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Identification of Quality Failures in Building Energy Renovation Projects in Northern China

Yuting Qi *, **Queena K. Qian**, **Frits M. Meijer** and **Henk J. Visscher**

Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628BL Delft, The Netherlands

* Correspondence: Y.Qi@tudelft.nl

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Abstract: Building energy renovations contribute significantly to energy sustainability and environmental protection. These advantages have increased the importance of renovating existing residential buildings in many countries. In China, the government has supported the energy-saving renovation of existing urban residential buildings since 2007. However, quality failures, which do not meet the technical requirements, occur during construction processes in building energy renovation projects. Although quality failures are regarded as a crucial problem in building energy renovation projects, the identification of quality failures and their sources, likelihood, impacts, and causes remain mostly unknown. This paper investigates the nature of quality failures in building energy renovation projects. A total of 25 quality failures were first identified through five cases, and interviews with six experienced construction professionals in China. A questionnaire survey was further conducted to evaluate the frequency of quality failures. The results show the nature of quality failures that arise during construction and their sources, occurrence frequency, causes, and impacts. The research reveals that quality failures are caused by defaults by workers; inadequate checking procedures; incomplete construction site surveys; inaccurate design work; fraud of construction companies; and inefficient cooperation between different departments. Above all, the behaviors of the main actors are responsible for poor construction quality. Additionally, emphasis on quality control during the renovation preparation stage is critical to ensure that quality failures are reduced in numbers and severity.

Keywords: Quality failures; building energy renovation projects; Northern China

1. Introduction

The building sector is one of the largest energy end-use sectors, accounting for a larger proportion of the total energy consumption than both industry and transportation combined, in many countries [1]. In China, energy consumption in building stock accounted for approximately 24.1% of total national energy use in 1996, rising to 27.5% in 2001, and may increase to approximately 35% by 2020 [2]. Building energy consumption is rising rapidly year by year in China [3,4].

In favor of developing the sustainability of using energy and reducing energy consumption, from 2007 onwards, the Chinese government has promoted the energy-saving renovation of existing urban residential buildings [5]. For building energy renovation projects in Northern China, the central government planned and guided the renovation of existing residential buildings. A large number of existing buildings were renovated, and building energy renovations entered a large-scale implementation stage in Northern China [6]. However, quality failures happen frequently in these types of building energy renovation projects, which do not meet the technical requirements [7]. Consequently, this has resulted in losses and the negative reputation of the building energy renovation sector.

The incidence of quality failures is a global problem in the construction market [8]. Forcada et al. [9] defined quality failures as those in which construction products failed to fulfill the technical requirements and so needed re-doing during the construction processes. The existence of quality failures has a direct impact on the energy performance of the buildings [10]. Furthermore, quality failures during construction processes are threats to the success of construction projects with their consequential overdue schedule and unexpected cost overruns. Moreover, quality failures erase the projected benefits of development programs [11,12]. Owing to past quality failures, residents' dissatisfaction is acting as the dominant barrier for the implementation of future building energy renovation [13]. Therefore, researching quality failures is necessary to achieve high-quality performance in building energy renovation projects.

While quality failures are increasingly regarded as well-known problems and have been widely discussed in the literature [14], the evaluations in existing studies have mainly focused on the impact of the quality failures [10]. Quality failures repeatedly appear in construction [15–17], so it is essential to find the common quality failures and avoid them happening in the future. The repeatability of quality failures would indispensably lead to efforts to identify frequency distribution [16,18,19]. The evaluation of the likelihood of quality failures is also a pivotal foundation to reduce common quality failures in the future.

In China, previous research efforts have attempted to find the negative influence of the quality failures in building energy renovation projects, as well as their technical solutions to rework [20,21]. Yet, little attention has been paid towards the identification and evaluation of the likelihood of quality failures, the sources of the quality failures and causes of the quality failures in building energy renovation projects in Northern China [20,22].

Therefore, this paper addresses this issue. The specific objectives are: (1) to identify the quality failures during the construction period in building energy renovation in Northern China; and (2) to provide the analysis of the quality failures by considering their sources, frequency, impacts, and causes. It is essential to provide a comprehensive understanding of the quality failures in building energy renovation projects. Furthermore, efforts for minimizing the quality failures should be measured. The fieldwork was conducted in Hohhot, the provincial capital of Inner Mongolia. Geographically, Hohhot is located in the northwest of the territory, where winters are long and cold and, consequently, building heating is a significant energy demand of the city. The city is chosen as the site for study because it is well known as a building energy renovation city.

Next, Section 2 is a review of related studies on quality and quality failures from both global and Chinese experiences, and which also demonstrates the main characteristics of building energy renovation projects in China. Section 3 introduces the research method. In Section 4, the quality failures and their sources are identified. The analysis of the likelihood of quality failures and the impacts and causes of common quality failures are presented in Section 4. Section 5 discusses the causes derived from the main actors' contributions to the quality failures in building energy renovation projects. Finally, a summary of the findings based on the analysis is presented in the conclusion in Section 6.

2. Literature Review

2.1. Definitions of Quality and Quality Failures

Quality is defined in the general construction industry. As defined by the International Standards Organization (ISO), quality is the totality of factors and characteristics of a product or service that bears on its ability to satisfy given needs. In the construction industry, various expressions have been adopted to define quality [23]. The American Society of Civil Engineers (ASCE) published the definition of quality as "conformance to predetermined requirements." According to the Construction Industry Institute (CII), the definition of quality is the conformance with established requirements. Meanwhile, quality can also be defined as: 'meeting the customer's expectations' or 'compliance with customer's specification' [23,24]. Sim and Putuhena [25] argued that the quality of construction can be guaranteed if quality standards and specifications have been earnestly implemented. Shanmugapriya and Subramanian [26] defined quality as one of the critical success factors in the construction industry, which must meet the predetermined requirements and specifications. In this paper, the authors define "acceptable quality" as the quality that should meet the technical requirements of regulatory agencies and the local government as to conform with applicable laws, regulations, codes, and policies.

Similarly, different definitions exist to describe the term quality failures. According to Forcada et al. [9] and Sommerville [27], words like 'quality failure,' 'non-conformance,' 'error,' 'fault,' 'defect,' and 'quality deviation' are used interchangeably to describe imperfections in the building construction industry. Mills et al. [28] defined quality failure as a "shortcoming or falling short in the performance of a building element." Watt [29] and Alencastro [10] came up with quality failures as "failing or shortcoming in the function, performance, statutory or user requirements of a building, which manifested within the structure, fabric, services, or other facilities of the affected building." The definition of ISO 9000: 2005 is "the failure to fulfill a requirement." In this paper, the authors define a quality failure as "the nonfulfillment of the technical requirement from Chinese governments".

Quality failures remain pervasive in residential buildings [9]. The quality of construction is essential for occupants [30]. For construction companies and other stakeholders, quality failures cause rework, repair, and other losses, and even impact on poor construction performance and energy-saving inefficiency [12,31]. At the project level, time, money, and other resources are wasted because of reworks and poor construction performance caused by quality failures [31–33]. The quality of both energy performance and the cost optimality is necessary to promote and analyze in construction projects, as stated in several [34–37]. Hence, there is an urgent need to avoid quality failures in construction projects.

2.2. Previous Studies on Quality Failures

Previous international studies on quality failures in construction projects include failures in classification, identification, and analysis.

The classifications of quality failures in previous studies include construction elements [38], locations [39], trades (such as bricklayer and carpenter) [40], and building areas (such as bathrooms, kitchens, lounges, bedrooms) [41].

