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Unravelling Causes of Quality Failures in Building Energy Renovation Projects of Northern China: Quality Management Perspective

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Abstract: To be successful, energy renovation construction programs in northern China require both proper understanding of the causes of quality failures and effective strategies for renovating existing residential buildings for energy savings. However, surprisingly, although in recent years more attention has been focused on studying quality failures and reducing their causes, such failures still frequently occur in building energy renovation projects. In practice, the causes are not isolated, but rather, stem from complex correlations that impede high-quality performance. Due to their neglect of the causal relationships among these factors in quality failures, project coordinators have been unsuccessful in managing the quality of construction projects. Considering a network of different causes, this work reports on efforts to identify and manage the causes of quality failures in construction processes. A new understanding of the nature of these causes was achieved by considering four sources of data: literature review, opinions of experts, interpretive structural modeling (ISM), and focus groups. Our analysis shows that not only do many causes directly influence construction quality in building energy renovation projects, but also these causes interact with each other. It is noteworthy that external causes remain associated with all internal causes. Drivers of these causes are lack of experienced project managers, unauthorized changes in design documents, incomplete building information in projects, and poor onsite coordination; eliminating them enables solutions to a number of other internal causes. Finally, solutions are proposed to improve the current situation. These solutions fall into the categories of people, materials and equipment, design, and organization, based on the quality management process. The findings of this work provide valuable information for helping both policy makers and practitioners adopt effective policies and measures to manage the construction quality of building energy renovation projects. **DOI: 10.1061/(ASCE)ME.1943-5479.0000888.** © *2021 American Society of Civil Engineers.*

Author keywords: Causes; Quality failures; Quality management; Building energy renovation; Interpretive structural model (ISM).

Introduction

Energy consumption and carbon emission reduction have become worldwide issues (Shrestha and Kulkarni 2013; Cho et al. 2019). In 2010, China became the world's largest energy consumer, accounting for 19% of global energy consumption (Zhao et al. 2014). Moreover, the proportion of building energy use in total energy consumption is increasing (Qi et al. 2020). In China especially, the existing building stock is responsible for approximately one-third of the country's total energy consumption (Hong et al. 2016). The total area of existing buildings in China was about 48.6 billion m^2, nearly twice the total of existing building areas in the European Union (Li and Shui 2015). Therefore, the largest energy-saving potential is in the existing Chinese building stock. Building energy renovations can improve energy-saving efficiency and enhance the sustainability of the existing buildings. Thus, building energy renovation projects have drawn an increasing level of attention from successive Chinese governments. In particular, beginning in 2007, a large-scale effort in building energy renovation has been underway in northern China (Liu et al. 2018). The national government started to renovate existing buildings on a large scale during the 11th Five-Year Plan period (2006–2010). Moreover, 400 million m^2 of building floor area of the existing residential buildings were required to be renovated during the 12th Five-Year Plan (2011–2015). The energy-saving renovation in existing residential buildings of 1.2 billion m^2 in northern China will be completed by 2020 (Chen et al. 2013).

However, quality failures frequently occurred in these construction energy-saving renovation projects, and consequently, these efforts failed to meet established technical requirements (Qi et al. 2019). Based on previous studies, the existence of quality failures has a major adverse effect on the energy performance of buildings (Alencastro et al. 2018). Furthermore, the impact of these quality failures covers energy performance throughout the operational lifecycles of the existing buildings, which may span many years. Due to quality failures, the building U-value is 1.6 times greater than predicted (Johnston et al. 2015), and these quality failures erase the energy benefits of renovation programs (Ede 2011). In China, it is hard to achieve the goals of energy efficiency because

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of quality failures, and such failure leads to conflicts with the aims of building energy performance (Qi et al. 2019). Consequently, these projects resulted in residents' dissatisfaction and fostered a negative reputation for the building energy renovation sector (Lo 2015). Therefore, it is critical to identify and manage the causes of quality failures in construction processes to avoid quality failures and improve construction quality, and in turn, save energy.

Energy-saving renovation programs adopt the same management models as traditional construction projects, so the roles and responsibilities of the construction participants remain during the project management processes. Because building energy renovation is funded by government, the government plays an investor role in the management of energy renovation projects. Ideally, the construction participants (including construction companies, supervision companies, government, and design companies) in renovation projects should be able to collaborate in implementing five areas of management action: people, materials, equipment, design, and organization.

This paper focuses on building energy renovation projects in the Chinese context. Although slight differences exist in quality management of different countries, most models of quality management consider these five categories: people (Zhang et al. 2014b; Safapour and Kermanshachi 2019); materials (Gschoesser et al. 2012; Inyim et al. 2016); equipment (Eteifa and El-Adaway 2018; Mahamid et al. 2012); design (Wang et al. 2015, 2014; Dehghan et al. 2015; Safapour and Kermanshachi 2019); and organization (Li et al. 2012; Oppong et al. 2017; Liu and Guo 2014; Li 2014). The suggestions based on these five areas of quality management can be useful for reducing the internal causes of problems and thereby ensuring quality in global and Chinese experiences. Therefore, this paper also provides suggestions from these five perspectives, which will help concerned stakeholders to develop effective measures and improve their knowledge of managing quality.

In practice, the causes of failure are not isolated, but rather, stem from complex correlations in impeding high-quality performance (Tan et al. 2019). Due to their neglect of the causal relationships among these factors in quality failures, project coordinators have been unsuccessful in managing the quality of construction projects. Thus, it is important to gain deeper insight into the intricate relationships among the causes (Shen et al. 2016).

There is a large body of research devoted to identifying and analyzing the causes of quality failures (e.g., Hughes and Thorpe 2014; Love et al. 2010; Aiyetan 2013; Kakitahi et al. 2015; Dixit et al. 2017; Xiang et al. 2012), these previous studies, as explained in the literature review, have predominantly identified and ranked individual factors without recognizing these factors as part of a network of causes working together (Hwang et al. 2014). Hence, based on their limited understanding, they offered information on how quality is influenced by separate causes that, in reality, have interactive relationships.

Based on the aforementioned argument, the specific objectives of this paper are to: (1) identify the causes of quality failures in building energy renovations; (2) assess the relationships between causes of quality failures in building energy renovations; (3) cluster these causes based on their driving power and dependence power; and (4) provide recommendations from a management perspective.

According to previous studies (Mathiyazhagan et al. 2013; Dubey et al. 2015), the interpretive structural modeling (ISM) and matrix impact cross-reference multiplication applied to a classification (MICMAC) techniques are commonly used methods to structure and find root factors, and they have also been more recently used in other construction projects.

Therefore, these objectives are achieved by devising a mixed-method approach, that is, by combining ISM and MICMAC techniques. The ISM method is a systems analysis method to establish a hierarchy structure among causes. The MICMAC technique is employed to analyze the driving power and dependence power for each cause. The analysis serves to identify which causes are behaving as driving causes in energy renovation projects, and which are performing as dependent causes. Empirical cases selected for this paper were situated in Hohhot, the provincial capital of Inner Mongolia, in northern China. This city was chosen because it is a typical city in a building energy renovation context. Hohhot is a northern city of the heating areas in China, where the coldest month is January, with an average temperature of about −12°C. The hottest month is July, with an average temperature of about 22°C. In Hohhot, the energy-saving renovation of existing buildings started in 2008, and the administrative and technical regulations of building energy renovations issued by the national government have been applied.

Next, the notions of identification and analysis of the causes of quality failures at a project level are introduced and reviewed. This literature review serves as a background for understanding the nature of quality management of energy-saving renovation projects in China. Then, the methodology is introduced to test the validity of these causes, identify relationships among the causes affecting construction quality, and classify the causes based on their driving power and dependence power. Following that, ISM is used to map the relationship between the causes and MICMAC is used to group the causes. The results of the analyses of the relationships and grouping of causes are then presented. In the next section, there is a discussion on the causal maps and classifications. The authors' recommendations are provided based on a quality management perspective, in which arguments are made for the implementation of a renovation policy and for the roles of the stakeholders in renovation projects. Finally, findings and main contributions of this work are summarized for achieving high-quality performance in building energy renovation projects.

Literature Review

Quality, Quality Failures, and Quality Management in Construction Projects

Different concepts of quality were introduced by previous studies. According to the International Standards Organization (ISO), quality is defined as the totality of factors and characteristics of construction products that need to satisfy given needs. Munier (2012) explained quality in terms of the actions and procedures that lead to the product in such a way that the product matches or even surpasses expectations. Meanwhile, quality is also defined as meeting the customer's expectations or compliance with customer's specifications (Battikha 2003; Jha and Iyer 2006). Sim and Putuhena (2015) defined quality as "conformance with established requirements by governments." The concept of quality is also defined as meeting the predetermined requirements and specifications of a construction project (Shanmugapriya and Subramanian 2015).

