Quality failures in Energy-saving renovation projects in Northern China

Yuting Qi

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A+BE | Architecture and the Built Environment | TU Delft BK

21#08

Design | Sirene Ontwerpers, Véro Crickx

ISBN 978-94-6366-415-8
ISSN 2212-3202

This dissertation is open access at https://doi.org/10.7480/abe.2021.08

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Quality failures in Energy-saving renovation projects in Northern China

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Thursday, 29 April 2021 at 12.30 o'clock

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This study was financed by China Scholarship Council

Acknowledgements

My PhD research would not have been produced without the participation of a large group of people. I am grateful to these people who have offered me support, encouragement, and help.

First of all, my supervision team poured in a large amount of effort to help me grow in my research path. I would like to express my sincere thanks to my promoter Prof. Henk Visscher. Thank you for your positive critical influence on my research. You placed trust in me and gave me the freedom to make my own decisions. Because of Henk, I learned to make an overall picture and plan of the research and deal with stress to do some interesting things, such as tennis, cycling, running, etc.

I am so lucky to meet Dr. Queena Qian, who guided my research path and gave me valuable comments from the first word of the research proposal to the completion of this book. Thank you because you have always been there for me. Your help is not only in my professional work but also in my personal life and development. I cannot walk through the whole PhD process without you. Thanks to Queena for most warm memories, such as dumplings, hot pot, coffee break, and so many nice talks.

Dr. Frits Meijer added significantly to this work because of your helpful comments and ideas. I would like to thank Frits for your willingness to support and sharpen this research. Our meetings were always fun and felt like a family to work together. I will never forget your encouragement to me.

Secondly, I would like to thank all my friends and colleagues in the Netherlands. Laure gave me confidence when I was confused. Thank Roger and Juan for every discussion concerning the organization of my research. I wish to thank Ling, Jiefang, Hongjuan, Dan, Qian, Bo, Chi, Yu for their help, advice, and friendship. Paula always worked with me at the last second before the building was closed. Thank Paula, in particular, for your warm help upon both journal choices and research structures. Thanks to Shima and Arash for sharing your stories and tasty food. Ad, Arjen, Herman, Nico, Boram, Cynthia, Job, and Alfred, thank you all for being my excellent colleagues.

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Thirdly, I want to acknowledge my family in the Netherlands: Zanni, Xinting, Zhangpan, Chengcheng, Weiyuan, Jingwen, Kuou, Sharon, Pandixiong, Shushu, Ayi, PH, Andy, Yabo, and Ben. Thank you all for caring for me and helping me again and again. Thanks also go to Haiyan, Meixia for countless warm talks and valuable input to this work. It is necessary to express my sincere thanks to Qiaoqiao. Thank you for everything! One of the most significant achievements for me is to know you.

I wish to thank my friends in China. Jinfeng, Yunxia, Xinyi, Xiaoxue, Xinyue, thank you for your understanding and tolerance. Specially thanks to Xiaojie, Xinpei, Rui for being with me in this corona situation. I am also grateful for the China Scholarship Council and its generous funding support.

As a final word, I would like to acknowledge my parents, who walked along with me for your support and dedication. I love you!

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Summary

The building sector contributes to about one-third of the total energy consumption worldwide (Liu, Li, et al. 2020). In China, the proportion of building energy consumption has increased rapidly year-by-year (Zheng et al. 2019). More specifically, the energy consumption of the building sector may increase to about 35% by 2020. Therefore, achieving good performance in energy-saving renovation projects in existing residential buildings is essential for reducing energy consumption (Liu, Li, et al. 2020).

The energy-saving renovation of an existing building is a critical strategy in achieving a long-term energy goal in the Chinese context. In response to the high energy consumption, the Chinese government encourages that the energy-saving renovation projects of the existing residential buildings should be widely carry out in Northern China (Chen et al. 2015). However, in China, building energy renovation projects are subjected to quality failures resulting in energy wastage, a decrease in the energy efficiency of the project, an increase in project cost, and thus negatively affecting the overall performance of the renovation projects. To sum up, the existence of quality failures has a negative impact on the energy performance of the buildings in energy-saving renovation projects, and they are threats to the projected benefits of development programmes. In order to avoid them happening in the future, it is essential to find and analyse the causes of quality failures in energy-saving renovation projects of the existing residential buildings. Therefore, this thesis examines the causes of quality failures in building energy renovation projects in Northern China. The main research question is “**What are the main causes of quality failures for the energy-saving renovation projects of existing residential buildings in Northern China?**” Based on the main question above, four steps are taken for a deeper understanding of the causes of quality failures in energy-saving renovation projects of the existing residential buildings in Northern China.

