzing the relationships between the input variables (likelihood of occurrence and severity of a risk) to measure output (risk level) is tedious and further subjective, and does not provide numerical values to prioritize risks (Islam et al. 2019a; Jung et al. 2016). These limitations are addressed in Islam et al.'s (2019a) *fuzzy group* decision-making approach. In FGDMA, a group of experts evaluate the likelihood of occurrence and severity of nonconformities. The model applies some equations (Eqs. 1 to 8) to aggregate experts' judgments considering their professional competency weights (Kabir et al. 2016) and finds defuzzified scores for nonconformities. Then, the defuzzified scores are explained based on Fig. 1 (triangular membership functions of different linguistic variables) and Table 1 (description of the linguistic variables) to find importance levels (likelihood of occurrence, severity, and importance) of nonconformities and make inference considering specific project's context.

Accordingly, this study adopts Islam et al.'s (2019a) FGDMA, which assesses nonconformity using the likelihood of occurrence and severity of each nonconformity, with its detection time (i.e., before, during, or after construction) in particular work packages (Abdelgawad and Fayek 2010; Mohammadi and Tavakolan 2013). The experts evaluate the likelihood of occurrence and severity of each nonconformity based on the linguistic variables "none" to "extreme" (Li and Wang 2016). The linguistic variables are then transferred to fuzzy triangular numbers following Islam et al. (2019a) and Li and Wang (2016).

Fig. 1 shows triangular fuzzy membership functions for different assessment levels (very low to extremely high). The triangular fuzzy membership function is chosen for its computational simplicity (geometrical triangular shape) and accommodating three-point estimate (pessimistic, most likely, and optimistic values), and is commonly used in similar risk and uncertainty studies (Chileshe and Dzisi 2012; Elbarkouky et al. 2016; Gerami Seresht and Fayek 2019; Zegordi et al. 2012). Table 1 describes each linguistic variable, the corresponding defuzzified range used in computing nonconformities, and explains the assessment findings.

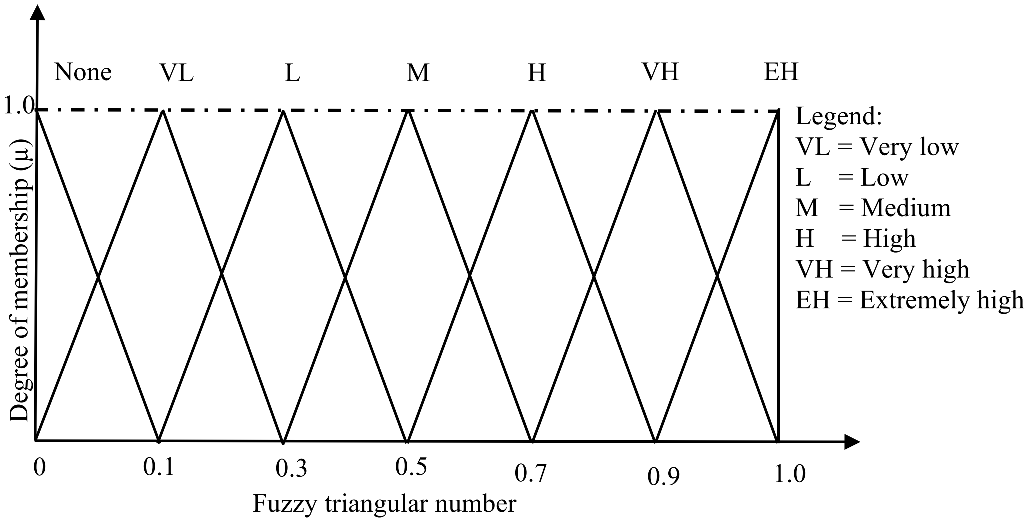

Fig. 1. Triangular fuzzy membership functions

Table 1. Mapping building construction nonconformities in different construction phases with varying project scenarios

Project phase	Nonconformity (Code)	Building ownership not specific							Private building			
		Mixed building	Not specific (NS)			Residential building			Mixed building		Residential building	
		NS	HRB	NS	NS	LRB	NS	NS	NS	HRB	NS	LRB
		Pheng and Wee (2001)	Santoso et al. (2003)	Ahzahar et al. (2011)	Ercan and Kara (2021)	Macarulla et al. (2013)	Tayeh et al. (2020)	Liu (2003)	Islam et al. (2021b)	Wasfy (2010)	Yoon et al. (2021)	Paton-Cole and Aibinu (2021)
Planning and design	Incorrect site survey (PD1)	X	X				X					
	Incorrect soil investigation (PD2)		X						X			
	Architectural design errors (PD3)		X	X								
	Structural design errors (PD4)			X							X	
	Insufficient detailing in drawings/designs (PD5)	X	X					X				
Steel fabrication in foundation	Insufficient concrete cover of reinforcement (SFF1)				X		X		X			
	Deviation of pile/footing centers from their layout positions (SFF2)					X			X			
	Incorrect reinforcement (size) due to deviation from the design (SFF3)					X				X		
	Incorrect size of reinforcement bar hooks and development length (SFF4)								X			
Steel fabrication in Superstructure (beam-column-slab)	Vertical misalignment of column (floor to floor) (SFS1)					X			X			
	Insufficient concrete cover of reinforcement (SFS2)				X				X			
	Incorrect reinforcement (size of re-bar) due to deviation from the design (SFS3)					X				X		
	Insufficient size of laps (SFS4)								X			
	Spacing of the stirrup deviating from the design specification (SFS5)								X			
	Inaccurate size of reinforcement bar hooks and development length in beams (SFS6)								X			
	Misalignment (horizontal) of the beam (SFS7)					X						
	No stirrup in beam-column joint (SFS8)								X	X		
	Incorrect electrical piping creating a structural problem (SFS9)					X				X		
	Incorrect opening for sanitary/water supply piping (SFS10)					X						
	Insufficient sand netting (CQ1)								X			