Defining the success of a construction project depends on the quality of construction (Wanberg et al. 2013; John et al. 2014). Quality failures are used to describe imperfections in the building construction industry in terms such as *nonconformance, error, fault, defect, and quality deviation* (Forcada et al. 2014; Sommerville and McCosh 2006). According to Alencastro et al. (2018), quality failure is a "failing or shortcoming in the function, performance, statutory, or user requirements of a building."

In line with Qi et al. (2019), the definition of a quality failure in this paper is the nonfulfillment of the technical requirements from governments. Based on this definition, the authors carried out a series of research studies in the current Chinese context of building energy renovation projects (Qi et al. 2019). First, numerous quality failures were identified, such as cracks of roof concrete, misalignment of the waterproof roof layer, or missing rivets. Second, the authors conducted a comprehensive investigation on systematic identification and analysis of the causes, including the importance of a cause and the level of effort required to address a cause [for more details, see Qi et al. (2019)]. This paper contributes solutions for reducing the causes of quality failures through improved quality management at the project level.

In a construction project, effective quality management can reduce the possibilities of quality failures (Kuei et al. 2008; Jraisat et al. 2016). Over the past couple of decades, the concepts of quality management have evolved. This paper adopts the definition used by the previous studies (Asif et al. 2009; Niu and Fan 2015) in which *quality management* is broadly defined as an umbrella term for a number of quality improvement elements, such as quality assurance, quality control, total quality management, Six Sigma, and integrated management system. All these elements share a core focus on systematic attention to improve quality in projects (Niu and Fan 2015).

Quality Management Actions in Building Energy Renovations in China

It is important to state that most quality failures can be avoided at management level when quality management actions are dedicated and focus on detail (Kuei and Lu 2013; Brinkhoff et al. 2015). The success of quality management depends heavily on management actions, and thus proper quality management actions must be adopted (Othman and Azman 2011).

In the context of China, the quality management actions are based on previous research studies (Liu and Guo 2014; Li 2014; Wu et al. 2013). These management actions are discussed next under the four categories of people, materials and equipment, design, and organization.

People

People refers to the project managers, chief supervisors, site supervisors, and workers involved in the construction stages of renovation projects.

Project managers and chief supervisors play a critical role in construction projects (Zhang et al. 2014b). They need to enforce the key technical points, supervise quality during the construction stage, organize workers, and manage construction sites (Wang 2012). Moreover, a specific construction plan implemented by the project manager can help control the various stages of projects directly (Tang 2014). Thus, project managers, who are required to provide certification, must have rich management experience and renovation knowledge in building renovation projects (People's Republic of China 2000).

The chief supervisors employed by supervision companies have the authority to: (1) stop or delay the execution of the works or any part of the works; (2) reject any materials or equipment; (3) impose any testing or further testing of the works or materials; and (4) sign quality reports (Zhang and Yu 2016). The site supervisors are delegated to the governments, and they need to ensure management of any onsite conditions that will degrade quality and document any quality failures (Ye et al. 2014).

Local governments are responsible for checking the certifications of project managers. Local governments also educate project managers and chief supervisors regarding technical knowledge and scope of responsibility before project construction.

Workers directly affect construction quality in building energy renovation projects (Zhang et al. 2014b). They are required to gain some professional knowledge and experience before joining a construction organization (Ye et al. 2014). Project managers must provide technical education and operational skills to workers and supervise the workers' behavior (Zhang et al. 2014b).

Materials and Equipment

Quality of construction materials and equipment is the critical management factor in determining level of construction quality (Liu and Guo 2014). *Materials* refers to raw materials, auxiliary materials, semifinished products, components, and fittings, among others (Cui 2017). Meanwhile, construction machinery, construction tools, facilities, and instruments belong to the equipment category (Li 2018). Construction companies procure the materials, such as expanded polystyrene insulation (EPS), and prepare equipment (Huang et al. 2013). Before the construction stage, project managers must test the technical performance of construction materials and equipment (Shang and Pheng 2014). Officers in the government and supervisors must check the certifications of construction materials and equipment (People's Republic of China 2000). During the construction stage, project managers need to conduct evidential tests and onsite inspections, supervised by onsite supervisors (People's Republic of China 2002)

Design

Based on the site survey and original building information, design is necessary for renovation projects and construction work (Wang 2017). The designers provide a set of construction design documents, including specifications, technical drawings, and other relevant documents, which guide construction processes and materials used (People's Republic of China 2002). Design companies need first to check their own design documents completed (People's Republic of China 2002). At the construction preparation stage, local governments and supervision companies organize meetings for construction companies to check and discuss the design documents (Wang et al. 2014). During construction, if there are errors found in those design documents, any changes must be approved by the chief supervisors (People's Republic of China 2002).

Organization

In the Chinese quality management model, quality must be supervised by the internal organizations of private companies (Shang and Pheng 2014; Zou et al. 2009). For example, design companies also manage the design process to avoid quality failures caused by design mistakes. Construction companies build their own rules and quality responsibility systems to manage the quality, which include examination of materials and equipment before installation (People's Republic of China 2002), and the interactions and interrelationships between main stakeholders largely determine the quality management of the construction projects (Jraisat et al. 2016).

Quality management in building energy renovation projects involves multiple main stakeholders. Efficient cooperation among stakeholders is supported by quick and efficient communication (Wang 2012). Construction companies must provide construction information to supervision companies promptly, and supervision companies need to provide monthly progress reports on construction schedule and cost to local government.

Main Stakeholders in Quality Management in China

The performance of individual stakeholders remains essential because quality management is a function of the performance of each stakeholder (Jraisat et al. 2016). The Chinese quality management

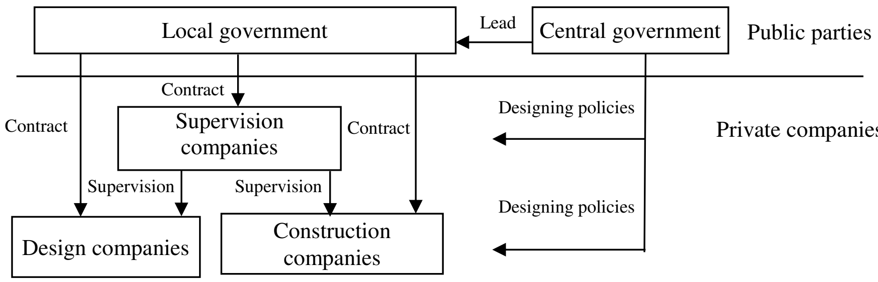

Fig. 1. Relationships among main stakeholders in renovation construction projects.

model is implemented through a mixed management system (Wu et al. 2012). The main stakeholders during quality management processes are classified into two categories, public parties and private parties (Fig. 1).

For the public party, the central government, a most critical investor, leads all management processes of stakeholders through top-down mandatory requirements for building energy renovation projects in China. Specifically, the Chinese central government is responsible for developing the overall program, assigning responsibility for renovation tasks, designing the quality supervision and administration system of construction projects, and devising the evaluation method for the program (Guo et al. 2016).

Local governments (including provincial governments, municipal governments, and district governments) are responsible for implementing renovation projects to align with central government's policy, organizing the renovation projects locally (Lu et al. 2014). The local governments find private companies through tendering, and contract out the tasks of supervision and construction to these private companies. Also, local governments delegate supervision companies to supervise construction (People's Republic of China 2000).

On the other hand, private parties are companies that are usually composed of construction companies, supervision companies, and design companies. The task of construction companies is to guarantee renovation construction to achieve goals of cost, time, quality, safety, environment, and others. The construction company is a direct participant during the construction process, when the activities are the most complicated and greatly impact construction quality. In particular, construction companies prepare the necessary resources for construction (workers, materials, and machines) and provide the construction schedule and information. Construction companies are required to test the quality of the materials and machines, doing evidential tests and onsite inspections. Construction companies are also responsible for checking design documents within construction processes.

Supervision companies assist local governments in managing construction quality. The local governments and supervision companies oversee the work processes of design companies and construction companies. Supervisory tasks include plan approval, site inspection, evidential tests, and final check before delivery of renovation projects. Supervisors must check key procedures by onsite inspection; otherwise, construction procedures cannot continue.

Design companies are responsible for checking the original documents of the existing buildings, conducting onsite surveys, and providing design documents.