Quality failures were identified and analyzed according to two major categories: the impact and frequency of quality failures. In terms of the impact on cost, Mills, Love, and Williams [28] found quality failures deplete construction projects with an increase in direct cost. Also, quality failures can impact on energy performance. Quality failures in the construction stage are acknowledged as causes of the mismatch between the energy performance as predicted in design documents and as measured in operation [10].

Some studies were conducted that evaluated and ranked quality failures from the frequency perspective. Forcada et al. [39] identified common quality failures in new building construction like incorrect fixtures and incomplete tile grouting. Georgiou [40] refined and ranked the various quality failures to find significant quality failures like cracks to grout.

Many researchers in different regions have identified various causes of quality failures. Love et al. [42] showed that the changes in the design documents are likely to happen on construction projects and to cause quality failures. In India, Dixit et al. [43] introduced one of the leading causes as poor coordination between various trades in construction projects. Additionally, Shanmugapriya and Subramanian [26] indicated that the non-conformance to codes and standards in the process was ranked first, which influences quality negatively in India. In Spain, Forcada et al. [39] attempted to show that bad craftsmanship is the typical cause for the quality failures. Also, Forcada et al. [9] continued to show that poor craftmanship is more likely to cause technical faults than non-conformance materials or products used. Kakitahi et al. [12] described inadequate communication, graft, and a dishonesty environment as the three substantial causality factors to cause quality failures in Uganda. The causes of quality failures can be explained by defining causes as stemming from internal or external to the project. Internal causes are those causes that originated within the projects, such as incomplete design documents and poor craftsmanship. While external causes are originated outside the projects, such as culture environment and the natural environment.

In the context of China, Gang et al. [44] claimed that the inappropriate treatment of the external wall is most likely to happen. Chen et al. [45] and Liu [7] observed the quality failures in the existing building renovation, such as the wrong dimension of opening doors and windows, and the invalid fill between the frame and window panes. Qiao [46] regarded the cracks as universal quality failures during the external wall renovations. Wang [20] gave recommendations on the technical level regarding the quality failures of the renovations of the external wall during the construction processes. Due to the novelty of building energy renovation projects, specific quality failures have not been yet treated in the academic literature in a systematic way in the Chinese context. Even with the consideration of the previous studies worldwide, quality failures and their sources, frequency, impacts, and causes in building energy renovation projects have still not been fully identified in China.

2.3. Main Characteristics of Energy-Saving Renovations of Existing Residential Buildings in China

In China, a variety of regional climates influences the energy consumption of buildings. China covers a land area of approximately 96 million km^2, from subtropical zones in the south to cold zones in the north [47]. China's diverse climates are classified into five climate zones according to the Standard of Climatic Regionalization for Architecture (CNS, 1993a): Severe Cold Zone, Cold Zone, Hot Summer and Cold Winter Zone, Hot Summer and Warm Winter Zone, and Mild Zone. Of these, the Severe Cold Zone and Cold Zone are both located in Northern China.

Based on the five climate zones in China, regulatory rules are made for implementation in the areas needing heating of buildings, including codes or standards, in order to manage quality and avoid quality failures. The relevant levels of government issue the building regulations to assure at least a basic construction quality level in existing residential buildings. Therefore, in order to promote the construction quality of building energy renovation projects, the Chinese government issued a set of administrative regulations and technical specifications [48]. The administrative regulations give descriptions about the administrative and organizational requirements, e.g., the roles and responsibilities of main stakeholders (see Section 2.3.1), and the renovation process (see Section 2.3.2). On the other hand, technical specifications refer to the main construction steps and technical requirements for construction quality (the details are illustrated in Section 2.3.3).

2.3.1. Responsibilities of Main Stakeholders

In 2000, the central government introduced 'Regulations on quality control of construction projects to ensure the main stakeholder compliance with quality control'. The implementation of this mandatory administrative regulation is mostly confined to new building projects and renovation projects. Building energy renovation projects are carried out by combinations of different departments of governments, construction companies, supervision companies, design companies, and others. Since the local government, construction companies, supervision companies, and design companies in renovation processes are fully involved, they are naturally the main stakeholders.

The local government usually takes the lead in most building energy renovation projects. Correspondingly, they need to organize the whole project and contract the tasks with the companies. In terms of quality control, local governments are required to delegate supervision companies to supervise the construction quality and to do on-site inspections [49].

Construction companies direct construction processes to influence construction quality with preparing workers, materials, machines, and other necessities for construction and the construction scheme is organized, arranged, and checked in construction preparation. Construction companies need to establish a quality responsibility system to control their own construction quality [49]. In particular, construction companies are required to test the quality of the materials and equipment, doing evidential tests and on-site inspections.

Supervision companies co-supervise with local government such as on-site inspections, evidential tests, and final checks [49]. The obligations of Design companies are to provide a site survey and design documents [49].

2.3.2. Renovation Processes

According to previous studies, complete building energy renovation processes are arranged with three stages, renovation preparation stages, renovation stages, and post-renovation stages [50]. These stages are divided into particular sub-stages, including a decision-making phase, survey, and design phase, construction design phase, construction phase, acceptance phase, and usage phase by the administrative regulations, as shown in Figure 1 [50].

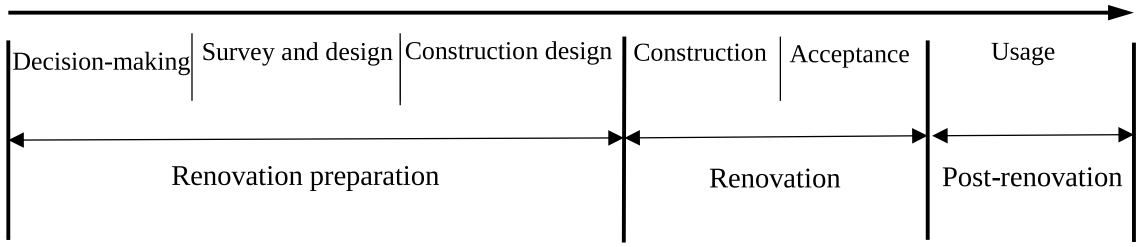

Figure 1. The stages of renovation projects (Modified from Wu et al. [50]).

In the decision-making phase, the feasibility with renovating existing buildings is studied before building energy renovation projects are set up [51]. The major work is to judge the essentiality of building energy renovations and the local government determines which buildings will be renovated.

A site survey is necessary to know the structure, appearances, existing installation, and other characteristics about building energy renovation projects before the design stage [52]. Based on the survey information, the design is necessary for the renovation projects and use of construction work. The design company provides a set of construction design documents, including specifications, technical drawings, and other relevant documents, which guide construction methods and materials in the survey and design phase.

For the construction design phase, construction companies need to make construction plans to arrange construction resources, such as men, materials, and machines [53]. Moreover, the management plan for high construction quality also needs to be made by construction companies. The management plan is critical for stakeholders to avoid quality failures.

The activities in the construction sub-phase are the most complicated and have a significant impact on construction quality, because this phase contributes a substantial part of the renovated work. The achievement of a high-quality performance depends on the assurance of the completed construction quality of renovation projects in every construction step. Furthermore, the main construction steps are required in technical specifications.

After the completion of the renovation construction, quality acceptance must be carried out by specific stakeholders, including government, supervision companies, design companies, and construction companies. Quality acceptance is the last procedure to control construction quality in several stages of renovation projects, prior to the user taking possession [54].