Project phase	Nonconformity (Code)	Building ownership not specific							Private building			
		Mixed building	Not specific (NS)			Residential building			Mixed building		Residential building	
		NS	HRB	NS	NS	LRB	NS	NS	NS	HRB	NS	LRB
		Pheng and Wee (2001)	Santoso et al. (2003)	Ahzahar et al. (2011)	Ercan and Kara (2021)	Macarulla et al. (2013)	Tayeh et al. (2020)	Liu (2003)	Islam et al. (2021b)	Wasfy (2010)	Yoon et al. (2021)	Paton-Cole and Aibinu (2021)
Concrete quality (throughout the structure)	Insufficient stone washing (CQ2)								X			
	Inaccurate mixing ratio of cement, sand, and stone (CQ3)					X	X					
	Inaccurate water-cement ratio (excessive dry/loose) (CQ4)						X					
	Insufficient curing (CQ5)						X				X	
	Premature stressing on concrete (CQ6)						X		X			
	Insufficient compaction/vibration (CQ7)		X	X			X					
	Poor gradation of course/fine aggregates (CQ8)	X		X			X					
Formwork/ shuttering	Defective formwork (FW1)						X					
	Holes in formwork (FW2)								X			
	Gaps in formwork joints (causing leakage) (FW3)								X			
	Early removal of formwork (FW4)						X		X			
Monitoring and control (quality)	Insufficient work inspection (MC1)								X	X	X	
	Insufficient full-time supervision (MC2)								X	X	X	
	Consultant/designer not invited for supervision (MC3)								X			
	Insufficient material field tests (MC4)								X			
	Lack of site order book for record keeping of site-related information (MC5)									X		
	Insufficient periodic laboratory testing of materials (MC6)								X			

Note: HRB= High-rise building; LRB= Low-rise building; NS= Not specific

The step-by-step procedure of modified FGDMA is described below:

1. The fuzzy triangular number (FTN) for the corresponding linguistic term is extracted following the scenarios and descriptions in Table 2. Triangular fuzzy numbers provide decision-makers with information regarding the nonconformity factor as they contain a three-point estimate (e.g., high severity means 0.5, 0.7, 0.9) rather than a crisp value. This allows the flexibility to adopt appropriate construction quality management strategies for project execution phases.
2. Using the FTN, a fuzzy decision matrix (*FDM*) for the likelihood of occurrence (*LO*) or severity level of individual nonconformity (*nc*) in a project phase (*p*) is formed by

$$\left(\boldsymbol{FDM^{nc}_{LO/SL}}\right)_{\boldsymbol{p}} = \begin{bmatrix} \boldsymbol{l_1} & \boldsymbol{m_1} & \boldsymbol{u_1} \\ \vdots & \ddots & \vdots \\ \boldsymbol{l_n} & \boldsymbol{m_n} & \boldsymbol{u_n} \end{bmatrix} \qquad [1]$$

   where *l*, *m*, and *u* represent the low, medium, and upper values of likelihood of consequence of a nonconformity, respectively, and *n* represents the number of participating experts in the nonconformity evaluation.

3. The judgment ability of experts and the reliability of their judgments can vary for several reasons in a particular context, and thus need to be weighted accordingly. This a function of their professional position (*PP*), working experience (*EP*), experience gained working on other projects (*EO*), and academic qualifications (*AQ*) (Jung et al. 2015). The weighted judgement of each expert is then incorporated into the nonconformity assessment to increase decision reliability (Kabir et al. 2016). The weight ($\boldsymbol{w_i^{Ind}}$) is given by (Aboshady et al. 2013)

$$\boldsymbol{w_i^{Ind}} = (\boldsymbol{w_{pp}} + \boldsymbol{w_{EP}} + \boldsymbol{w_{EO}} + \boldsymbol{w_{AQ}})_{\boldsymbol{i}} \qquad [2]$$

   where $\boldsymbol{w_{PP}}, \boldsymbol{w_{EP}}, \boldsymbol{w_{EO}},$ and $\boldsymbol{w_{AQ}}$ indicate each expert's weights for *PP*, *EP*, *EO*, and *AQ*, *respectively.* To evaluate the experts' weights, each criterion ($\boldsymbol{i.e.}, \boldsymbol{w_{PP}}, \boldsymbol{w_{EP}}, \boldsymbol{w_{EO}},$ **or** $\boldsymbol{w_{AQ}}$) is assumed equal. The global weight of an expert ($\boldsymbol{w_i^g}$) is calculated by (Ameyaw et al. 2015)

$$\boldsymbol{w_i^g = \frac{w_i^{Ind}}{\sum_{i=1}^{n} w_i^{Ind}}\,;\, \sum_{i=1}^{n} w_i^g = 1} \qquad [3]$$

It is noted that the sum of all experts' global weights must equal unity, satisfying the principle of the aggregated fuzzy score (Jung et al. 2015).

4. The FDM for individual nonconformity (*nc*) of a project phase (*p*) is transformed into a weighted FDM (WFDM) by

$$\boldsymbol{\left(WFDM_{LO/SL}^{nc}\right)_p = \left(FDM_{LO/SL}^{nc}\right)_p * w_i^g = \begin{bmatrix} l_1 & m_1 & u_1 \\ \vdots & \ddots & \vdots \\ l_n & m_n & u_n \end{bmatrix} (.\mathrm{x}) \begin{bmatrix} w_1^g \\ \dots \\ w_n^g \end{bmatrix}}$$

$$\boldsymbol{= \begin{bmatrix} l_1 w_1^g & m_1 w_1^g & u_1 w_1^g \\ \vdots & \ddots & \vdots \\ l_n w_n^g & m_n w_n^g & u_n w_n^g \end{bmatrix}} \qquad [4]$$

5. The fuzzy score (*FS*) for the nonconformity likelihood of occurrence (*LO*) or severity level (*SL*) of a project is the sum of each column of the Eq. 4 matrix by

$$\boldsymbol{\left(FS_{LC/SL}^{r}\right)_p = \left[\sum_{i=1}^{n} l_i w_i^g, \sum_{i=1}^{n} m_i w_i^g, \sum_{i=1}^{n} u_i w_i^g\right]} \qquad [5]$$

6. The nonconformity detection time $\boldsymbol{FS_{DT}^{nc}}$ also is used to assess the importance level of a nonconformity, with similar equations to Eqs. 1 to 5 applied for the fuzzy detection time calculation.