ISM Method and MICMAC Technique

To gain greater insight, the ISM method and MICMAC technology were adopted to develop a structural model of these critical factors.

ISM is an approach for identifying and summarizing relationships between causes (Shi et al. 2016). This methodology can be used for understanding the complex relationships among several variables defined for a problem. These relationships are either individually or group interdependent. In other words, ISM is used for examining the effect of each cause on others as well as for measuring relationships to achieve the objectives of the research. Valmohammadi and Dashti (2016) found that ISM is an effective tool to investigate the interrelationships among specific causes.

This method has many applications, including identification and analysis of internal relationships between the barriers to implementation of green supply chain management (Mathiyazhagan et al. 2013; Al Zaabi et al. 2013); identification of the critical factors for green supply chain management (Mathiyazhagan and Noorul Haq 2013); study of the integration of independent theories for a sustainable manufacturing framework (Dubey et al. 2015); identification and prioritization of risk sources in a virtual organization (Alawamleh and Popplewell 2011); analysis of the interactive networks of the risks in green building projects (Yang et al. 2016); identification and analysis of the internal relationships between supply chain management enablers (Gorane and Kant 2013); identification of the root barriers to the development of renewable resources (Rezaee et al. 2019); and prioritization and categorization of the principles for total quality management implementation (Mehta et al. 2014).

The theoretical foundation of ISM is systems science, while most other multivariate methods are based on statistical analyses (Shi et al. 2016). There are other multivariate analysis methods to build the relationship models, such as structural equation model (Tarhini et al. 2014; Qureshi and Kang 2015), Bayesian network model (Leu and Chang 2013; Zhang et al. 2014a), and fault tree analysis (Aljassmi and Han 2014; Cheng and Li 2015). Compared with these methods, ISM does not have strict statistical constraints on the sample size. Furthermore, the topic of quality failures is sensitive, and a database of quality failures in construction projects is lacking. Therefore, it is difficult to find a sufficient sample of valid respondents for data surveys. However, application of ISM can overcome these limitations (Shen et al. 2016). Commonly, the ISM technique suggests the use of expert opinions to create the contextual relationship among the causes (Kumar et al. 2013). In using the ISM method, emphasis is given to the quality, rather than quantity, of respondents. Therefore, ISM was more appropriate for this work compared with other methods.

MICMAC is often used to carry out the classification of causes on driving power and dependence power (Shen et al. 2016). This method was developed by Duperrin and Godet (1973) to study the diffusion of impacts through reaction paths and loops for developing hierarchies among causes. Also, MICMAC is a standard method to identify and analyze the factors in a complex system.

Research on Causes of Quality Failures in Construction

Previous studies highlighted the causes affecting the quality of construction, and each study has contributed to identifying some causes. There are various causes of quality failures in construction projects, which can be either internal or external to the projects (Balasubramanian 2012). Internal causes originate from within the project, and can be solved through quality management at the project level. Therefore, this paper focuses on the internal causes and focuses on the causes in view of quality management.

This study included a global search and examination of relevant scholarly literature. Given the vast number of articles on the causes of quality failures in general, to develop our initial list of identified causes, we build on 18 articles (Tables 1 and 2) in which the authors present the causes of quality failures. Based on overviews of the literature in the field, the 16 cases provide explanations for the failures of construction quality.

However, the process of identifying the causes has some limitations. For example, the causes of quality failures in new building projects are also identified because of the high correlation between renovation projects and new building projects. To conduct a comprehensive review of the causes of quality failures of building energy renovation projects in the Chinese context, interviews with experts were organized to assist in obtaining the final list of the causes.

Review of Internal Causes

Various causes of quality failures are classified into internal and external causes according to whether they stem from inside or outside the projects (Page 2010). In construction projects, quality management has increased in importance as a means for controlling the internal causes, such as poor labor skills (Adenuga 2013; Enshassi et al. 2017), inferior materials (Janipha and Ismail 2013), and lack of clear instructions given by site supervisors (Jingmond and Ågren 2015), and others. These internal weaknesses could be reduced or completely avoided through better attention to quality management at the project site level.

Through a literature survey, we clarified various kinds of causes that degrade quality performance. Most of the internal causes are associated with lack of operational workforce (Jingmond and Ågren 2015), incomplete construction site survey (Aiyetan 2013), lack of construction plan (Aiyetan 2013; Dixit et al. 2017), and wrong checking procedures (Ye et al. 2014; Love et al. 2010; Hughes and Thorpe 2014; Oyedele et al. 2015).

Chong and Low (2005) investigated and identified that the causes of quality failures are manifold. Aljassmi and Han (2014) found the majority of quality failures were related to lack of workers' skills. The findings of Aljassmi and Han are very much in line with those of Chong and Low (2005). In addition to these, Forcada et al. (2014, 2012) carried out a series of research studies in the current construction market. They found that poor craft skills, nonspecified materials, or products are likely to cause quality failures. In an investigation of building construction projects, Hughes and Thorpe (2014) identified causes of quality failures as poor supervisor competency and incomplete drawings. Love et al. (2010) summarized the main causes as ineffective information technologies, lack of clear working procedures, and insufficient changes.

Dixit et al. (2017) noted that the causes of failure are poor site coordination, lack of competency, fragmented supply chain, lack

Table 1. List of identified internal causes from a literature review

Causes	Description of causes	References
Poor operational skilled workers	Operational skilled labor in construction processes lacking	Jingmond and Ågren (2015), Schultz et al. (2015), Oyedele et al. (2015), Aljassmi and Han (2014), Forcada et al. (2012, 2014), Chong and Low (2005), Aiyetan (2013), Ashokkumar (2014), and Yong (2016)
Poor checking procedures of site supervisors	Onsite supervision and feedback processes cause failures	Ye et al. (2014), Aiyetan (2013), Love et al. (2010), Hughes and Thorpe (2014), and Oyedele et al. (2015)
Use of poor materials	The quality of construction materials is nonspecified	Ye et al. (2014), Aiyetan (2013), Oyedele et al. (2015), and Janipha and Ismail (2013)
Inadequate equipment performance	Mechanical equipment is nonspecified	Jingmond and Ågren (2015) and Hughes and Thorpe (2014)
Inaccurate design work	There are mistakes and discrepancies in design documentation	Aiyetan (2013), Jingmond and Ågren (2015), Hughes and Thorpe (2014), and Ahzahar et al. (2011)
Incomplete construction site survey	Designers or construction companies ignore or produce a deficient site survey	Aiyetan (2013)
Unauthorized changes in design documents	Construction companies change design documentation without the agreement of designers	Love et al. (2010)
Incomplete building information in projects	Technical information or original documentation is missing	Ye et al. (2014), Aiyetan (2013), Jingmond and Ågren (2015), Kakitahi et al. (2015), Love et al. (2010), and Hughes and Thorpe (2014)
Unsettled plan or lack of construction plan	Construction companies ignore or make deficient construction planning	Aiyetan (2013) and Dixit et al. (2017)
Poor site management	Workers, material, and equipment on site are not strictly managed and controlled	Aiyetan (2013) and Dixit et al. (2017)
Poor onsite coordination	The speed of communication onsite among main stakeholders is low	Aiyetan (2013), Schultz et al. (2015), and Dixit et al. (2017)

Table 2. List of identified external causes of quality failures (from literature review)

Causes	Descriptions	References
Complex onsite environment	Site conditions are limited, such as narrow construction spaces	Ye et al. (2014) and Hughes and Thorpe (2014)
Fraud of construction companies	Construction companies cut corners by cheating in work	Schultz et al. (2015) and Enshassi et al. (2017)
Working under high cost pressure	Budget and funding for renovation projects are insufficient	Aiyetan (2013), Schultz et al. (2015), Kakitahi et al. (2015), and Enshassi et al. (2017)
Working under high time pressure	Design time and construction time are both urgent	Aiyetan (2013), Schultz et al. (2015), and Enshassi et al. (2017)
Adverse natural conditions	The natural environment presents interferences such as low temperature, inadequate solar energy, rain interference	Ye et al. (2014)

of commitment, improper construction planning, and inefficient site management. Meanwhile, Aiyetan (2013) investigated the causes of quality failures and developed suggestions for management to improve quality in the areas of poor communication, inexperience of personnel, and nonspecified concrete. Oyedele et al. (2015) identified and ranked five most important causes: poor quality of materials, low level of skill and labor experience, inadequate inspection and testing, poor site installation procedures, and lack of quality assurance. Kakitahi et al. (2015) cited inadequate communication as a major factor in quality failures. Based on an interview and questionnaire survey, Ye et al. (2014) investigated and prioritized 39 causes of quality failures, the top three being unclear project process management, poor quality of construction technology, and use of inferior construction materials.