2.3.3. Construction Steps

The implementation of the building renovation program started in 2007. Government-led is a standard mode applied in building energy renovation projects. In the government-led model, the top-down mandatory requirements for renovating technology are set from the central government. To achieve energy intensity targets, the Chinese central government developed 'Technical guidelines for heat supply meter and energy-saving renovation of existing residential buildings in Northern heating areas' at the national level [55]. With different regional circumstances, the provincial government has potential autonomy to issue their own technical documents. For example, in Inner Mongolia (where Hohhot is located), the provincial government introduced 'Technical guidelines for Energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region' [56]. Accordingly, the municipal government and district government are responsible for the implementation of the technical requirements.

Based on technical specifications, the main construction steps in building energy renovation projects are studied to find the sources of quality failures. The construction procedures are described as three technological measurement categories, which are door and window, roof, and the external wall (see Figures 2–4 for details) [56]. In three different categories, all of them started with preparation and ended with site cleaning. 'Technical guidelines for Energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region' requires the compulsory use of expanded polystyrene insulation (EPS), which is a type of thermal insulation material and can have a huge effect on the long-term performance.

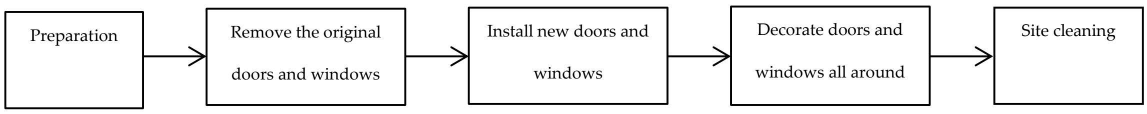

Figure 2. Construction flow in door and window renovation.

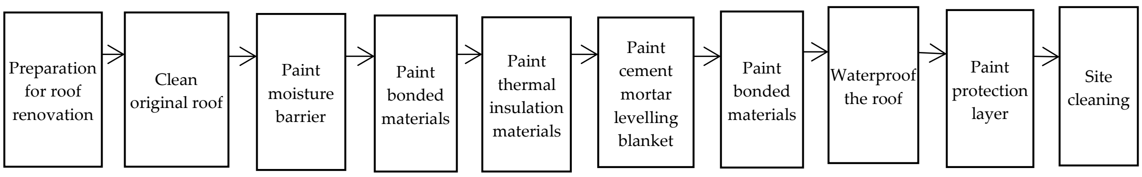

Figure 3. Construction flow in roof renovation.

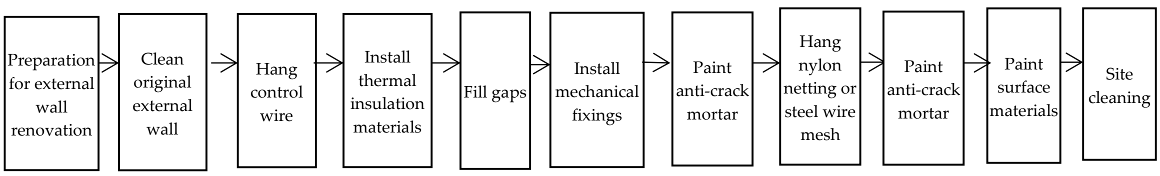

Figure 4. Construction flow in external wall renovation.

3. Methodology

Using a three-step process, this study aimed to identify the common quality failures during the construction period and investigate their sources, impacts, and causes. First, case studies of building energy renovation projects were carried out to find quality failures and investigate their sources, impacts, and causes. Second, the findings from the case studies were validated by six experts with over eight years of experience in building energy renovation projects. Finally, the quality failures were evaluated to be further analyzed by a survey questionnaire (Figure 5).

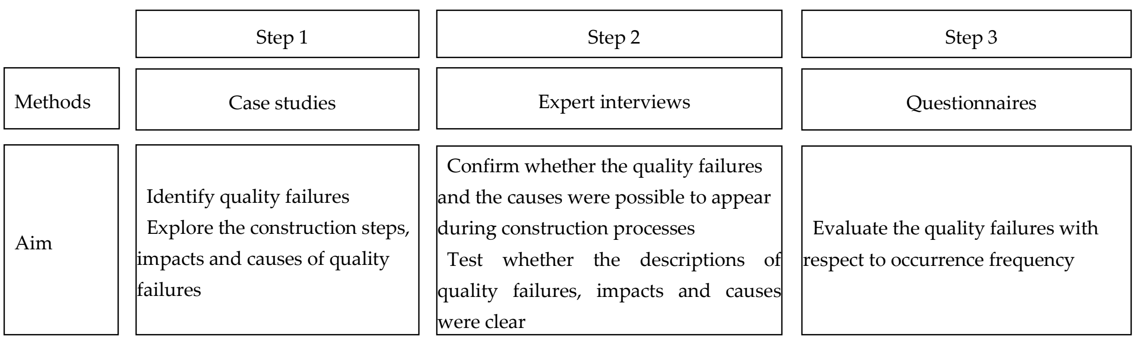

Figure 5. Research methodology.

3.1. Step 1—Case Studies

A case study approach was undertaken to identify the quality failures and explore their sources, impacts and causes. Five cases were selected, located in the urban area of Hohhot. Hohhot is a typical northern city in China. As the center in the Inner Mongolia Autonomous Region, Hohhot city has developed rapidly in China. In Huhhot, the coldest month is January with an average temperature of approximately −12 °C, and the hottest month is July with an average temperature of approximately 23 °C (Figure 6). It is a typical city of the heating areas in northern China in an energy-saving renovation context. The energy-saving renovation of existing buildings started in Hohhot since 2008, and the administrative and technical regulations of building energy renovations issued by the governments have been applied. In this study, five building energy renovation projects were selected to investigate quality failures, and their sources, impacts and causes.

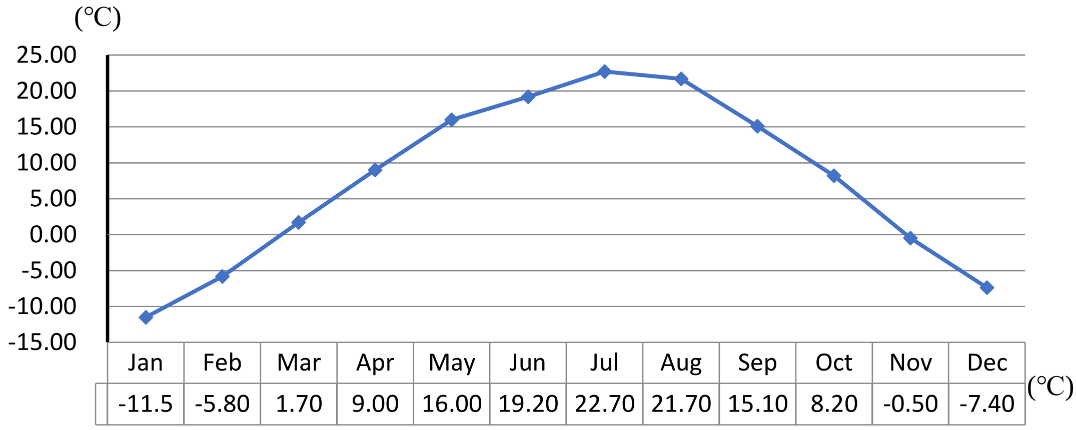

Figure 6. Average temperature in Hohhot (by the authors).

The five cases of building renovation projects were selected to be representative of the residential building renovation situations (Figure 7). They cover a broad diversity of different construction conditions such as location, contract value, renovation size, construction companies, supervision companies and the current status of building energy renovation projects (the details are illustrated in Table 1). The diversity of project characteristics is intended to know what and how quality failures occurred, based on their particular context and conditions.