7. The total importance score to identify the level of a nonconformity depends on the likelihood of occurrence, severity level, and its detection time. Thus, the fuzzy score $\boldsymbol{(\mathbf{FS}_{nc})_{L,M,U}}$ of a nonconformity is calculated by Eq. 6 and is adapted from Xu et al.'s (2010) fuzzy synthetic evaluation approach for risk assessment as

$$\boldsymbol{(\mathbf{FS}_{nc})_{L,M,U} = \left(\sqrt{(FS_{LO}^{nc})_P * (FS_{SL}^{nc})_P * (FS_{DT}^{nc})_P}\right)_{L,M,U}} \qquad [6]$$

where $\boldsymbol{(FS_{LO}^{nc})_p}$, $\boldsymbol{(FS_{SL}^{nc})_p}$, and $\boldsymbol{(FS_{DT}^{nc})_p}$ are fuzzy scores for the likelihood of occurrence, severity level, and detection time, respectively, for a nonconformity involved in a project phase (*p*) or whole project (*P*). Although conventional fuzzy *If-then* rules are usually applied to make inferences regarding the importance of a nonconformity (based on its likelihood of occurrence, severity level, and detection time), they have been criticized for their inability to deal with subjective biases (Novak 2012): hence, Xu et al.'s (2010) suggested alternative technique is used instead.

8. The nonconformity level (i.e., "none" to "extreme") is defined by the defuzzification, which is computed as (Abdelgawad and Fayek 2010)

$$\boldsymbol{f(x_i) = (\mathrm{FS}_{nc})_{Deff.} = \frac{(\mathrm{FS}_{nc})_L + 4*(\mathrm{FS}_{nc})_M + (\mathrm{FS}_{nc})_U}{6}} \quad [7]$$

The FGDMA model is used for building construction nonconformity assessment by developing an Excel spreadsheet (Microsoft® Excel® for Microsoft 365 MSO (Version 2205) 32-bit). However, the developed model can be adopted to other Excel versions too.

Eliciting expert judgments

Construction nonconformities can be investigated by direct observation/site visits, document study, interviews, or questionnaire survey of domain experts (Islam et al. 2021b; Paton-Cole and Aibinu 2021). Semi-structured interviews with domain experts provide a common way of collecting data for project quality management research (Almahmoud et al. 2012; Gutierrez and Hussein 2015). This process allows the participants to incorporate any important additional information. In the present study, the nonconformities in different phases of building construction projects were initially identified by a literature review followed by semi-structured interviews and discussion with a panel of six experts similar to Islam et al. (2021b) and Liu (2003). The panel experts were randomly selected from a combination of academic and industry professionals and consisted of two public university professors in civil (construction) engineering with 15 to 20 years of experience in both academic and professional fields, two building design and construction consultants with 10 to 15 years of experience, and two project managers working in the building construction industry for 20 to 25 years.

The final list of construction nonconformities is mapped against different building projects with corresponding references (Table 2). Each nonconformity is coded to link to its group name. For instance, the planning and design (PD) group has five nonconformities; thus, they are coded as PD_1, PD_2, PD_3, PD_4, and PD_5. Similarly, the concrete quality (CQ) group has eight nonconformities and coded accordingly as CQ_1 to CQ_8. These nonconformities were then used to develop the questionnaire for eliciting expert judgments. The questionnaire contains three parts: (a) the attributes of experts (academic qualifications, professional position, and years of relevant working experience); (b) characteristics of the building projects; and (c) the nonconformities' likelihood of occurrence, severity, and detection time in building construction phases. To evaluate their likelihood and severity, the experts evaluated each nonconformity on a linguistic scale from *absence or no impact* to *extremely frequent or severe* based on completed or partially completed projects where they were working. The detection time of each nonconformity before, during, or after construction was assessed linguistically as having a "low", "medium", or "high" impact on construction quality. These qualitative terms also follow Table 1 for fuzzy-based nonconformity assessment. The questionnaire was distributed to 130 Bangladeshi building construction professionals by online contact and 100 by direct visits, resulting in 95 responses.

Table 2. Linguistic variables and corresponding fuzzy numbers

Level of nonconformity likelihood/severity	Fuzzy triangular number (FTN)	Defuzzified number range	Description
Extremely high	0.9, 1.0, 1.0	0.90 to 1.00	Almost certain chance of the risk event occurring, and construction quality is extremely compromised
Very high	0.7, 0.9, 1.0	0.70 to <0.90	Very high chance of the risk event occurring, and most significant in deteriorating construction quality
High	0.5, 0.7, 0.9	0.50 to <0.70	High chance of the risk event occurring, and significant in deteriorating construction quality
Medium	0.3, 0.5, 0.7	0.30 to <0.50	Likely chance of occurring the risk event, and moderately significant in deteriorating construction quality
Low	0.1, 0.3, 0.5	0.10 to <0.30	Rare chance of the risk event occurring, and little significance in deteriorating construction quality
Very low	0, 0.1, 0.3	0.025 to < 0.10	Very rare chance of occurring the risk event, and very little significance in deteriorating construction quality

Level of nonconformity likelihood/severity	Fuzzy triangular number (FTN)	Defuzzified number range	Description
None	0, 0, 0.1	0 to < 0.025	Risk event almost never happens, and/or deteriorates construction quality

The experts were randomly selected from the building construction industry of Bangladesh. This involved collecting the email addresses of civil engineers listed in the Institute of Engineers Bangladesh (IEB) (http://www.iebbd.org/) and the authors' fellow alumni (civil engineering graduates) list for the first step to invite them to participate in the online survey. Afterward, the researchers directly visited owners, contractors, field engineers, and consulting firms in major cities in Bangladesh to distribute the questionnaire and invite them to participate in the survey. As they all work in the same domain (i.e., building design and construction), they were randomly selected for data collection (Islam et al. 2021b; Love and Edwards 2004a; Tayeh et al. 2020). The importance of selecting the Bangladeshi construction industry lies in its population density and construction growth. The industry contributes 12-15% of national GDP through its linkage industries (Islam and Suhariadi 2018). The private sector plays a vital role, with 43% of total investment (approximately USD 1.5 billion) in building large apartments, shopping complexes, and education buildings (REHAB 2017). The public sector also invests substantial capital in building academic institutions (schools, colleges, and universities); health complexes; and commercial, industrial, and multi-complex buildings. However, shoddy construction work, construction code violations, and poor quality materials have caused devastating building collapses in the capital city Dhaka and surrounding areas (Islam et al. 2021a; b; Wikipedia 2013). Thus, construction quality and associated nonconformities have significant importance in delivering quality and sustainable construction for city dwellers' safe living places.