This study collected 11 internal causes from the international literature. Table 1 shows the sources and descriptions of these internal causes. To identify representative causes affecting the quality of renovation construction in the Chinese context, an interview survey was conducted.

Review of External Causes

The origin of some causes is outside the projects, such as the regulatory environment, prevalent culture, and natural environment (Table 2). Therefore, quality management at a project level cannot prevent the effects of these external causes. From a global view, Schultz et al. (2015) identified two significant external influences on quality failures: planning of budgetary conditions and time schedules. Kakitahi et al. (2015) identified graft and dishonesty of private companies as external causes of quality failures. Similarly, Enshassi et al. (2017) studied the three external causes of quality failures including fraud, competitive pressure, and schedule pressure.

In building energy renovation projects in the Chinese context, a government-led approach is a standard mode. In the government-led model, top-down mandatory requirements for renovating technology are set at the central government. As the unique features in building renovation projects, strict legal energy targets and financial support from the government can exacerbate the pressure of working under strict and cost and time demands in China.

Methodology

As described in Fig. 2, the interrelationships of causes and their classifications are studied by three methods: ISM, MICMAC, technique, and focus groups. The step-by-step procedure involved in the ISM method and MICMAC technique is as follows. The schematic approach of the present study is shown in Fig. 3.

Step 1: The causes of quality failures considered for the building energy renovations are identified by literature review and interviews with experts.

Step 2: A contextual relationship is defined between the identified causes, considering each pair of causes as well as expert opinions based on semistructured interviews. The experts are asked about each pair of causes to make comments about whether there is a relationship between the two causes or not. Warfield (1974) defined the contextual relationship as conceptual links between the system components matched with the system objectives.

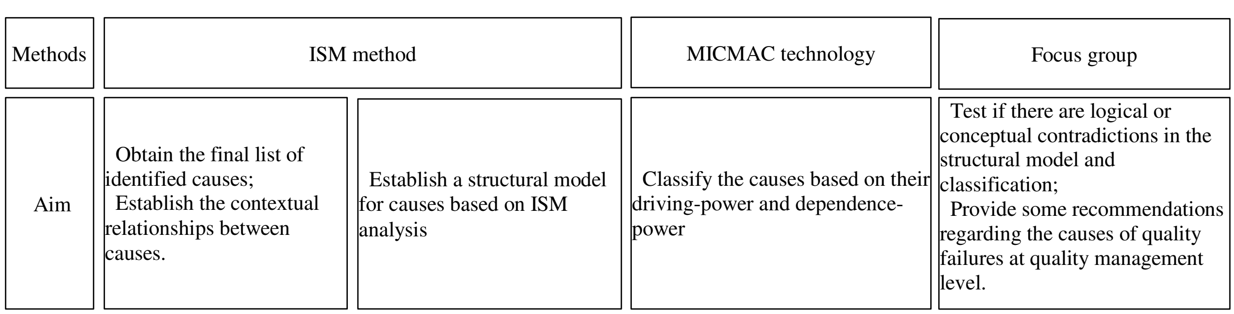

Fig. 2. Research methodology.

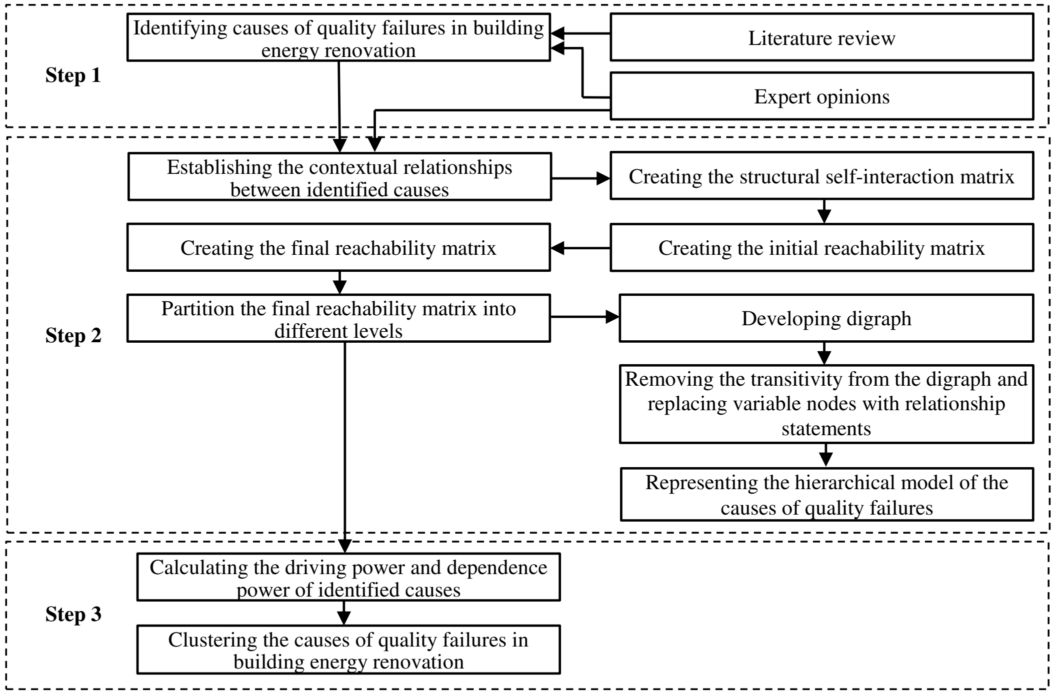

Fig. 3. Flow diagram to identify and analyze the internal relationships of the causes of quality failure for building energy renovation. (Modified from Rezaee et al. 2019.)

The structural self-interaction matrix (SSIM) is a binary matrix and indicates pairwise relationships among the factors of the system under consideration. Therefore, SSIM was developed for the causes to show the paired relationships between them. An initial reachability matrix contained direct relationships and is changed from SSIM.

The initial reachability matrix is changed to the final reachability matrix, which is assessed for transitivity as an underlying assumption in ISM. The direct and indirect relationships are considered: If cause A is related to cause B and cause B is related to cause C, then cause A is necessarily related to cause C.

The final reachability matrix is partitioned into different levels using reachability and antecedent sets. A directed graph is drawn, and the transitivity relationships are removed. The resultant digraph is created to an ISM.

Step 3: The MICMAC technique is used to analyze the driving and dependence powers of cause. The MICMAC principle is based on the multiplication properties of matrices (Mathiyazhagan et al. 2013). The following section illustrates the details of these steps in ISM and MICMAC.

Identifying Causes of Quality Failures

In international scholarly literature (Table 1), various causes affecting the quality of construction projects were investigated, which were provided for reference to elicit the opinions of experts. Interviews with experts were organized to identify the causes in the Chinese context. It was important to ensure that the interviewees were knowledgeable about both building energy renovations and quality management. To find effective interviewees, all experts were selected based on their resumés, considering their experience in renovation projects. They had sufficient knowledge of building energy renovations and more than 8 years of quality management experience. It was considered that their opinions are effective for analysis. In using the ISM method, the emphasis is not given to the number of experts, so the quantity of experts does not have a very large influence (Shen et al. 2016). In total, 22 experts were invited, and their opinions were collected. Based on the opinions of these experts, the final list of causes of quality failures was obtained, and the contextual relationships between causes were established. The profiles of the interviewees are in Table 3.

The experts' group consisted of 10 project managers working in construction companies, 5 supervisors from the supervision companies, 2 designers, and 5 government officials in the fields of building energy renovation. Their opinions have been used in two sections to finalize a list of causes and determine causal relationships among these causes.

In this work, the opinions of different experts had the same weight. When disagreements among experts existed, these experts were contacted for further discussion. After two rounds of discussion, the experts reached agreement for all causes and their relationships. The 18 causes are listed in Table 10 based on the literature and discussions with 22 experts. From the literature, 16 causes were taken, and after discussion with the experts, two of these causes were included in the study.

In building energy renovation projects in the Chinese context, project managers' lack of management experience and renovation knowledge may result in quality failures. Additionally, due to the wrong flow of construction processes, some quality failures may occur, such as concrete cracks. Consequently, 18 causes are considered (Table 10).