Figure 7. The residential building renovated in the case study (by the authors).

Table 1. Five cases: contexts and conditions.

NO.	Contract Value	Building Floor Area (m^2)	Building Age	Construction Period (Days)	Technology	Status
1	9.5 million RMB (1.2 million Euros)	45,800	2006–2008	300	Window: install double glass windows; Roof: install EPS; External wall: install EPS	Ongoing
2	11 million RMB (1.3 million Euros)	52,086	2000–2003	320	Window: install double glass windows; Roof: install EPS; External wall: install EPS	Completed
3	5.5 million RMB (0.7 million Euros)	24,900	1999–2002	120	Window: install double glass windows; Roof: install EPS; External wall: install EPS	Ongoing
4	15.1 million RMB (1.9 million Euros)	77,738	1996–1999	320	Window: install double glass windows; Roof: install EPS; External wall: install EPS	Completed
5	12 million RMB (1.5 million Euros)	55,620	2000–2003	320	Window: install double glass windows; Roof: install EPS; External wall: install EPS	Completed

The building floor area within the five cases covers approximately 77,738 m^2 and the smallest covers approximately 24,900 m^2. The range of the contract value is from 5.5 million RMB (0.7 million Euros) to 15.1 million RMB (1.9 million Euros). In terms of the geographical location, they are widely distributed over major administrative districts in Hohhot city (Figure 7). The stage of construction status is also regarded as a key element to finding the causes of the quality failures when the cases are selected. In this study, two cases were under construction, and three cases were completed. Together, the five cases reveal quality failures identified as universal and typical of the different construction companies and supervision companies.

From the perspective of building energy renovation technologies used, the renovation measurements of all cases included the renovation of doors and windows, external walls, and roofs. All cases implemented the same administrative requirements of the energy-saving renovation regulations for existing residential buildings. Additionally, the local technical regulations clearly defined the main construction steps (see in Section 2.3.3) and technical requirements (see the key technical specifications in Table 2) of building energy renovation projects. Thus, the authors argue that the quality failures identified in these five cases are representative of those arising in the main construction steps of building energy renovations in Northern China.

The main stakeholders are employed in government, construction companies, supervision companies, and design companies. In order to provide a comprehensive view of the research question, 16 experts from different backgrounds were interviewed in the cases. Among all the interviewees, six were project managers, four were quality supervisors from the supervision company, two were designers and four were government officials (Table 3).

At the time of the interview, these 16 interviewees in five cases had participated in the whole project processes from projects started to construction acceptance. They were asked to describe the quality failures according to the construction steps (in Figures 2–4), and then explain the causes of the quality failures by reference to the construction quality reports and on-site documents.

Table 2. Technical specification of building energy renovation projects in Huhhot. (Source: 'Technical guidelines for energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region').

Items	Standards
Doors and windows replacement	
Heat-transfer coefficient	2.6 W/(m^2·K) or lower
Air ventilation rate	2.5 m^3/(m^2h) or lower
Roof thermal insulation	
Material	Expanded polystyrene (EPS)
Bulk density	25 kg/m^3 or higher
Heat-transfer coefficient	0.25 W/(m^2·K) or lower
Thermal conductivity of the insulation	0.041 W/(m·K) or lower
Tensile strength	0.10 MPa or higher
Compressive strength	100 kPa or higher
Dimensional stability	0.3% or lower
External wall thermal insulation	
Material	Expanded polystyrene (EPS)
Bulk density	20 kg/m^3 or higher
Heat-transfer coefficient	0.4 W/(m^2·K) or lower
Thermal conductivity of the insulation	0.037 W/(m·K) or lower
Tensile strength	0.20 MPa or higher
Compressive strength	140 kPa or higher
Dimensional stability	0.3% or lower

Table 3. Background of the interviewees in the five cases.

Cases	Cd.	Profile
1	1	Officer of Hohhot housing security and housing authority
	2	Project manager of a Construction company
	3	Construction company
	4	Designer of a Design Company
2	5	Officer of Inner Mongolia Autonomous Region Building Energy Efficiency Evaluation Station
	6	Construction manager of a Construction company
	7	Supervisor of a Supervision Company
3	8	Officer of Department of housing and urban–rural development in Inner Mongolia
	9	Project manager of a Construction company
	10	Supervisor of a Supervision Company
4	11	Officer of Hohhot housing security and housing authority
	12	Project manager of a Construction company
	13	Supervisor of a Supervision Company
5	14	Project manager of a Construction company
	15	Supervisor of a Supervision Company
	16	Designer of a Design Company

3.2. Step 2—Expert Interviews

In order to make the data on quality failures more reliable and complete, separate semi-structured interviews were conducted with six experts consisting of one supervisor from government, four project managers, and one supervisor from the supervision company. All these experts in the interviews have been engaged in building energy renovations for more than eight years and have rich experiences on project management and quality control. They were requested to confirm the quality failures and the causes identified from cases according to their own experience. The semi-structured interviews allow new ideas to be brought up, so new quality failures were identified as a result of what the interviewees said. The final list of quality failures is shown in Table 1.

3.3. Step 3—Questionnaire Survey

A case study approach was conducted to establish a foundation of the quality failures and to support the development of a survey questionnaire. The purpose of the questionnaire survey is to estimate the magnitude of the occurrence frequency of the separate quality failures identified. The questionnaire contains two parts. Before the main body, the introduction provided the definition of quality failures as well as the objectives of this survey. The first section included questions about respondent profiles.

In the second section, the respondents were asked to describe the frequency of quality failures with linguistic values. The linguistic values represented an interval of different frequency. Based on the fuzzy set theory to analysis data [57], the linguistic values designed were "very high", "high", "moderate", "low", and "very low".

The questionnaire survey was conducted in Northern China. All of the respondents were engaged in building energy renovations and were familiar with construction quality during the whole construction processes at the management level. A total of 330 questionnaires were delivered to respondents. Of these, 92 questionnaires were received and deemed to be valid, representing a response rate of 27.9%.

3.4. Fuzzy-Set Evaluation Method

Several studies have used Likert scales in their questionnaire surveys and adopted parametric statistical methods, such as the *t*-test [58,59]. In this traditional method, human judgments were represented as exact numbers [60]. However, many intermediate statements in actuality existed between exact numbers. Since some of the descriptions of the frequency are qualitative, it is tough for participants in a questionnaire survey to express the preferences using exact numerical values [61]. In the practical evaluation of the frequency of quality failures, it is common that participants in questionnaire surveys tend to express their opinions on words rather than crisp values based on their experience [62].

Fuzzy set evaluation is often used to incorporate the linguistic information [62–64]. Also, the final evaluation could be directly shown as the interval of occurrence frequency of the quality failures, and occurrence frequency vectors could be obtained eventually, which contains the rich and pivotal information to depict quality failures [63]. In previous studies, Fu [65] and Kar [66] applied a fuzzy-set evaluation to evaluate factors with quantitative and qualitative criteria. Therefore, the fuzzy-set theory is utilized in this study to deal with an ambiguous occurrence frequency of quality failures from subjective decisions by respondents.

4. Results

This section may be divided by subheadings. It should provide a concise and precise description of the results, their interpretation as well as the conclusions that can be drawn.