Results and Discussion

Background of the respondents

The expert judgments were obtained using the random sampling method to ensure the diversified representation of different stakeholders, including their professional positions, educational backgrounds, and varying levels of experience, to reduce subjectivity and biases involved in eliciting expert judgment (Islam et al. 2021b; Love and Edwards 2004a; Tayeh et al. 2020). Fig. 2 illustrates the profiles of the 95 experts who participated in this study, showing they represent a good combination of private owners, contractors, and consultants, with most (32) being consultants, followed by private owners and contractors. They hold different executive positions, including general manager, project director, project manager, and project engineer. The majority (40) are project engineers, who are field-level experts and readily available in the project sites. The bulk of respondents hold a BSc Engineering degree, with varying academic levels also represented. The participants have an average of 10 years of experience working in construction projects. They have different levels of experience (years) working in building construction projects, which helps ensure diversified knowledge levels (Islam et al. 2019a; Xu et al. 2010). Some have additional experience (an average of five years) in other construction projects along with building projects. Therefore, the respondents can be taken to have a sufficient variety of knowledge and experiences to avoid any significant bias in subjective knowledge-based risk assessment of construction projects (Islam et al. 2019a; Li and Wang 2016).

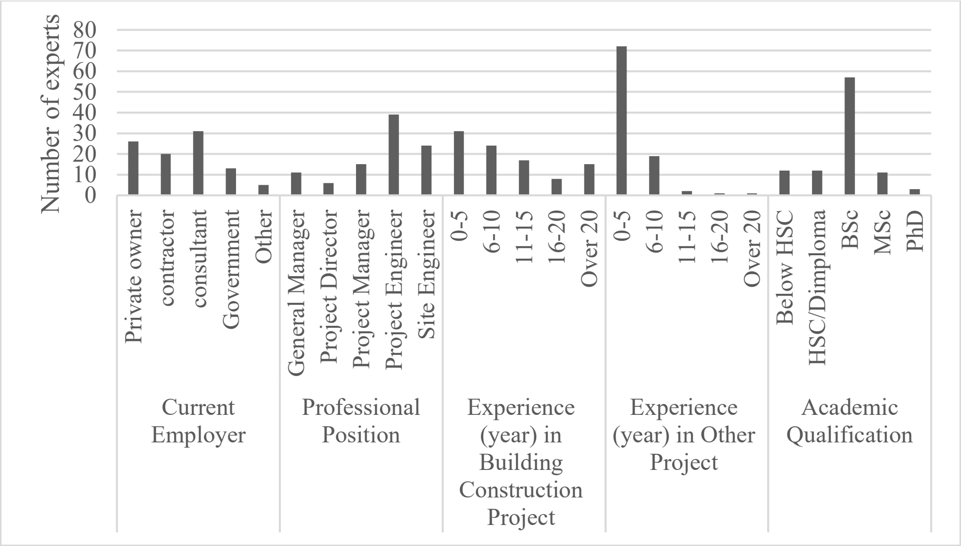

Fig. 2. Experts' profiles indicating different levels of expertise

In the survey questionnaire, each expert was also asked to answer some questions regarding their recently completed or partially completed project on which the nonconformities were assessed. For example, project ownership, functional type, floor area, building height based on the number of stories, estimated cost, and contract type were asked to the experts. Hence, similar to the experts' profiles, their projects also have a wide variety of characteristics presented in **Fig. 3**. It is observed that the majority (70) of the projects are private buildings, followed by government buildings. Residential buildings are the most common, followed by multipurpose buildings – defined as the buildings where residential apartments, offices, or other commercial activities are accommodated. The majority (55) are small buildings with a floor area up to 500 m^2. Low-rise buildings up to 5-stories high dominate, followed by 6-10 story buildings and a small percentage over 10 stories. Most (70) have an estimated cost of less than BDT 50 million (USD 600 thousand), with a unit price followed by a lump-sum contract type.

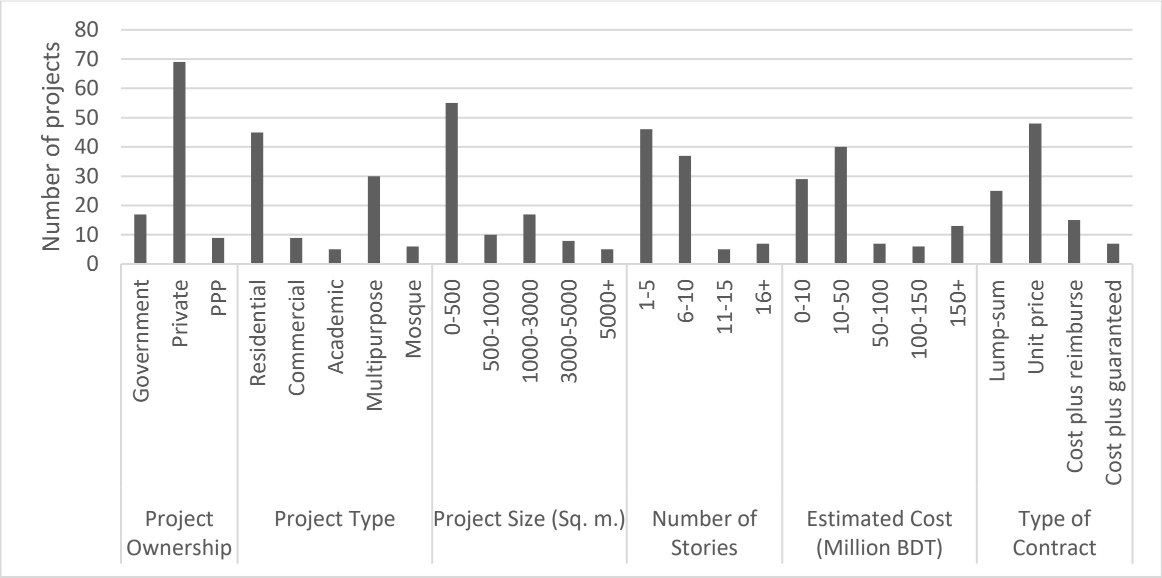

Fig. 3. Details of the projects' profiles

Major nonconformities

Table 3 shows the overall nonconformity scenario in building construction projects by analyzing the total 95 responses using Eqs. 1-7, containing the defuzzified results of only the 20 most important nonconformities owing to space limitations. The construction phases are restricted to reinforced cement concrete work (i.e., foundation to slab casting) and disregard nonstructural brickwork, plastering, and other finishing tasks (plumbing, electrical, mechanical, painting, etc.). As is shown, the nonconformities identified as causing the most threat to the quality of building projects are the premature concrete stressing (CQ_6); inaccurate water-cement ratio (CQ_4); insufficient concrete compaction/vibration (CQ_7); lack of full-time supervision (MC_2); insufficient curing (CQ_5); and inaccurate mixing ratio of cement, sand, and stone (CQ_3). Four of the top five factors concern onsite concrete production. 17 out of 20 nonconformities have scores between 0.40 to 0.50. All nonconformities are identified as medium-level risk in terms of deteriorating construction quality. As Table 1 shows, these medium-level risks can be defined as triangular fuzzy numbers, i.e., 0.3, 0.5, and 0.7, interpreted as having (i) a medium chance of occurrence and causing moderate impact on construction quality, (ii) a high chance of occurrence and causing significant harm to construction quality, and (iii) a very high chance of occurrence and causing very significant harm to construction quality, respectively. Of these, the prevalent nonconformities are mostly relevant to concrete production (CQ_6, CQ_4, CQ_7, and CQ_5) with the addition of lack of full-time site supervision (MC_2).