Establishing Structure Model for Causes of Quality Failures

Internal causes can be avoided or reduced through better project management, and mitigating these internal causes can sharply reduce quality failures through improvements in management

Table 3. Profile of experts and interview method

Group	No.	Profile	Interview method (first round, second round)
Construction company (10)	1	Project manager	Face to face, face to face
	2	Project manager	Face to face, face to face
	3	Project manager	Face to face, e-mail
	4	Project manager	Face to face, phone
	5	Project manager	Face to face, face to face
	6	Project manager with senior engineer certification	Face to face, phone
	7	Project manager with senior engineer certification	Face to face, face to face
	8	Project manager with senior engineer certification	Face to face, face to face
	9	Project manager with senior engineer certification	Face to face, face to face
	10	Project manager with senior engineer certification	Face to face, phone
Supervision company (5)	11	Onsite supervisor	Face to face, phone
	12	Onsite supervisor	Face to face, face to face
	13	Chief supervisor	Face to face, face to face
	14	Chief supervisor	Face to face, face to face
	15	Chief supervisor	Face to face, e-mail
Design company (2)	16	Designer	Face to face, phone
	17	Senior designer	Face to face, phone
Government (5)	18	Officer in the provincial government	Face to face, e-mail
	19	Officer in the municipal government	Face to face, face to face
	20	Officer in the municipal government	Face to face, phone
	21	Officer in the municipal government	Face to face, face to face
	22	Officer in the district government	Face to face, face to face

procedures (Qi et al. 2020). Thus, the 13 internal causes for analyzing the management of energy renovation projects are discussed in this section.

To establish the structure of the internal causes, the level partitions between causes need to be identified first. The results of identifying the level partitions of the causes are shown in Table 7, including the columns of reachability set, antecedent set, intersection set, and level. The process of partition analysis is as follows.

1. Final reachability matrix

   Based on experts' views and using symbols V, A, X, and O, the contextual relationships are defined between any two causes (i and j). The following are the four symbols used to denote the direction of the relationship between the causes (i and j):

   V: Cause i will help achieve cause j;
   A: Cause j will help achieve cause i;
   X: Cause i and j will help achieve each other; and
   O: Cause i and cause j are unrelated.

   The resulting matrix is the SSIM (Table 4). Then, the SSIM format is initially converted into the initial reachability matrix format by transforming the values of each cell of the SSIM into binary digits (i.e., ones and zeros) in the initial reachability matrix, according to the following rules:

- If, in SSIM, the entry in the cell (i, j) is V, then in the initial reachability matrix, the cell (i, j) becomes 1, and the cell (j, i) entry becomes 0.
- If, in SSIM, the entry in the cell (i, j) is A, then in the initial reachability matrix, the cell (i, j) becomes 0, and the cell (j, i) entry becomes 1.
- If, in SSIM, the entry in the cell (i, j) is X, then in the initial reachability matrix, the entries in both the cell (i, j) and (j, i) become 1.
- If, in SSIM, the entry in the cell (i, j) is O, then in the initial reachability matrix, the entries in both the cell (i, j) and (j, i) become 0.

The initial reachability matrix only reflects direct relationships (see Appendix). On the other hand, the final reachability matrix shows indirect relationships and direct relationships. Thus, in the final reachability matrix, if cause 1 influences cause 2, and cause 2 influences cause 3, cause 1 necessarily influences

Table 4. Structural self-interaction matrix

Causes	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Poor operational skilled workers	—	A	O	O	O	O	O	O	A	V	O	O	O
2. Lack of experienced project managers		—	O	V	V	O	V	O	X	V	V	V	V
3. Poor checking procedures of site supervisors			—	V	V	O	O	O	A	O	O	O	O
4. Use of poor materials				—	O	O	O	O	O	A	O	A	O
5. Inadequate equipment performance					—	O	O	O	O	O	A	A	O
6. Inaccurate design work						—	A	O	A	O	O	O	O
7. Incomplete construction site survey							—	O	A	O	V	O	O
8. Unauthorized changes in design documents								—	O	O	O	O	X
9. Incomplete building information in projects									—	V	V	O	X
10. Wrong construction flow										—	A	A	O
11. Unsettled plan or lack of construction plan											—	V	O
12. Poor site management												—	O
13. Poor onsite coordination													—

Table 5. Final reachability matrix

Causes	1	2	3	4	5	6	7	8	9	10	11	12	13	Driving power	Rank
1	1	0	0	1	0	0	0	0	0	1	0	0	0	3	5
2	1	1	1	1	1	1	1	1	1	1	1	1	1	13	1
3	0	0	1	1	1	0	0	0	0	0	0	0	0	3	5
4	0	0	0	1	0	0	0	0	0	0	0	0	0	1	7
5	0	0	0	0	1	0	0	0	0	0	0	0	0	1	7
6	0	0	0	0	0	1	0	0	0	0	0	0	0	1	7
7	0	0	0	1	1	1	1	0	0	1	1	1	0	7	2
8	1	1	1	1	1	1	1	1	1	1	1	1	1	13	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	13	1
10	0	0	0	1	0	0	0	0	0	1	0	0	0	2	6
11	0	0	0	1	1	0	0	0	0	1	1	1	0	5	3
12	0	0	0	1	1	0	0	0	0	1	0	1	0	4	4
13	1	1	1	1	1	1	1	1	1	1	1	1	1	13	1
Dependence power	5	4	5	11	9	6	5	4	4	9	6	7	4	—	—
Rank	5	6	5	1	2	4	5	6	6	2	4	3	6	—	—

cause 3. The final reachability matrix is obtained by incorporating the transitivity (Table 5). The reachability and antecedent sets are obtained from the final reachability matrix.

2. Reachability set and antecedent set

The reachability and antecedent sets for each cause are obtained from the final reachability matrix. The reachability set for a particular cause consists of the cause itself and the other cause to which it may reach, called reachable causes. A concerned cause's reachable causes are those causes with the value of 1 in the row corresponding to the concerned cause in the final reachability matrix in Table 5. For example, concerning cause 1, its reachable causes include causes 4 and 10, so the reachability set for cause 1 consists of causes 1, 4, and 10. As a result, the reachability sets for all causes can be obtained, as shown in the Reachability set column in Table 6.

The antecedent set for a particular cause consists of the cause itself and the other causes that may reach to it, called reached causes. Reached causes of a concerned cause are those causes with the value of 1 in the column corresponding to the concerned cause in the final reachability matrix in Table 5. For example, concerning cause 1, its reached causes include causes 2, 8, 9, and 13, so the antecedent set for cause 1 consists of causes 1, 2, 8, 9, and 13. As a result, the antecedent sets for all causes are obtained, as shown in the Antecedent set column, in Table 6.

3. Intersection set

When the reachability and antecedent sets exist for each cause, the causes' partitioning is conducted. Subsequently, the intersection set for a particular cause consists of the causes in its reachability set and antecedent set. In other words, the intersection set is defined as an overlap of reachability and antecedent sets. For example, the intersection set for cause 1 consists of cause 1 in Table 6. As a result, the intersection sets for all causes are obtained, as shown in the Intersection set column in Table 6.

4. Identification of level partition between causes

The cause of which the reachability sets equal their intersection sets are the same is the top-level cause. For example, as seen in Table 6, causes 4, 5, and 6 have the same reachability set and intersection set. These three causes are partitioned as top-level. According to the principle of ISM, eliminating these causes (4, 5, and 6) and repeating the same procedure for other causes creates different cause levels (Table 7). A similar calculation process is conducted to identify other causes as other levels. In this paper, the partition procedure of the identified causes is performed at six iterations, shown in Table 7.

Table 8 presents the final results obtained from six iterations. The hierarchical levels of all causes are built, and both direct and indirect interrelationships among the causes are determined from the reachability set. Thus, the graph is generated from the hierarchical levels and the reachability set by the vertices and edges (Jharkharia and Shankar 2005). Then, the indirect links among the causes are removed to obtain the interpretive structural model.

The relationships of the causes of the quality failures in building energy renovation are shown by arrows in Fig. 4 as an ISM model.