The first step is to identify and analyse the quality failures in energy-saving renovation projects of the existing residential buildings. Namely, previous researches pay little attention to the identification of quality failures and their sources, likelihood, impacts, and causes in building energy renovation projects in Northern China. This thesis conducts a case study approach to establish a foundation and to support the development of a survey questionnaire. Five residential buildings in Hohhot (a Northern city in China) that meet the renovation requirements

are selected on the criteria such as location, contract value, renovation size, construction companies, supervision companies and the current status of building energy renovation projects. Hohhot is the case city for data collection in this thesis. The implementation of energy-saving renovation has been applied in Hohhot since 2008, which is one of the pilot cities. The thesis identifies a total of 25 types of quality failure. The most common quality failures include 'Incorrect installation of the steel nails' 'Incorrect size of the new window frame and door frame', 'Untreated wall around the new windows', 'Unqualified fire resistance of EPS boards', 'The detachment between the different EPS boards', 'Misalignment of the waterproof roof layer', 'Cracks of roof concrete', 'Uncleaned wall', 'Missing interface treating mortar' and 'Missing rivets'. The causes of these quality failures are workers' defaults; inadequate checking procedures; incomplete construction site survey; inaccurate design work; fraud of construction companies; and inefficient cooperation between different departments. Thus, it is a vital step to provide knowledge about those construction behaviours, which are likely to lead to quality failures occurring.

The second step is to identify and analyse all the causes as the foundation for reducing quality failures. The novelty of this study lies in the fact that it explored and analysed the causes systematically from two main aspects in the context of China: the importance of a cause and the level of effort required to address a cause. Validated through interviews with experts, this thesis identifies 18 causes of quality failures in energy-saving renovation projects. Using both a questionnaire survey and a focus group, this thesis finds critical causes, which have a significant effect on construction quality. The detailed analysis of these causes in Northern China concludes that the "Incomplete construction site survey" is ranked as the highest level of the impacts on quality, and the most common cause is "Incomplete building information in projects". In order to clearly understand the causes, it is essential to separate them based on the efforts required to tackle a cause. The "Working under high-cost pressure", "Working under high-time pressure", "Adverse natural conditions", and "Fraud of construction companies" are external to projects at the macro scale, with a high level of required action for tackling the challenge. Action on the external cause is essential for reducing quality failures. The project coordinators cannot directly influence them because, by definition, external causes originate outside the project.

After the identification and analysis of the causes in the first and second steps of this thesis, the deeper insights from a quality management perspective are explored in **the third step**. Many causes of quality failures not only directly influence the construction quality, but also they interact in building energy renovation projects. Previous studies have predominantly identified and ranked causes without taking into account a network of different causes. There are both direct and indirect/underlying factors of influence. In order to explain how the intricate relationships among the causes affect the quality of building energy renovation projects, the interpretive structural modelling (ISM) and Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC) techniques are applied. The information is offered about how quality is influenced by separate causes that have interactive relationships. The external causes remain associated with all internal causes. The study revealed that FOUR factors: “lack of experienced project managers,” “unauthorized changes in design documents,” “incomplete building information in projects,” and “poor on-site coordination” are root causes. Their reduction or elimination helps the solving of several other internal causes. On the other hand, causes including “Use of poor materials,” “Inadequate equipment performance,” and “Inaccurate design work” are known as the most direct causes. The implementation of quality management can ensure that quality failures are not only prevented in advance but also solved. Based on the quality management actions, management strategies were obtained by combining the hierarchy structure among causes. In the context of China, the quality management actions are identified from five perspectives, including people, materials, machines, design, and organization, based on previous research studies (Liu and Guo 2014; Li 2014b).

This thesis in **the fourth step** explores how the actors and their interactions affect and cause quality failures during the renovation policy implementation process. The implementation of the renovation policies can also affect the construction quality of energy renovation projects. Actors’ interaction is vital to a proper understanding of policy-processes and policy outcomes, which help explain the causes of quality failures from a policy perspective in building energy renovation projects. In existing studies, actors and their interactions during the renovation implementation seem too often neglected in the discussion about why quality failures occur. Based on the policy network theory, the actors’ interests and resources actors have in energy-saving renovation projects are mapped. A comparative case study reveals what is done with the implementation of the renovation, and how the implementation of renovation brings about the causes of quality failures in building energy renovation projects. The public-private collaboration is a vital part of construction preparation and construction processes. Also, in terms of renovation funding, the residents’ involvement will have a hindrance to the implementation of the building energy renovation projects and affect the construction quality negatively. As a norm, local governments just focus on the construction time schedule rather than ensuring the technical conformance for energy-saving and thus addressing climate change.

This thesis mainly concludes the causes of quality failures in the building energy renovation projects. First, it is important to state that most of the quality failures can be avoided at the management level. The causes of quality failures possibly occur during the construction management processes, which affect the overall quality and energy performance, like incomplete construction site survey, poor checking procedures of supervisors, poor operational skilled workers. Second, some external causes originated at a policy level and outside the project, like working under high-cost and high-time pressure, fraud of construction companies. The implementation of building energy renovation projects is considered as one of the main causes of quality failures. These two dimensions complement each other to analyse the causes of quality failures in energy-saving renovation projects at management and policy levels in Northern China. The contribution of this thesis is to illustrate the causes of quality failures at management and policy levels, and how the causes of quality failures happened in energy-saving renovation projects in Chinese context.