4.1. Identified Quality Failures In Building Energy Renovations in Northern China

Table 1 presents the quality failures identified from five cases and the distribution of quality failures within the five cases. Various quality failures occurred needing rework or repair with extra cost and time. According to the 'Regulations on quality control of construction projects to ensure the main stakeholder compliance with quality control,' the rework and repair of the quality failures must be recorded by construction companies during the construction period. A recording of one of the construction documents needs to be checked by supervision companies and government in order to avoid the dispute. Once the quality failures are recorded in documents of the cases, the checkbox will be ticked, as shown in Table 4. The results show that 25 quality failures are identified as falling into three technical categories: door and window (D), roof (R), and the external wall (E).

Table 4. The distribution of quality failures in five cases.

Technology Measurements	No.	Quality Failures	Cases (No.)				
			1	2	3	4	5
Door and window (D)	D1	Incorrect installation of the steel nails	√		√		√
	D2	Incorrect size of the new window frame and door frame	√	√	√	√	√
	D3	Misalignment between the new doors and windows and the wall		√	√	√	
	D4	The untreated wall around the new windows	√				√
Roof (R)	R1	Missing vapor barriers				√	
	R2	Non-specified fire resistance of EPS boards		√		√	
	R3	Non-specified volume-weight and thickness of EPS boards		√			
	R4	Adhesive area problems	√	√	√	√	√
	R5	The detachment between the different EPS boards	√	√			
	R6	Cracks of the roof leveling blanket	√		√	√	√
	R7	The detachment of waterproof roof layer	√				√
	R8	Misalignment of the waterproof roof layer	√	√	√		√
	R9	Cracks of roof concrete		√	√	√	√
External wall (E)	E1	Uncleaned wall				√	√
	E2	Missing interface treating mortar	√		√		√
	E3	Unacceptable levelness of the control wire			√		
	E4	Non-specified fire resistance of EPS boards		√	√		
	E5	Non-specified volume-weight and thickness of EPS boards				√	
	E6	Adhesive area problems	√		√	√	
	E7	The detachment between the different EPS boards				√	
	E8	Missing rivets		√			√
	E9	Non-specified rivets		√			
	E10	Incorrect drilling		√			
	E11	Non-specified anti-crack mortar					√
	E12	Non-specified nylon net			√		

Of the identified quality failures in construction steps, the number of quality failures happened in external wall renovation ranked the highest followed closely by the number of quality failures in roof renovation. On the other hand, the experts just identified four quality failures in door and window renovation.

4.2. Sources of Quality Failures

Table 5 presents the distribution of quality failures in the construction steps and identification of the main construction steps where quality failures arose. The results reveal that the first three quality failures appear in the installing process of new doors and windows for the doors and windows renovations, so installing is a key construction step to control quality.

Table 5. Construction steps of quality failures.

Technology Measurements	No.	Quality Failures	Construction Steps
Door and window	D1	Incorrect installation of the steel nails	Install new doors and windows
	D2	Incorrect size of the new window frame and door frame	
	D3	Misalignment between the new doors and windows and the wall	
	D4	The untreated wall around the new windows	Decorate doors and windows all around
Roof	R1	Missing vapor barriers	Paint moisture barrier
	R2	Non-specified fire resistance of EPS boards	Install thermal insulation materials
	R3	Non-specified volume-weight and thickness of EPS boards	
	R4	Adhesive area problems	Paint adhesive materials
	R5	The detachment between the different EPS boards	Install thermal insulation materials
	R6	Cracks of the roof leveling blanket	Paint cement mortar leveling blanket
	R7	The detachment of waterproof roof layer	Waterproof the roof
	R8	Misalignment of the waterproof roof layer	
	R9	Cracks of roof concrete	Paint protection layer
External wall	E1	Uncleaned wall	Clean original external wall
	E2	Missing interface treating mortar	Install thermal insulation materials
	E3	Unacceptable levelness of the control wire	Hang control wire
	E4	Non-specified fire resistance of EPS boards	Install thermal insulation materials
	E5	Non-specified volume-weight and thickness of EPS boards	
	E6	Adhesive area problems	
	E7	The detachment between the different EPS boards	Fill gaps between different EPS boards
	E8	Missing rivets	Install mechanical fixings
	E9	Non-specified rivets	
	E10	Incorrect drilling	
	E11	Non-specified anti-crack mortar	Paint anti-crack mortar
	E12	Non-specified nylon net	Hang nylon netting or steel wire mesh

During roof renovation processes, the main sources where most quality failures are identified are 'waterproof roof' and 'install thermal insulation materials. 'Detachment of waterproof roof layer' and 'misalignment of waterproof roof layer' occur during waterproofing roof. Similarly, 'non-specified EPS boards' and 'detachment between the different EPS boards' are the quality failures of installing thermal insulation materials.

Regarding the external wall renovation, the quality failures are more likely to take place in 'install thermal insulation materials' and 'install mechanical fixings.' During installing mechanical fixings of the external wall renovation processes, there exist 'missing rivets', 'non-specified rivets', and 'incorrect drilling'.

4.3. Occurrence Frequency of Quality Failures

Table 6 and Figure 8 show the percentage of the respondents' evaluation of the quality failures concerning the occurrence frequency according to the different linguistic variables.

Table 6. The percentage table of respondent evaluation of the quality failures (N = 92).

No.	Quality Failures	The Percentage of Respondents on Linguistic Variables					
		Very High	High	Moderate	Low	Very Low	Total
D1	Incorrect installation of the steel nails	3.0	14.0	29.0	42.0	12.0	100.0
D2	Incorrect size of new window frame and door frame	5.0	30.0	18.0	25.0	22.0	100.0
D3	Misalignment between the new doors and windows and the wall	1.0	10.0	27.0	36.0	26.0	100.0
D4	Untreated wall around the new windows	8.0	12.0	21.0	37.0	22.0	100.0
R1	Missing vapor barriers	3.0	10.0	24.0	27.0	36.0	100.0
R2	Non-specified fire resistance of EPS boards	8.0	11.0	29.0	27.0	25.0	100.0
R3	Non-specified volume-weight and thickness of EPS boards	7.0	12.0	16.0	40.0	25.0	100.0
R4	Adhesive area problems	4.0	12.0	25.0	27.0	32.0	100.0
R5	Detachment between the different EPS boards	4.0	13.0	32.0	29.0	22.0	100.0
R6	Cracks of the roof levelling blanket	10.0	8.0	27.0	28.0	27.0	100.0
R7	Detachment of roof waterproof layer	3.0	9.0	28.0	42.0	18.0	100.0
R8	Misalignment of roof waterproof layer	5.0	25.0	25.0	22.0	23.0	100.0
R9	Cracks of roof concrete	4.0	18.0	28.0	27.0	23.0	100.0
E1	Uncleaned wall	3.0	15.0	34.0	32.0	16.0	100.0
E2	Missing interface treating mortar	5.0	21.0	26.0	30.0	18.0	100.0
E3	Unacceptable levelness of the control wire	2.0	12.0	24.0	35.0	27.0	100.0
E4	Non-specified fire resistance of EPS boards	7.0	10.0	25.0	32.0	26.0	100.0
E5	Non-specified volume-weight and thickness of EPS boards	4.0	14.0	20.0	34.0	28.0	100.0
E6	Adhesive area problems	4.0	9.0	23.0	37.0	27.0	100.0
E7	Detachment between the different EPS boards	4.0	10.0	29.0	34.0	23.0	100.0
E8	Missing rivets	5.0	10.0	34.0	31.0	20.0	100.0
E9	Non-specified rivets	5.0	12.0	20.0	38.0	25.0	100.0
E10	Incorrect drilling	4.0	10.0	25.0	39.0	22.0	100.0
E11	Non-specified anti-crack mortar	4.0	14.0	21.0	39.0	22.0	100.0
E12	Non-specified nylon net	7.0	11.0	18.0	38.0	26.0	100.0