The last column of Table 3 shows the dominating detection time of each nonconformity. Most factors are encountered during construction, with only two factors (CQ_6 and CQ_5) detected after construction, and a single factor, architectural design error (PD_3), identified before construction. The detection times are quite consistent (i.e., 90% the same) for the factors CQ_3, CQ_4, and no stirrup in beam-column joint (SFS_8) and the top-ranked factors, with four out of five factors having a similar score (60% to 70%).

Table 3. Detailed FGDMA outcomes

Nonconformity code	Detection		Frequency		Impact		Overall Risk		Rank	Dominant detection time
	Score	Level	Score	Level	Score	Level	Score	Level		
CQ_6	0.614	H	0.382	M	0.499	M	0.489	M	1	After work (67%)
CQ_4	0.490	M	0.407	M	0.572	H	0.485	M	2	During work (91%)
CQ_7	0.528	H	0.389	M	0.511	H	0.472	M	3	During work (66%)
MC_2	0.510	H	0.449	M	0.451	M	0.469	M	4	During work (73%)
CQ_5	0.618	H	0.338	M	0.493	M	0.469	M	5	After work (68%)
CQ_3	0.498	M	0.355	M	0.561	H	0.463	M	6	During work (92%)
MC_1	0.514	H	0.393	M	0.469	M	0.456	M	7	During work (72%)
SFS_8	0.476	M	0.386	M	0.480	M	0.445	M	8	During work (90%)
FW_3	0.487	M	0.383	M	0.467	M	0.443	M	9	During work (80%)
MC_6	0.460	M	0.422	M	0.447	M	0.443	M	10	During work (54%)
MC_5	0.478	M	0.499	M	0.350	M	0.437	M	11	During work (82%)

Nonconformity code	Detection		Frequency		Impact		Overall Risk		Rank	Dominant detection time
	Score	Level	Score	Level	Score	Level	Score	Level		
MC_4	0.447	M	0.434	M	0.429	M	0.437	M	12	During work (62%)
FW_1	0.468	M	0.386	M	0.425	M	0.425	M	13	During work (71%)
MC_3	0.472	M	0.372	M	0.411	M	0.416	M	14	During work (73%)
PD_5	0.443	M	0.382	M	0.413	M	0.412	M	15	During work (68%)
CQ_1	0.439	M	0.335	M	0.438	M	0.401	M	16	During work (64%)
CQ_8	0.443	M	0.370	M	0.390	M	0.400	M	17	During work (65%)
CQ_2	0.433	M	0.362	M	0.402	M	0.398	M	18	During work (67%)
FW_2	0.468	M	0.332	M	0.394	M	0.394	M	19	During work (76%)
PD_3	0.410	M	0.364	M	0.397	M	0.390	M	20	Before work (53%)

In terms of group representations of the top 20 nonconformities, 19% are related to concrete quality, 18% to monitoring and control, 17% to formwork/shuttering, 16% to superstructure steel fabrication, and 15% to both planning/design and foundation steel fabrication. The first three of these are mostly controllable during construction with proper monitoring and control, which needs the combined involvement of contractor's staff and owner's supervision team with quality materials from the suppliers.

Nonconformities with project variables

As Fig. 4 shows, the nonconformity scenario varies according to project functional type, with premature concrete stressing (CQ_6) having a defuzzified score close to 0.60 – a higher risk level for all types except academic buildings, with a risk score less than 0.30 (rare frequency and little significance in deteriorating construction quality). Inaccurate water/cement ratio (CQ_4) is similar to premature concrete stressing except for the academic buildings, where the factor reaches just above 0.30, meaning moderate to high risk for construction quality. Other factors are insufficient concrete compaction (CQ_7), lack of full-time site supervision (MC_2), and insufficient curing (CQ_5). Overall, multipurpose, residential, and commercial buildings have poor quality construction, as most nonconformities have a medium- to high-level risk, while mosques and academic buildings have comparatively good quality construction.