Table 6. Level partition: Iteration 1

No.	Reachability set	Antecedent set	Intersection set	Level
1	1,4,10	1,2,8,9,13	1	
2	1–13	2,8,9,13	2,8,9,13	
3	2–5	2,3,8,9,13	2,3	
4	4	1–4,7–13	4	1
5	5	2,3,5,7–9,11–13	5	1
6	6	2,6–9,13	6	1
7	4–7,10–12	2,7–9,13	7	
8	1–13	2,8,9,13	2,8,9,13	
9	1–13	2,8,9,13	2,8,9,13	
10	4,10	1,2,7–13	10	
11	4,5,10–12	2,7–9,11,13	11	
12	4,5,10,12	2,7–9,11–13	12	
13	1–13	2,8,9,13	2,8,9,13	

Table 7. Level partition: Iterations 1–6

No.	Reachability set	Antecedent set	Intersection set	Levels
1	1,4,10	1,2,8,9,13	1	3
2	1–13	2,8,9,13	2,8,9,13	6
3	2–5	2,3,8,9,13	2,3	2
4	4	1–4,7–13	4	1
5	5	2,3,5,7–9,11–13	5	1
6	6	2,6–9,13	6	1
7	4–7,10–12	2,7–9,13	7	5
8	1–13	2,8,9,13	2,8,9,13	6
9	1–13	2,8,9,13	2,8,9,13	6
10	4,10	1,2,7–13	10	2
11	4,5,10–12	2,7–9,11,13	11	4
12	4,5,10,12	2,7–9,11–13	12	3
13	1–13	2,8,9,13	2,8,9,13	6

Table 8. Level partitions for causes

No.	Causes	Level
4	Use of poor materials	1
5	Inadequate equipment performance	
6	Inaccurate design work	
3	Poor checking procedures of site supervisors	2
10	Wrong construction flow	
1	Poor operational skilled workers	3
12	Poor site management	
11	Unsettled plan or lack of construction plan	4
7	Incomplete construction site survey	5
2	Lack of experienced project managers	6
9	Incomplete building information in projects	
8	Unauthorized changes in design documents	
13	Poor onsite coordination	

Analyzing Causes' Driving Power and Dependence Power

In general, a cause with a higher dependence power indicates that several other causes should be addressed before that cause can be eliminated. A cause with a higher driving power means that its elimination enables several other causes to be solved (Attri et al. 2013; Tan et al. 2019). Following the classification adopted by previous researchers (Mandal and Deshmukh 1994), the causes are divided into four groups: (1) autonomous variables where both driving and dependence powers are low; (2) dependent variables where driving power is low, but dependence power is high; (3) driver variables where driving power is high, but dependence power is low; and (4) linkage variables where both driving and dependence powers are high.

For analyzing and categorizing the driving and dependence powers of causes, MICMAC analysis was used. In the final reachability matrix (Table 5), the driving and dependence powers of each cause are provided along with the respective cause's rank. Furthermore, the diagram of driver and dependence power obtained from MICMAC offers insight into the relative importance and interdependencies among these causes.

Driving power is the number of causes influenced by a cause. On the other hand, dependence power is the number of causes influencing one cause and making it reachable. Then, causes are divided into four clusters, including autonomous, dependent, linkage, and independent.

Each cause is categorized into one of the four clusters of MICMAC (Fig. 5).

Validating Causes' Map and Classification

The validity and reliability of the aforementioned analyses were tested. A focus group was used to verify whether the implications of the structural model and cause classification were consistent with the current situation. Based on the professional knowledge of the participants, the logic and integrity of data results were examined, and some recommendations were provided.

In this study, a focus group session was undertaken in Hohhot. Hohhot is a typical northern China city where the coldest month has an average temperature of about −12°C and the hottest month has an average temperature of about 22°C. Hohhot has implemented energy renovation projects for its existing buildings since 2008. A focus group was selected rather than using other data collection methods because focus groups can generate information on the collective views of the selected participants. Thus, this method is useful for enriching our understanding of experts' experiences and knowledge regarding the causes of quality failures.

According to Yu et al. (2018), the characteristics of participants were: (1) having efficient knowledge regarding building energy renovation projects and more than 8 years of renovation experience; (2) having undertaken quality management tasks in building energy renovation projects; and (3) holding a management position (i.e., project managers, construction supervisors, officers in government, designers) in project teams.

In the focus group, 10 participants served as representatives of all departments at management level, consisting of three officers

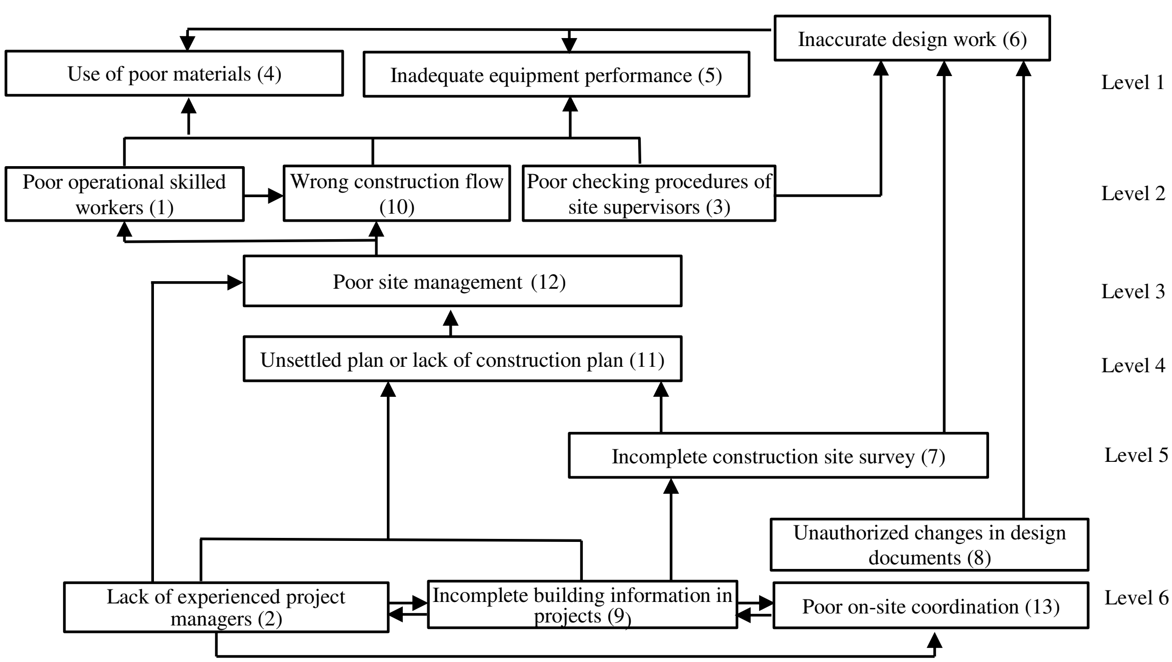

Fig. 4. ISM model of causes of quality failures.

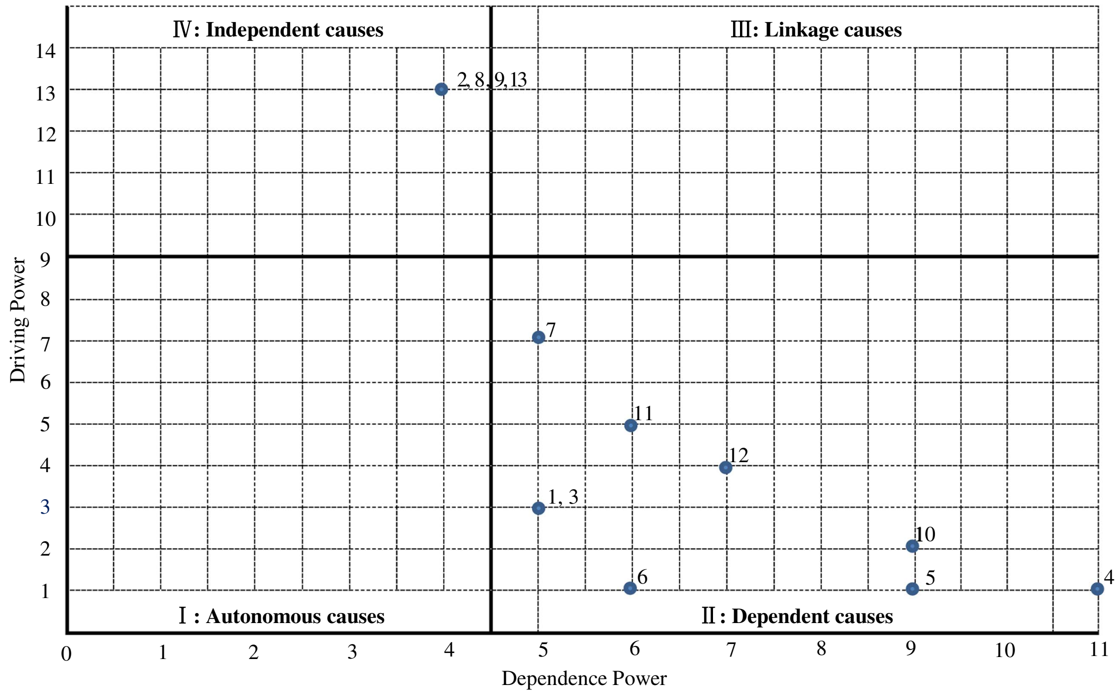

Fig. 5. Clustering the causes of construction quality.

from government, two project managers, two technical engineers, two supervisors from the supervision company, and one designer. They have been engaged in building energy renovations and met the aforementioned principles (details are given in Table 9). The goals of the focus group were to (1) test to verify if there are logical or conceptual contradictions in the structural model and classification and (2) provide some recommendations regarding the causes of quality failures. All expert participants in the focus group were considered able to provide valuable information to achieve the survey goals, and they were invited to test the structural model and classification. Meanwhile, the context of energy renovation in existing Chinese buildings should be considered.