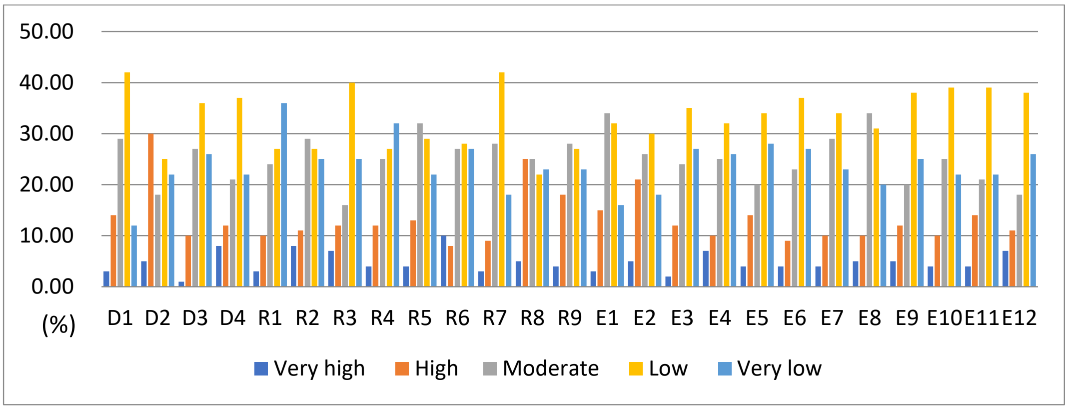

Figure 8. The percentage graph of respondent evaluation of the quality failures.

The fuzzy set theory defines set membership as a possibility distribution. A fuzzy set is a pair (S, n) where S is a set and n is a degree of membership of the set S (). For each, n(x) is called the grade of membership of x in (S, n). If n(x) = 0, then x is called not included in the fuzzy set (S, n); if n(x) = 1, x is called fully included; and if 0 < n(x) < 1, x is called fuzzy member. For a finite set, $S = \{x_1, \ldots, x_n\}$, the fuzzy set (S, n) is often denoted by $\{n(x_1)/x_1, \ldots, n(x_n)/x_n\}$. $n(x_1)/x_1$ means that the degree of membership of x_i in S is $n(x_i)$ [67,68]. The degree of membership mitigates the weakness of the traditional cut-off value method for identifying quality failure with high frequency. Therefore, in applying fuzzy set theory, the membership degree of a quality failure in the fuzzy set is used to identify whether or not the quality failure is common. The linguistic variable of the frequency is measured between 1 (very low) to 5 (very high) in this study. The probability of quality failure is considered very low if the mean of the variable of this quality failure is less than 2. Hence, referring to a specific quality failure, only a variable above 2 will be further considered for analyzing the frequency of the quality failures. Based on the fuzzy set evaluation method [69], the degree of membership for each indicator can be described as follows:

$$\mathrm{n}(\mathrm{x_i}) = \int_2^{\infty} f(V_{\mathrm{xi}})dx \quad (1)$$

where V_{xi} is a popular variable above 2 for the quality failure $\mathrm{x_i}$, and $f(V_{\mathrm{xi}})$ represents the probability of the occurrence for the V_{xi}. The degree of membership for each quality failure can be calculated by using Equation (1). Here, the V_{xi} can be introduced to normalize the distribution, thus, the value of standard deviation (SD) should also be given consideration [68].

The means and standard deviations of the variable of the frequency are shown in Table 7. Moreover, according to Equation (1), the means, the value of standard deviation, and the degree of membership n of each quality failure can be calculated. The results are shown in Table 7.

Table 7. The degree of membership of indicators for common quality failures.

No.	Quality Failures	Mean	SD	n(xi)
D1	Incorrect installation of the steel nails	2.554	0.987	0.713
D2	Incorrect size of new window frame and door frame	2.717	1.252	0.717
D3	Misalignment between the new doors and windows and the wall	2.239	0.987	0.596
D4	Untreated wall around the new windows	2.467	1.181	0.654
R1	Missing vapor barriers	2.174	1.125	0.562
R2	Non-specified fire resistance of EPS boards	2.489	1.200	0.658
R3	Non-specified volume-weight and thickness of EPS boards	2.348	1.171	0.617
R4	Adhesive area problems	2.304	1.165	0.603
R5	Detachment between the different EPS boards	2.489	1.104	0.671
R6	Cracks of the roof leveling blanket	2.446	1.244	0.640
R7	Detachment of roof waterproof layer	2.370	0.991	0.646
R8	Misalignment of roof waterproof layer	2.685	1.231	0.711
R9	Cracks of roof concrete	2.543	1.162	0.680
E1	Uncleaned wall	2.576	1.040	0.710
E2	Missing interface treating mortar	2.663	1.151	0.718
E3	Unacceptable levelness of the control wire	2.272	1.060	0.601
E4	Non-specified fire resistance of EPS boards	2.391	1.167	0.631
E5	Non-specified volume-weight and thickness of EPS boards	2.326	1.159	0.611
E6	Adhesive area problems	2.261	1.088	0.595
E7	Detachment between the different EPS boards	2.391	1.079	0.642
E8	Missing rivets	2.500	1.084	0.678
E9	Non-specified rivets	2.348	1.143	0.620
E10	Incorrect drilling	2.359	1.065	0.632
E11	Non-specified anti-crack mortar	2.402	1.110	0.641
E12	Non-specified nylon net	2.337	1.170	0.613

In order to decide whether or not an indicator is a common quality failure, a benchmark value should be preset. The λ-cut set approach is adopted in this study. The $n(x_i)$ should meet a certain given value (λ), then the quality failure (x_i) will be considered as an indicator with high frequency. For example, if λ = 0, all indicators belong to the common quality failures set, while, if λ = 1, there will be fewer or even none of the indicators in the common quality failures set. In Table 7, the values of $n(x_i)$ range from 0.562 (R1) to 0.718 (E2), and the mean of $n(x_i)$ is 0.65. Therefore, it is reasonable to consider that, if the degree of membership of a quality failure ($n(x_i)$) is equal to or greater than 0.65, x_i is selected as a common quality failure. Moreover, λ = 0.65 is a commonly used threshold in fuzzy set theory (e.g., [70]). Therefore, λ = 0.65 is adopted as the criterion to select common quality failures in this study. Adopting this criterion in conjunction with Table 7 results in D1, D2, D4, R2, R5, R8, R9, E1, E2, and E8 being identified as common quality failures.

4.4. Causes of Quality Failures

Table 8 presents the causes of quality failures within building energy renovation projects. In looking into how the quality failures arise in building energy renovation projects in Northern China, two key factors are summarized, including the stakeholders (those who should be responsible for quality failures), and the stages (the renovation processes when the causes happened). They are useful for the understanding of the causes of quality failures.

4.5. Impacts and Causes of Quality Failures

With the results of the interviews with experts, the following quality failures are obtained based on the level of impact and frequency, which are the attributes of quality failures.

Construction preparation plays an essential role in controlling construction quality. A weak site survey and lack of a construction plan cause the quality failures of inferior installation enclosure component (doors and windows), and most frequently, incorrect size of the new window frame and door frame (D2). During the survey and design phase, designers or workers make errors in measuring and recording the size of the doors and windows. In particular, if the construction plan is not clear, the workers will ignore to check the actual dimensions on the construction site. Consequently, if the size of the new window frame and door frame is wrong, new doors and windows cannot be installed. The new windows and doors have to be re-purchased. Not only the renovations of the windows and doors but also the renovations of the external wall have to stop to wait for the transportation of the new windows and doors. Similarly, incorrect installation of the steel nails (D1) and the untreated wall around the new windows (D4) occur because the preparation is not detailed in terms of worker's responsibilities and material requirements. Rework of installation windows and doors will hinder the completion of the renovation projects on time.