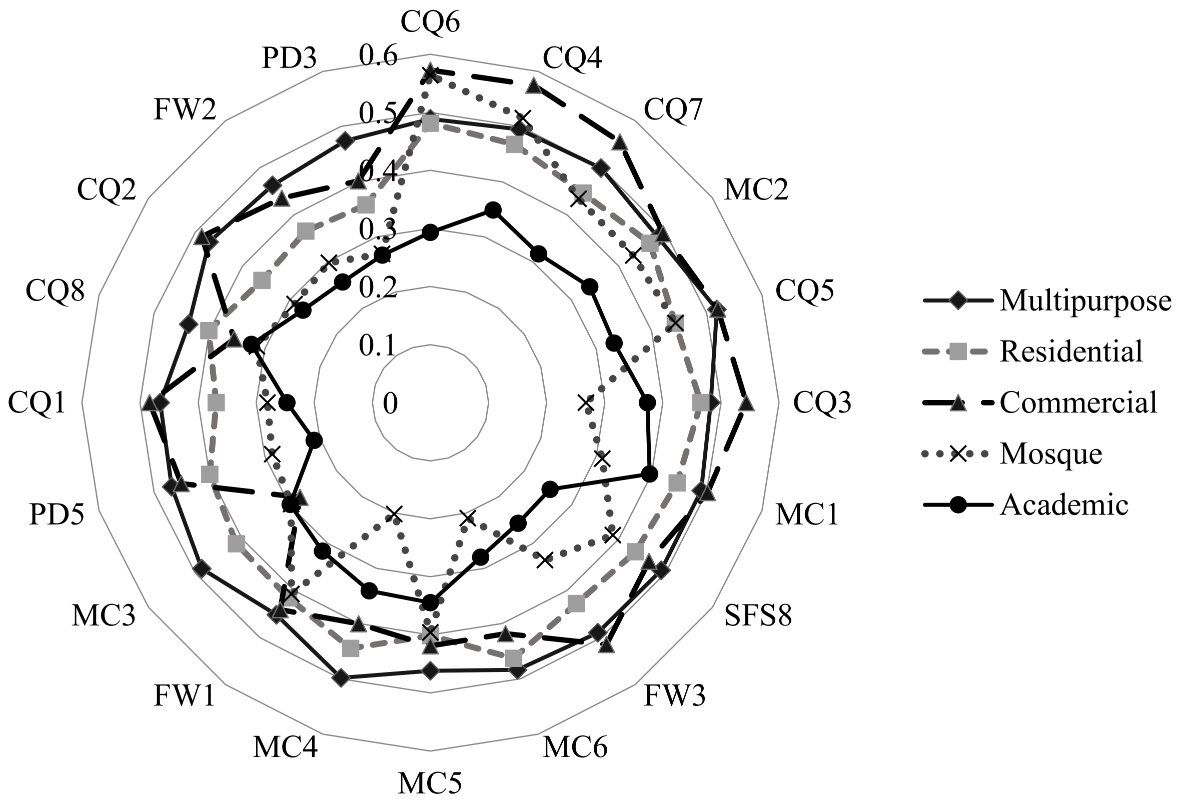

Fig. 4. Comparative nonconformity scenario with respect to project functional types

Table 4 contains 15 different project scenarios to better understand the context of project nonconformities and their profile in terms of building ownership, story height, and functional type, showing that the nonconformity levels of multipurpose low-rise (1-5 stories) government buildings have the highest level of risk (0.605), which means this group has frequent nonconformities and a significant effect on the deterioration of construction quality. This result is expected, as all of the 20 nonconformities except 'lack of site order book for record-keeping of site-related information' (MC_5) in this project group have a high-level risk score of above 0.50. Such nonconformities as insufficient curing (CQ_5) and insufficient work inspection (MC_1), for instance, have a very high-risk level (above 0.70) as they have a very high chance of occurrence and the most effect on the deterioration of construction quality.

The next worse quality project is government-owned high-rise (at least 11 stories) residential projects with a risk score of 0.592, followed by privately-owned low-rise multipurpose buildings (0.546) and government-owned high-rise multipurpose buildings (0.523). The last row of Table 4 shows that the construction quality of all high-rise buildings, including those with 6-10 stories, have high-level nonconformity. This constitutes a serious threat to the occupants, investors/developers, and the construction quality control authority as Bangladesh is an earthquake- and other natural disasters-prone country, which sharply increases vulnerability to structural collapse (Apu and Das 2020; Omar et al. 2021). However, although the construction quality of private low-rise academic and high-rise commercial buildings is generally quite good (nonconformity scores below 0.30), such factors as premature concrete stressing (CQ_6), consultant/designer not invited for supervision (MC_3), and insufficient periodic laboratory testing of materials (MC_6) have a very low score (less than 0.10), which severely reduces their average nonconformity score.

Table 4. Nonconformities analysis based on different project scenarios

Nonconformity code	Government								Private							Public private partnership		
	1-5 stories			6-10 stories			At least 11 stories		1-5 stories		6-10 stories				At least 11 stories	1-5 stories		6-10 stories
	Multipurpose	Mosque	Academic	Commercial	Multipurpose	Residential	Multipurpose	Residential	Commercial	Multipurpose	Academic	Residential	Commercial	Multipurpose	Multipurpose	Multipurpose	Mosque	Multipurpose
CQ_6	0.671	0.499	0.253	0.676	0.505	0.528	0.386	0.527	0.652	0.575	0.398	0.439	*0.058*	0.262	0.554	0.290	0.575	0.420
CQ_4	0.674	0.385	0.394	0.619	0.471	0.701	0.626	0.478	0.688	0.548	0.190	0.455	0.344	0.324	0.487	0.550	0.538	0.423
CQ_7	0.575	0.564	0.300	0.750	0.519	0.785	0.528	0.410	0.560	0.533	0.356	0.478	0.570	0.415	0.539	0.424	0.395	0.392
MC_2	0.617	0.550	0.360	0.556	0.475	0.757	0.528	0.409	0.546	0.604	0.260	0.528	0.356	0.478	0.468	0.451	0.397	*0.052*
CQ_5	*0.709*	0.655	0.330	0.606	0.492	0.386	0.528	0.388	0.588	0.597	0.290	0.514	0.058	0.318	0.558	0.508	0.353	0.286
CQ_3	0.688	0.378	0.350	0.600	0.515	0.785	0.528	0.458	0.669	0.542	0.422	0.469	0.372	0.312	0.491	0.349	0.234	0.359
MC_1	*0.705*	0.479	0.452	0.593	0.536	0.528	0.528	0.392	0.550	0.584	0.190	0.511	0.356	0.421	0.435	0.476	0.261	0.121
SFS_8	0.593	0.468	0.217	0.510	0.452	0.386	0.386	0.465	0.496	0.574	0.356	0.398	0.422	0.395	0.533	0.440	0.357	0.319
FW_3	0.624	0.153	0.273	0.510	0.488	0.559	0.325	0.428	0.610	0.550	0.190	0.427	0.372	0.435	0.468	0.477	0.381	0.359
MC_6	0.515	0.268	0.263	0.566	0.515	0.701	0.785	0.437	0.473	0.551	0.300	0.478	*0.052*	0.370	0.495	0.472	0.191	0.423
MC_5	*0.428*	0.206	0.254	0.376	0.450	0.202	0.626	0.369	0.551	0.551	0.528	0.419	0.308	0.477	0.486	0.387	0.441	0.298
MC_4	0.616	0.497	0.354	0.419	0.450	0.510	0.701	0.434	0.417	0.685	0.300	0.462	0.422	0.361	0.477	0.551	*0.098*	0.332
FW_1	0.624	0.311	0.324	0.401	0.497	0.626	0.325	0.409	0.524	0.501	0.260	0.424	0.260	0.326	0.467	0.308	0.430	0.376
MC_3	0.597	0.484	0.398	0.326	0.497	0.528	0.701	0.329	0.335	0.558	*0.017*	0.496	*0.052*	0.317	0.560	0.396	0.207	0.267
PD_5	0.531	0.347	0.224	0.559	0.471	0.662	0.356	0.319	0.404	0.391	0.160	0.391	0.300	0.388	0.553	0.466	0.269	0.369
CQ_1	0.617	0.356	0.275	0.430	0.497	0.604	0.528	0.328	0.522	0.584	0.160	0.408	0.472	0.333	0.419	0.545	0.252	0.368
CQ_8	0.635	0.345	0.286	0.422	0.430	0.701	0.528	0.393	0.391	0.501	0.422	0.405	0.308	0.255	0.458	0.356	0.297	0.334
CQ_2	0.626	0.319	0.307	0.503	0.471	0.785	0.626	0.316	0.571	0.501	0.160	0.388	0.344	0.340	0.473	0.437	0.276	0.332
FW_2	0.550	0.260	0.272	0.520	0.488	0.472	0.528	0.334	0.507	0.448	0.190	0.393	0.190	0.336	0.506	0.469	0.308	0.398
PD_3	0.507	0.294	0.255	0.503	0.428	0.626	0.398	0.296	0.361	0.549	0.300	0.389	0.356	0.316	0.583	0.407	0.262	0.509