The focus group started with introducing the objectives and definitions of the causes. Prior to the discussion, each participant was asked to review the relationships between the causes of quality failures and their groups. Interactive thematic discussions followed. In terms of the relationships between causes, each participant was encouraged to offer ideas and recommendations for these causes. Consequently, the results from the ISM method and MICMAC technique were supported and validated by the focus group.

Table 9. Number and profile of focus group participants

Group	No.	Profile
Construction company (4)	1	Project manager
	2	Project manager
	3	Technical engineer
	4	Technical engineer
Supervision company (2)	5	Onsite supervisor
	6	Chief supervisor
Design company (1)	7	Designer
Government (3)	8	Officer in municipal government
	9	Officer in municipal government
	10	Officer in district government

Results

Causes of Quality Failures

Table 10 presents the 18 causes identified from the literature review and experts' interviews. A focus group classified the internal causes into four management perspectives: people, materials and equipment, design, and organization.

Table 10. Identified causes from literature review and interviews

Origin	Categories	No.	Causes
Internal	Man	1	Poor operational skilled workers
		2	Lack of experienced project managers
		3	Poor checking procedures of site supervisors
	Material and equipment	4	Use of poor materials
		5	Inadequate equipment performance
	Design	6	Inaccurate design work
		7	Incomplete construction site survey
		8	Unauthorized changes in design documents
	Organization	9	Incomplete building information in projects
		10	Wrong construction flow
		11	Unsettled plan or lack of construction plan
		12	Poor site management
		13	Poor onsite coordination
External		14	Complex onsite environment
		15	Fraud of construction companies
		16	Working under high cost pressure
		17	Working under high time pressure
		18	Adverse natural conditions

Structural Model for Internal Causes of Quality Failures Based on ISM Analysis

According to Fig. 4, all 13 internal causes are summarized in six levels. Four causes appear at the root level, as follows: Lack of experienced project managers (2); Unauthorized changes in design documents (8); Incomplete building information in projects (9); and Poor onsite coordination (13). These are the most dominant causes in hindering high-quality performance in building renovation projects. Also, Incomplete building information in projects (9) is cited as a cause of incomplete construction site survey (7). A construction site survey is a fundamental process in the implementation of building renovation projects. Thus, Inaccurate design work (6) and Unsettled plan or lack of construction plan (11) are caused by incomplete construction site survey (13) related to design companies and construction companies. Poor construction plan (11) and Lack of experienced project managers (2) lead to Poor site management (12), which is one of the causes of wrong construction flow (10). Because the majority of construction workers have education levels at junior middle school or below, site management may not be understood by workers, causing an inadequate operational workforce in building energy renovation projects. Use of poor material (4) and Inadequate equipment performance (5) are causes of quality failures, which are directly connected to Poor operational skilled workers (1), Inadequate checking procedures of site supervisors (3), Inaccurate design work (6), and Wrong construction flow (10).

Driving and Dependence Powers of Causes

According to Fig. 5, the first cluster includes autonomous causes with low driving and dependence power. Poor operational skilled worker (1), Poor checking procedures of site supervisors (3), Use of poor materials (4), Inadequate equipment performance (5), Inaccurate design work (6), Incomplete construction site survey (7), Wrong construction flow (10), Unsettled plan or lack of construction plan (11) and Poor site management (12) are dependent causes with low driving power but high dependence power in the second cluster. No cause is situated in the third cluster, which includes linkage causes with high driving power and dependence power. Lack of experienced project managers (2), Unauthorized changes in design documents (8), Incomplete building information in projects (9), and Poor onsite coordination (13) are independent causes with high driving power but low dependence power in the fourth cluster. Additionally, a cause with high driving power is defined as the primary cause and is placed on the linkage-cause cluster or independent-cause cluster. According to the results, causes 2, 8, 9, and 13 are the major ones due to their high driving power.

In the labor category, there are three causes: Poor operational skilled workers (1), Lack of experienced project managers (2), and Poor checking procedures of site supervisors (3). The highest level of the structural model contains Lack of experienced project managers (2). Poor checking procedures of site supervisors (3) is at level 2, and it is listed as dependent causes. Poor operational skilled workers (1) also has low driving power and high dependence power. In the material and equipment category, Use of poor materials (4) and Inadequate equipment performance (5) are at Level 1, which are driven by causes at higher levels. The design category has three causes. Unauthorized changes in design documents (8) has strong driving power. Inaccurate design work (6) and Incomplete construction site survey (7) are dependent causes. Five causes come under the organizational category. Incomplete building information in projects (9) and Poor onsite coordination (13) are considered priorities, and have strong driving power. Five causes come under the organizational category. Incomplete building information in projects (9) and Poor onsite coordination (13) are considered priorities, and have strong driving power. Dependent causes have weak driving power but strong dependence power, including Wrong construction flow (10), Unsettled plan or lack of construction plan (11), and Poor site management (12).

Discussion

Interrelationship among Internal Causes

It should be restated that the causes of quality failures do not occur in isolation but are interrelated. The ISM model diagram (Fig. 4) shows the interaction among the causes, and maps several processes feeding forward to the occurrence of the causes. Lack of experienced project managers, Unauthorized changes in design documents, Inefficient information transfer, and Poor onsite coordination are very significant causes because they form the base of the ISM hierarchy. Not only do these four causes negatively impact construction quality in building energy renovation projects, but they also influence other causes. On the other hand, causes including Use of poor materials, Inadequate equipment performance, and Inaccurate design work are placed on the first level, and are known as the most direct causes. Other causes may impact these three causes as the hindrance of high construction quality.

This finding is in line with previous studies. Organizational problems are also identified as the primary root cause of quality failures (Jingmond and Ågren 2015). In contrast, Aljassmi and Han (2012) pointed out that inferior construction materials, workers' competence limitations, and inadequate supervision are priority considerations for reducing quality failures.

Clearly, then, the findings of this paper provide valuable information for understanding the pathways of the interactions among different causes of quality failures. Considering the roles of various causes, the following solutions for reducing quality failures have emerged. These solutions are provided in the context of quality management. They are presented next under the categories of people, materials and equipment, design, and organization.

People

Project managers play a vital role in driving the entire project. The results indicate that project managers can significantly affect other causes of quality failures in China. Taking two Asian counterparts, Malaysia and Iran, as examples, the major contributor to quality failures is that project managers are not able to properly manage construction projects (Yaman et al. 2015; Ghoddousi and Hosseini 2012).

According to Hwang and Ng (2013), the project manager needs to fulfill not only the traditional roles of management and organization, but also must manage the project in an efficient and effective manner with respect to sustainability. Recommendations listed subsequently delineate project managers' responsibilities in building energy renovation projects. Project managers should be responsible for the following functions:

- defining general quality management practices,
- managing onsite construction,
- verifying the efficiency and effectiveness of quality management, and
- informing the supervisors and local governments of quality failures.

The advice for local government is to increase investment to educate project managers on their responsibilities, and organize meetings at which they can share their experiences.

The cause, Poor checking procedures of site supervisors, has relatively closer relationships with each worker and with the presiding government. The site supervisor has a close working relationship with the deputy government and a line with them directly on all matters concerning quality. In line with previous findings, supervisors directly interact with workers most intensively and frequently (Fang et al. 2015). There was no work procedure to check each batch of material and equipment, for example, concrete, windows, and EPS. Attar et al. (2012) illustrated that the incompetent supervisor is a top factor affecting construction projects. In Poland, Głuszak and Leśniak (2015) also found that poor supervision of construction work is prevalent.

Key work checklists are designed by the chief supervisors based on the technical requirements of the government. However, it was found that project managers and site supervisors were not supporting the use of the key work checklists because completing these checklists slows down their work. Additionally, without proper supervision over workers' construction behavior, workers may ignore some construction steps in an effort to speed up the work. Moreover, site supervisors do not check for themselves but call for other site staff to conduct inspections.