Non-specified fire resistance of EPS boards (R2) occurs because the construction companies procure the non-specified installation material (expanded polystyrene insulation (EPS)) to maximize their profit. Meanwhile, the quality failures of EPS boards are exacerbated by a lack of adequate supervision. The on-site supervisors do not strictly control the quality of EPS boards. Fire resistance is an essential technical performance of EPS boards. If fire resistance cannot meet the technical requirement, potential fire safety hazards will happen for residents who are living in renovated buildings.

The detachment between the different EPS boards (R5) is the unfilled gaps between different EPS boards. The main reason is workers lacking experience on the installation of the thermal insulation materials and the treatment of the gaps between the different EPS boards. The poor airtightness and energy efficiency performance in the usage stage are the consequences because of the detachment between the different EPS boards (R5).

Table 8. Causes of the quality failures (by the authors).

Quality Failures	Causes			
	Code	Stakeholders	Renovation Processes	Explanations
Incorrect installation of the steel nails (D1)	D1-1	Design companies	Survey and design	Design companies do not mention the sizes of steel nails in design documents.
	D1-2	Workers	Construction	Workers make errors in choosing sizes of steel nails.
Incorrect size of the new window frame and door frame (D2)	D2-1	Project managers; Designers	Survey and design; Construction design	Since there are no details on the design documents and construction plans, the investigation of the construction site is insufficient.
	D2-2	Supervisors	Construction design	Supervision companies do not check the construction plan.
	D2-3	Workers	Construction design	Workers make errors in measuring and recording the size of the doors and windows.
	D2-4	Construction companies	Construction design	Deferent construction departments have ineffective communication on the information of the size of the doors and windows.
The untreated wall around the new windows (D4)	D4-1	Construction companies	Construction design	Construction departments lack effective communication on the responsibilities of the external wall treatment.
	D4-2	Supervisors	Construction	Supervision companies supervise insufficiently.
	D4-3	Workers	Construction	On-site workers ignore this construction step.
Non-specified fire resistance of EPS boards (R2)	R2-1	Construction companies	Construction	Construction companies cut corners by cheating in work.
	R2-2	Supervisors	Construction	Supervision companies supervise insufficiently.
The detachment between the different EPS boards (R5)	R5-1	Workers	Construction	Workers make errors on the treatment of gaps between the different EPS boards.
Misalignment of the waterproof roof layer (R8)	R8-1	Workers	Construction design	The workers lack experience on waterproof the roof in building energy renovations.
	R8-2	Project managers	Construction design	Project managers do not emphasize to workers the knowledge of the waterproof.
	R8-3	Workers	Construction	In order to speed up, workers ignore checking the waterproof.
	R8-4	Workers	Construction	It is a challenge to control construction temperature for workers lacking operation skills.
Cracks of roof concrete (R9)	R9-1	Project managers	Construction design	Project managers lack the knowledge about the proportion of concrete materials.
	R9-2	Workers	Construction	Workers make errors on the construction flow of mixing concrete.
	R9-3	Supervisors	Construction	Supervisors check the mix-concrete insufficiently.
	R9-4	/	/	Low solar energy and temperature cause concrete cracks.
Uncleaned wall (E1)	E1-1	Project managers	Construction design	Project managers do not provide critical points in quality control.
	E1-2	Supervisors	Construction design	Supervisors ignore to check the external wall clearing.
	E1-3	Workers	Construction	Workers skip this procedure in order to reduce cost and time.
	E1-4	Project managers	Construction	There are no details about wall cleaning in the construction plan.
Missing interface treating mortar (E2)	E2-1	Construction companies	Construction	Construction companies cut corners by cheating in work.
	E2-2	Workers	Construction	In order to speed up, workers ignore interface treating mortar
Missing rivets (E8)	E8-1	Construction companies	Construction	Construction companies change design documents unauthorized
	E8-2	Supervisors	Construction	Supervision companies do not check the mechanical fixings carefully.

Misalignment of roof waterproof layer (R8) occurs due to a poorly-skilled workforce, high cost and time pressure of the construction companies. In cases, the waterproof material is sensitive to low temperature and scarce solar energy, which are the characters for the typical climate in Northern China. Therefore, it is difficult to control the quality of the waterproof layer in many cases. With a complicated construction site like immovable obstructions on the roof of existing buildings, the requirement for operational skills is higher than that in other building projects. Furthermore, it takes a longer time and so more money to handle the waterproof material under the condition of low temperature. It is a challenge to construction companies with a limited schedule and cost. The quality failures are detected in the waterproof layer. Consequently, non-specified waterproof layer is related to an unfortunate combination with the roof. Water leakage may be the result during the usage phase.

Cracks of roof concrete (R9) are discovered in roofs due to construction worker errors with mixing the concrete. Moreover, another reason is that project managers do not transfer knowledge about the proportion and flow of mixing concrete materials. Concrete cracks are common in renovation projects, and consequently, the high rework cost will influence the overall cost increase in projects.

Cleaning wall is the first construction step in the renovation of the external wall because the original external wall is covered by dust. Uncleaned wall (E1) appears when the workers skip this step to speed up the renovation process. For the project managers, they do not emphasize and transfer to the workers the critical points of cleaning the walls. Lack of the construction plan also causes the cleaning wall operation to be ignored. The impacts of Uncleaned wall (E1) are that thermal insulation material soon shows signs of cracking or chipping off, which is a significant quality issue, again hindering the completion of the building renovation projects on time. Paving interface treating mortar is regarded as the first step during the installation of thermal insulation materials to avoid the EPS boards chipping off. The main reason for Missing interface treating mortar (E2) is that construction companies skip this construction step to minimize the material cost. Missing rivets (E8) occur in installing mechanical fixings of the renovation of the external wall. Construction companies modify the number and the distribution of rivets, unauthorized by cutting corners to maximize their profit. Also, the on-site supervisors have a weak inspection of installing mechanical fixings. Consequently, the problems of missing interface treating mortar and rivets are potential hazards of thermal insulation materials falling off, or cracks that are serious safety issues for the on-site workers and residents who are living in renovated buildings.

5. Indications of Causes

The analysis of the quality failures reveals stakeholder responsibilities for poor construction quality in building energy renovation projects in Northern China. In line with previous findings [11,71], the participant causes are direct factors to affect construction quality. According to Table 5, the employment of inexperienced/untrained workers and project managers in construction companies is considered to lead to quality failures. The on-site supervisors in supervision companies and designers in design companies are also involved. The widespread fraud found in organizational management and construction companies also contributes the quality failures, in line with Jingmond and Ågren [16].

5.1. Worker's Default

The possible reason for quality failures provided by Yong [72] and Mydin [73] is poor workmanship during the construction period. In the current situation, workers are with little professional knowledge gained before joining a construction organization. Therefore, workers lack the knowledge and have little experience of construction working in building energy renovation (see the causes R8-1, R8-4). With high time pressure, workers skip some construction steps such as 'checking the waterproof in roof', 'cleaning original external wall' (see the cause R8-3, E1-3) and make errors on operational processes, such as 'measuring and recording the size of the doors and windows', 'treating gaps between the different EPS boards', and 'mixing concrete' (see the causes D2-3, R5-1, and R9-2). Several solutions are proposed to make a plan to train future construction workers with technical education and operational skills.