Nonconformity code	Government							Private								Public private partnership		
	1-5 stories			6-10 stories		At least 11 stories		1-5 stories				6-10 stories			At least 11 stories	1-5 stories	6-10 stories	
	Multipurpose	Mosque	Academic	Commercial	Multipurpose	Residential	Multipurpose	Residential	Commercial	Multipurpose	Academic	Residential	Commercial	Multipurpose	Multipurpose	Multipurpose	Mosque	Multipurpose
Mean Score	*0.605*	0.391	0.307	0.522	0.482	0.592	0.523	0.396	0.521	0.546	*0.272*	0.444	*0.298*	0.359	0.500	0.438	0.326	0.337

Discussion

The application of FGDMA to the nonconformity assessment of building construction projects in Bangladesh reveals several insights. Concrete quality-related nonconformities, which are the contractor's responsibility, are mostly to blame for the poor quality of construction work, with premature concrete stressing the most frequent and severe. Premature concrete stressing means loading a concrete or reinforced concrete structure before 28 days. This corresponds with Islam et al.'s (2021b) previous research identifying nonconformities in the building construction projects in Bangladesh, where loading to immature concrete structuring and early removal of formwork were found responsible for premature concrete stressing. As confirmed by a study in Palestine (Tayeh et al. 2020), construction industries in developing countries can also experience similar early formwork removal problems; as reported in a Malaysian study (Ahzahar et al. 2011), these factors (removing formwork and immature loading) can be the root causes of cracking concrete, with a cause-effect analysis of building collapse in South Africa also finding early removal of formwork causing the collapse of a newly-cast slab (Emuze et al. 2015).

Such other onsite factors producing poor quality concrete as incorrect water/cement ratios, insufficient curing, and incorrect mixing ratios have also been observed in a previous field study in Bangladesh (Islam et al. 2021b). These factors are associated with poor workmanship and a lack of full-time quality assurance site supervisors. Poor workmanship is one of the most frequent factors identified as associated with both developing and developed countries (Forcada et al. 2013b; Hamma-Adama et al. 2020; Islam et al. 2021b; Ismail et al. 2015; Love and Edwards 2004b; Wasfy 2010; Yoon et al. 2021), while poor site management and lack of supervision, or lack of skilled personnel at site for ensuring the required construction quality has been reported in several countries including Hong Kong, U.K., and Australia (Auchterlounie 2009; Hardie and Saha 2014; Sun and Meng 2009) – a particular problem in Bangladesh being private building owners cutting costs by dispensing with full-time supervision by a skilled team (Islam et al. 2021b).

Similar to the residential buildings in Bangladesh, specific project-based studies in Spain (Macarulla et al. 2013) and Gaza Strip (Tayeh et al. 2020) found that such nonconformities as inaccurate mixing of concrete materials (CQ_3), an inaccurate water-cement ratio (CQ_4), and insufficient curing (CQ_5) are critical causes of substandard buildings. Insufficient inspection and lack of supervision are other major nonconformities in Bangladesh's residential building projects (Table 4). The importance of inspection and supervision issues are highlighted to overcome construction defects in residential buildings in South Korea (Lee et al. 2020) and Australia (Paton-Cole and Aibinu 2021). Our study also observed that multipurpose (residential and commercial) buildings have poor quality construction, which is strongly supported by Pheng and Wee's (2001) study in South Korea, Wasy's (2010) study in Saudi Arabia, and Tayeh et al.'s (2020) study in Gaza Strip.

However, the study differs from the previous work in the application of FGDMA's findings and investigating nonconformity detection times in the project execution phases. As stated in the methodology section, the strength of FGDMA is in its ability to address subjectivity, bias, or imprecision in expert-judgment-based risk evaluations, providing membership functions that can capture the gradual transition and overlap between degrees of belief (very low to extreme) in assessing nonconformities (Fayek 2020; Islam et al. 2019a), which neither RII nor averaging methods can address. For example, a risk score of 0.489 for CQ6 (premature stressing on concrete) by the RII or averaging technique indicates a moderate nonconformity level of the factor and has no further explanation. On the other hand, the defuzzified score of 0.489 for the same risk found by the FGDMA model can be defined as the triangular fuzzy function of 0.3, 0.5, and 0.7, according to Table 2. This defuzzified range means "likely chance of risk event occurring, and moderately significant in deteriorating construction quality". Moreover, the decision-maker (risk management team) can treat this risk as 0.3 (lower least likely bound in the moderate category), 0.5 (most likely), or 0.7 (upper least likely), considering the project context and the project manager's risk management attitude (i.e., optimistic, moderate, or pessimistic). Thus, the FGDMA model provides more decision-making freedom for project managers considering a particular project context.