To resolve these issues, local governments would check the reports upon specific supervision flows from onsite supervisors and build a systematic and practical checklist system to avoid missing inspection for site supervisors.

As a result of the shortage of skilled labor, a large number of semiskilled and poorly trained workers were used in renovation projects (Zhang et al. 2014b). Project managers instructed workers to specify the key points, but the workers themselves were unsure about how the key points could be controlled during construction. Besides, workers fail to specify the scope of their work. Therefore, project managers and site supervisors must inspect construction workers' work against the technical requirements specified by the governments. From a policy perspective, Visscher and Meijer (2014) suggested that mandatory certification of different parties will become more useful for construction processes.

Materials and Equipment

Two causes, Use of poor materials and Inadequate equipment performance, reflect final quality performance of building energy renovation projects. This result is in line with Francom and Asmar (2015). In an investigation of Indian construction projects, Thomas and Sudhakumar (2014) demonstrated a need to adopt effective material management practices at construction sites. The project manager must set up a centralized laboratory at the worksite to take material samples before deciding to use that material. The procedures of onsite quality management of materials and equipment are as follows:

- Materials and equipment ordering
- Certification checking
- Materials and equipment delivery to the site
- Materials and equipment sampling and testing
- Batching of materials and equipment

Nonspecified material and equipment must be rejected during the inspection by the project manager or site supervisor. The rejection report is sent to the chief supervisor and recorded. According to Hwang and Ng (2013), there is no proven track record of this procedure in Singapore. Therefore, the material and equipment checklist can be used to ensure that the project manager and site supervisor do not miss any inspections.

Design

The cause, Unauthorized changes in design documents, has more influence than other causes. The primary interest of construction companies is to reduce their costs and increase company income. To reduce cost, construction companies change design documents without authorization by designers. Juszczyk et al. (2014) in Poland noted that the modification of design documentation often occurs during construction, which is a reason for quality failures. Policies and regulations can be designed to increase penalties to discourage construction companies from changing design documents.

Globally, design errors can significantly affect quality in construction projects (Han et al. 2013; Rafindadi et al. 2014). The current study finds that the cause, Incomplete construction site survey, results in errors or changes in the design work. So, the effectiveness in addressing an incomplete construction site survey will, to a large extent, influence the design work of building energy renovation projects.

Design companies carry out site surveys and design. Thus, design companies need to implement their own quality management to ensure that their design work is properly prepared for construction. If any design details are unclear, special meetings can be held at the site between the designers and other site staff to resolve these problems. Design documents would be strictly checked by the project managers and site supervisors before construction begins (Głuszak and Leśniak 2015).

Organization

The efficient organization of the construction team is essential for the construction process (Głuszak and Leśniak 2015). Two causes, Incomplete building information in projects and Poor onsite coordination, are more likely to affect other causes and need to be given the highest priority to avoid. Janipha and Ismail (2013) noted that information is important to ensure that the right decisions are made and appropriate action can be taken in the future. Hence, often, inaccurate information led to incorrect construction implementation.

Designers can systematize the collection of building information to ensure that all requirements are defined before detailed design work proceeds. Especially before incomplete information affects the site survey, the original documents can be thoroughly checked and adequately detailed.

For onsite coordination, Doloi et al. (2012) and Doumbouya et al. (2016) proposed that effective cooperation between the different stakeholders helps to share the project information. In China, standard practice is that when key work is to be completed by the construction companies, the latter would inform the site supervisors. However, to speed up work, project managers do not inform the site supervisors to conduct checks. Some of the site supervisors are asked to fill out the checklist even if the work has not been completed. A solution is to use an efficient information sharing system, such as the Building Information Model (BIM), in building energy renovation projects to improve communications among onsite participants. Meijer and Visscher (2017) also advised governments to develop some online tools to further guide and organize onsite participants through the construction process.

Three causes, Wrong construction flow, Unsettled plan or lack of construction plan, and Poor site management, depend largely on others. Usually, if other causes are addressed, dependent causes are addressed accordingly. Thus, it is generally accepted that these causes are not crucial. This finding is indeed a clear contrast to the findings of Doloi et al. (2012), that site management is a vital factor for achieving success in Indian construction projects.

Relationship between External and Internal Causes

External causes are essential to be addressed for achieving high-quality performance (Hwang and Ng 2013). However, project coordinators cannot directly influence them because external causes originate from outside the project, for example, when projects are placed under high cost pressure and time pressure. These external causes cannot be detached from national policy contexts. Thus, in line with Hwang and Ng (2013), this study shows that external causes have become root causes of quality failures in building energy renovations, and have impacts on internal causes. For example, both high time and cost pressures have a commanding driving force to change construction coordinators' behavior to save construction time and cost; these behaviors, such as making unauthorized changes in design documents, can cause quality failures during renovation processes. Han et al. (2013) found that schedule pressure can propagate negative impacts on numerous construction activities.

To address the external causes of quality failures, it is proposed that, when implementing renovation policies, the administrative implications of these policies are considered in the light of prevailing renovation regulatory structures, approaches, and attitudes.

Summary and Conclusions

The process of building energy renovation is part of an essential strategy for achieving goals in reduction of energy consumption in the existing building stock. However, this study shows that in the current Chinese renovation projects, the resulting construction quality after renovation is not well ensured. These quality failures hinder the completion of the renovation projects on time, and failures of poor airtightness and poor energy efficiency performance are the consequences of quality failures in the usage stage. Thus, it is hard to achieve predicted energy efficiency rates due to quality failures, which negates the original goals of improving building energy performance.

Various causal factors affect construction quality, some of which are internal to the projects. To make decisions for managing resource allocation and mitigate quality failures, proper analysis of these internal causes of quality failures is crucial.

Traditional studies on causal analysis usually provide a list of relative vital causes. However, in practice, the causes have significant overlaps and relationships that are difficult to see. Therefore, this study thoroughly analyzed the interrelationships of the internal causes in renovation projects and their driving power and dependence power by using ISM and MICMAC techniques. The results obtained from these methods show the structural relationship among the four main causes affecting construction quality: Lack of experienced project managers (2); Unauthorized changes in design documents (8); Incomplete building information in projects (9); and Poor onsite coordination (13). These are the driving causes with high driving power. Efforts to address and eliminate these factors would enable elimination of several other internal causes. Consequently, solving these causes of quality failures should be prioritized.

Combining the obtained results, this paper provides appropriate strategies to improve quality performance at the project level through management actions. The solutions were grouped, based on the quality management process, in terms of people; materials and equipment; design; and organization. It should also be highlighted that, because external causes remain associated with all internal causes, external causes must be addressed at the government level regarding policies and regulations of building energy renovations.

An understanding these interactive causes and their solutions may help project practitioners to take better-informed management actions and so avoid continuing quality failures, to ensure successful building energy renovations with high-quality performance. Moreover, the findings of this paper are useful for both developing and newly industrializing countries that may be contemplating the implementation of quality management for building energy renovation projects.

A possible limitation of this work is that the focus has been to explore only the causes of quality failures that are internal to projects; for a fuller picture of all the influences at play, future work should also focus on the external causes of quality failures, especially those at the policy level. Additionally, the scope of this research is building energy renovation projects of northern China, and thus cases chosen were only in the Chinese context. Further cases could be considered from other regions of the world. Finally, although the empirical base could be improved, gathering better data is a topic that has not yet been studied widely in China and should be the goal of future work.

Appendix. Initial Reachability Matrix

No.	Causes	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Poor operational skilled workers	0	0	0	0	0	0	0	0	0	1	0	0	0
2	Lack of experienced project managers	1	0	0	1	1	0	1	1	0	1	1	1	1
3	Poor checking procedures of site supervisors	0	0	0	1	1	0	0	0	0	0	0	0	0
4	Use of poor materials	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Inadequate equipment performance	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Inaccurate design work	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Incomplete construction site survey	0	0	0	0	0	1	0	0	0	0	1	0	0
8	Unauthorized changes in design documents	1	1	1	0	0	1	1	0	0	1	1	0	1
9	Incomplete building information in projects	0	0	0	0	0	0	0	0	0	0	0	0	1
10	Wrong construction flow	0	0	0	1	0	0	0	0	0	0	0	0	0
11	Unsettled plan or lack of construction plan	0	0	0	0	1	0	0	0	0	1	0	1	0
12	Poor site management	0	0	0	1	1	0	0	0	0	1	0	0	0
13	Poor onsite coordination	0	0	0	0	0	0	0	1	1	0	0	0	0

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author upon reasonable request.

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