5.2. Lack of Experienced Project Managers

The project managers' missing management experience and little renovation knowledge result in quality failures (R9-1). Some construction workers challenge management about the technical requirements and their scope of responsibility. Often, project managers cannot provide and emphasize the key points to control quality during construction stages for workers (E1-1). Furthermore, a specific construction plan could help control the implementation steps of the projects directly [74], but project managers pay little attention to the construction plan (D2-1, E1-4). This finding is in line with previous studies. Doloi et al. [75] considered that if the construction plan is insufficient, then it is more likely to cause quality failures.

The following measures are suggested to improve the current situation. Because many project managers lack experience of renovating the existing buildings, the advice for local government is to organize meetings for the project managers to share their experiences. The incomplete construction plan can be explained by the weak implication of the administrative regulations for energy-saving renovation projects. Too few quantitative indicators for the specific descriptions of construction preparation are issued in the administrative regulations [76]. Consequently, uncompleted construction plans increase the number of quality failures. Therefore, the enforcement of a specific construction plan could be considered by policymakers in building energy renovation projects in Northern China.

5.3. Inadequate Checking Procedures by Supervisors

As can be seen from the results (see Table 2), the common sources where the quality failures arose are 'install new doors and windows,' 'install thermal insulation materials,' 'waterproof the roof,' and 'install mechanical fixings' in the construction stages. One of the main reasons for the quality failures occurring in these construction steps is the use of inappropriate materials such as the incorrect size of new windows and doors, inferior thermal insulation materials, and unqualified mechanical fixings, etc.

The inadequate supervision of materials and machinery is a reason for quality failures, such as raw materials (R2-2), semi-finished products, and mix-components (R9-3). Ye et al. [53] also stated that many on-site supervisors responsible for material and equipment management do not strictly control the quality of primary construction materials or apply enforced inspection. Additionally, the incomplete checking procedures do not provide the critical supervision points for on-site supervisors, which result in on-site supervisors ignoring some main construction steps, such as 'external wall clearing' (E1-2, E8-2). Furthermore, administrative supervisors responsible for construction documents fail to manage the construction plans during the construction design period (D2-2).

Despite all quality failures found occurring during the construction stages (see Table 2), there has been a tendency for the causes of quality failures to be induced at the construction design period [19]. Supervisors only focus on quality inspection and management at the construction stage, whereas construction preparation is ignored [50]. Therefore, the supervising of construction activities during construction design stages needs to be focused on steps such as construction plans, material, and equipment preparation. On the other hand, on-site supervisors would carry out the specific supervision flows in the construction design stages of building energy renovation projects.

5.4. Incomplete Construction Site Survey and Inaccurate Design Work

There are errors in the on-site investigation when a construction site survey is incomplete. An inadequate or incorrect site survey will make errors or changes in design documents such as 'the size of door and windows.' These errors probably cause quality failures (D2-1), hindering the goals of building energy performance. The suggestion is that the practical task to supervise the on-site survey and design document of a project would be allocated by the local government.

5.5. Fraud of Construction Companies

The quality failures may occur by organizations as a whole, rather than individual contributions from workers, project managers, supervisors, and designers in isolation. Jingmond and Ågren [16] highlighted that the organizational routine rather than individual behavior needs further attention. According to the nature of the private companies, the primary interest of construction companies is to maximize their company profits. Thus, the construction companies procure the unqualified installation material (R2-1) and make unauthorized changes in the distribution of rivets in design documents (E8-1) in order to reduce material cost.

The selection and usage of construction materials need to be checked strictly by supervision and management authorities to prevent low quality. If the material does not meet the requirements, high-quality performance of renovation projects is impossible. Construction companies in building energy renovation need to understand the importance of construction quality and regard construction quality as a critical factor to affect project value.

5.6. Inefficient Cooperation in Different Departments

The building energy renovation project involves multiple departments of construction companies. The cooperation between different departments is critical, while inefficient communication causes quality failures in building energy renovation projects (D2-4). The previous studies argue that poor department cooperation is a cause of quality failures [77,78]. For example, the procurement department cannot obtain the latest information from the construction department, resulting in the wrong size of the new doors and new windows.

The solutions are that the leadership team of the construction company needs to illustrate respective departmental responsibility. It would be necessary to raise departments' concern of corporate responsibility to reduce quality failures [79].

6. Conclusions

Building energy renovations play a vital role to reduce the energy consumption of existing residential buildings in China. Although there is legislation in place to reduce quality failures, such failures frequently occur during the construction stages in building energy renovation projects. Yet, as the authors argue that the prevention and possible eradication of quality failures are possible through the identification and evaluation of them.

The detailed analysis of quality failures identified that in the five cases in Northern China, it was concluded that the ten most common quality failures include 'Incorrect installation of the steel nails (D1)' 'Incorrect size of the new window frame and door frame (D2)', 'Untreated wall around the new windows (D4)', 'Unqualified fire resistance of EPS boards (R2)', 'The detachment between the different EPS boards (R5)', 'Misalignment of the waterproof roof layer (R8)', 'Cracks of roof concrete (R9)', 'Uncleaned wall (E1)', 'Missing interface treating mortar' and 'Missing rivets (E8)'.

These quality failures can cause unexpected losses, all too often. Rework of installation windows and doors (D2) will hinder the completion of the renovation projects on time. If the fire resistance of EPS boards cannot meet the technical requirement (R2), potential fire safety hazards will be created for residents who are living in renovated buildings. The poor airtightness and energy efficiency performance in the usage stage are the consequences because of the detachment between the different EPS boards (R5) and Concrete cracks (R9). Thus, it is hard to achieve the goals of energy efficiency rates, and such failure leads to conflicts with the aims of building energy performance.

Water leakage may be the result of Misalignment of roof waterproof layer (R8) during the usage phase. Due to water leakage, residents' complaints negatively affect the evaluations of the success of building energy renovations. Moreover, residents' dissatisfaction is acting as the dominant barrier for the successful implementation of future building energy renovation projects. Concrete cracks (R9) are common in renovation projects, and consequently, the high rework cost will influence the overall cost increase in these projects. The direct costs range from 5% to 20% of the contract value increase. The impacts of Uncleaned wall (E1) and Missing rivets (E8) are that thermal insulation material cracking or chipping off can be serious safety issues for the on-site workers and residents who are living in renovated buildings.

The research findings provide some useful suggestions for main stakeholders who participate in the whole project cycle to help them achieve successful projects. For example, construction companies are advised to improve the professional knowledge of their workers before they are allowed to join projects engaged in renovation works. This research also suggests that supervision companies would focus on improved on-site supervision and document management. Besides, design companies should not ignore the comprehensive site survey, so that the nature of the task is clearly described. To achieve high quality, adequate preparation is vital. Procedures for quality management and control should be undertaken in parallel with the preparation activities.

Despite the achievement of the research objectives, this study has limitations. The findings are interpreted in the context of China, which may be different from the context of other countries. Additionally, the respondent assessments of the frequency, impacts, and causes of the quality failures, are based on their experiences and perceptions. Thus, the interpretation of these data inevitably involved a degree of subjectivity.

The investigation of impacts and sources where quality failures arose in building energy renovations, especially the identification of the root causes of the quality failures, have provided invaluable knowledge about those construction steps and behaviors, which are likely to lead to quality failures occurring. Thus, the findings would be valuable both for an understanding of the nature of quality failures in construction processes, and for providing a foundation for exploring the causes of the quality failures. Future research can establish a framework of the causes of quality failures and focus on determining the interactions between these key causes.

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