This study also has an added value over all other similar studies in that it identifies the detection time of nonconformities, which educates the key stakeholders, including field professionals, to care about the nonconformities by developing an early nonconformity management plan. The most critical nonconformities are commonly identified in the "during construction" followed by "after construction". For instance, previous studies found cracks in concrete elements of a building linked to construction faults (material quality or workmanship). However, they did not investigate the root causes during construction. This study finds that premature concrete stressing (CQ_6) and insufficient curing (CQ_5) are some nonconforming activities identified after construction, and many others such as inaccurate mixing concrete materials (CQ_3) and an inaccurate water-cement ratio (CQ_4) identified during construction, and their priority ranking (Table 3) provide more insight into other nonconformities. Furthermore, 15 different project scenarios are presented in Table 4 against top-ranked nonconformities, which provide varying nonconformity levels for different building projects, including residential, commercial, multipurpose, and mosques; and high-rise or low-rise, private, or public buildings. These analyses provide additional detail to the stakeholders of nonconformities in diverse projects. Islam et al.'s (2021b) case studies cover three residential projects in Bangladesh, which provide nonconformity scenarios of residential but private buildings only without further details. Moreover, many other previous studies discussed in the literature review section did not present such a very detailed nonconformity scenario analysis. Thus, this study adds new knowledge for nonconformity management from the planning to execution phases of different building projects in Bangladesh and other economically similar South Asian countries.

Conclusion

The quest for optimal construction quality is becoming a continuing aspiration worldwide. Despite the advances in building materials, design and construction technologies, and the adoption of modern quality management approaches, the building construction industry is plagued with nonconformities, defects, and poor-quality construction. This research presented a study conducted in Bangladesh to identify critical nonconformity issues commonly encountered in building construction projects. The study proposed and applied a modified Fuzzy Group Decision-Making Approach (FGDMA) to proactively identify nonconformities by taking into account the likelihood, severity, and specific timing of occurrences of nonconformity instances. The outcomes of the FGDMA are also analyzed in terms of building ownership, story height, and functional type. The advantage of using the FGDMA is that it incorporates a mechanism to address subjective judgment or bias involved in traditional fuzzy decision-making through the rationalization of experts' experience level and judgment along with other project characteristics.

Several nonconformities in the project preconstruction thru construction phases are identified as significant in producing the poor building quality, leading to unsafe working and living places. Notably, premature concrete stressing, incorrect water-cement ratios, insufficient concrete compaction, lack of full-time site supervision, and stirrups in beam-column joints were identified as the critical nonconformities involved. A group risks analysis shows concrete-related factors produced by contractors to be the most severe nonconformities, followed by the monitoring and controlling group, in which the owner's responsibility is to arrange continuous full-time supervision by the consultant or project management team. A further analysis involving 15 project scenarios shows that the nonconformity level varies with the type of project owner and building size, number of stories, and functional type. Of these, government-owned low-rise (1-5 stories) multipurpose buildings are the most vulnerable structures for the occupants/users, followed by government-owned high-rise (11+ stories) residential buildings. Privately-owned low-rise multipurpose, government-owned medium-rise (6-10 stories) commercial, and privately-owned low-rise commercial buildings are also vulnerable.

This study contributes in several ways to the construction quality risk management body of knowledge. It uniquely identifies the construction nonconformities of different types of building projects by applying a fuzzy group decision-making approach with consideration of various project characteristics (project ownership, type, size, and story height). It will help owners, contractors, consultants, and other stakeholders to comply with the required quality of their projects. It is the first empirical study to comprehensively grasp the nonconformities in building construction projects, particularly in densely populated South Asian countries. The applied modified FGDMA-based construction quality risk assessment model significantly contributes to existing nonconformity assessment and management practices at building and other civil infrastructure projects, in that it considers expert weights to minimize subjective biases and accounts for risk detection time to assess nonconformities. These outcomes further guide professionals to find the dominating occurrence time of a specific nonconformity at the project planning stage. The approach can equally be applied to safety-related nonconformity analyses of buildings and other construction projects where expert judgment is the dominant mode of risk evaluation.

Recommendations

Recommendations to industry professionals

Based on the study findings, the following recommendations are made to the building industry professions:

(1) Supervision teams from both sides (contractor and owner) should be particularly careful to ensure that new concrete is sufficiently mature before being loaded – the highest-ranked critical nonconformity. Early de-shuttering creating premature stressing by its self-weight and premature loading slabs are two means of premature stressing, which can easily be avoided by suitable site supervision and strict guidelines/rules.

(2) The predominance of concrete production-related risks, with their concomitant serious consequences to the building structure, means that the field supervision team must ensure the correct mixing ratio is used in onsite concrete batching plants. The potential for increased automation or factory-made products could also be further investigated.

(3) Concrete compaction, the third most critical nonconformity, is usually carried out in Bangladesh using a manually-driven vibrator machine. The problem is the lack of knowledge and skill in handling the machine for correct compaction and lack of constructability due to the reduced space in such structural components as column and beam-column joints (Islam et al. 2021b). Thus, the design consultant needs

to check any such constructability problems before finalizing the design and working drawing, and the field supervision team must ensure correct concrete compaction during construction.

(4) Owners must arrange full-time site supervision in collaboration with the design consultant, contractor, and project management team to ensure that their building is constructed according to the design and specifications.

(5) Building construction regulatory authorities need to take special care in the case of low-rise buildings (1-5 stories) regardless of their functional types and owner, as these are identified as being more vulnerable in terms of construction quality.

Recommendations for future studies

This study is limited to the planning/design and construction stages of concrete structures of building projects. Such other parts of the construction phase as brickwork, plumbing fittings and fixtures, electrical wiring and fittings, painting and tiles fitting, and HVAC (Heating, Ventilation, and Air Condition) are not studied. Moreover, nonconformities in the operation and maintenance phase of buildings are also beyond the scope of this study. Thus, further studies are needed of these project phases to understand better the nonconformities and their detection times from a project life cycle perspective. While the fuzzy-based method can handle subjective judgment in nonconformity assessment, it does not capture any causal relationships between nonconformities. Fuzzy group decision-making combined with a structural equation modeling (Punniyamoorthy et al. 2011) or a canonical network model (Islam et al. 2019b) has the potential for identifying root causes in nonconformity assessment and analyses in building and similar construction projects in future. As a further limitation, the model's outcomes (nonconformity assessment and ranking) are not compared with other statistical or fuzzy approaches. Thus, a further study can be conducted to compare other methods (i.e., averaging or RII) and fuzzy approaches to identify the best suited model. The study can be further extended using different fuzzy membership functions such as trapezoidal and Gaussian, and their outcomes compared to justify the validation of using a particular type of membership function.

The study is also limited in selecting a panel of only six experts to revise the questionnaire for the final survey. For future studies, including more experts in the pilot study is recommended to ensure a better justification for the data obtained.

Data Availability Statement

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

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