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Samenvatting

De bouwsector draagt bij aan ongeveer een derde van het totale energieverbruik wereldwijd (Liu, Li et al.2020). In China is het aandeel van het energieverbruik van gebouwen de afgelopen jaren snel gestegen (Zheng, Yu et al.2019). In 2020 is het energieverbruik van de bouwsector ongeveer 35% van het totale energieverbruik. Het behalen van goede prestaties bij energiebesparende renovatieprojecten van woongebouwen is daarom essentieel om het energieverbruik te verminderen (Liu, Li et al. 2020).

De energiebesparende renovatie van een bestaand woongebouw is een cruciale strategie voor het behalen van het lange termijn energiedoel van China. In reactie op het hoge energieverbruik moedigt de Chinese overheid aan om de energiebesparende renovatieprojecten van de woongebouwen op grote schaal uit te voeren in Noord-China (Chen, Guan et al.2015). Bij deze renovatieprojecten is er echter sprake van kwaliteitsgebreken die resulteren in energieverspilling, een afname van de energie-efficiëntie van het project en een stijging van de projectkosten Deze kwaliteitsgebreken hebben een negatieve invloed op de energieprestaties van de renovatieprojecten en ze beïnvloeden de verwachte voordelen van het beleid in negatieve zin . Om te voorkomen dat ze in de toekomst gebeuren, is het essentieel om de oorzaken van deze kwaliteitsgebreken op te sporen en te analyseren. Dit proefschrift onderzoekt daarom de oorzaken van kwaliteitsgebreken bij energie-renovatieprojecten voor gebouwen in Noord-China. De belangrijkste onderzoeksvraag is “**Wat zijn de belangrijkste oorzaken van kwaliteitsverlies bij de energiebesparende renovatieprojecten van woongebouwen in Noord-China?**” Op basis van deze hoofdvraag zijn vier onderzoeksstappen gezet om meer inzicht in de oorzaken van het kwaliteitsverlies te krijgen.

De eerste stap is het identificeren en analyseren van de kwaliteitsgebreken bij energiebesparende renovatieprojecten. Eerder onderzoek besteedt namelijk weinig aandacht aan het identificeren van kwaliteitsgebreken, hun waarschijnlijkheid, de effecten en de oorzaken bij energie-renovatieprojecten voor gebouwen in Noord-China. In de eerste stap zijn casestudies uitgevoerd om het onderzoek verder te onderbouwen en is er een enquêtevragenlijst te ontwikkeld. Vijf woongebouwen in Hohhot (een noordelijke stad in China) die voldoen aan de renovatie-eisen, zijn geselecteerd op basis van criteria als locatie, contractwaarde, renovatiegrootte, bouwbedrijven, toezichthoudende bedrijven en de actuele status van energie-renovatieprojecten voor gebouwen. Hohhot is de stad waar de dataverzameling in dit proefschrift heeft plaatsgevonden. Energiebesparende renovaties worden sinds 2008 toegepast in Hohhot.. Het proefschrift identificeert in totaal 25 soorten kwaliteitsgebreken. De meest voorkomende kwaliteitsproblemen zijn ‘Onjuiste installatie van de stalen nagels’, ‘Onjuiste maat van het nieuwe raamkozijn en deurkozijn’, ‘Onbehandelde muur rond de nieuwe ramen’, ‘Onvoldoende brandwerendheid van EPS-platen’, ‘De onthechting tussen de verschillende EPS-platen’, ‘Verkeerde uitlijning van de waterdichte daklaag’, ‘Scheuren van dakbeton’, ‘Ongereinigde muur’, ‘Ontbrekende tussenlaag behandelende mortel’ en ‘Ontbrekende klinknagels’. De oorzaken van deze kwaliteitsstoringen zijn: fouten van werknemers; ontoereikende controleprocedures; onvolledig bouwplaatsonderzoek; onnauwkeurig ontwerpwerk; fraude van bouwbedrijven en inefficiënte samenwerking tussen verschillende afdelingen. Het is dus een cruciale stap om kennis te verschaffen over deze gedragsaspecten in de bouw die waarschijnlijk leiden tot kwaliteitsgebreken.

De tweede onderzoeksstap is het identificeren en analyseren van alle oorzaken als basis voor het verminderen van kwaliteitsgebreken. De nieuwe van deze studie is dat de mogelijke oorzaken systematisch zijn onderzocht en geanalyseerd vanuit twee aspecten die van belang zijn in de Chinese context: het relatieve belang van een oorzaak en de inspanning die nodig is om een oorzaak aan te pakken. In dit proefschrift worden 18 oorzaken van kwaliteitsgebreken geïdentificeerd die een rol spelen bij energiebesparende renovatieprojecten. Dit is gevalideerd door middel van interviews met experts. Met behulp van zowel een vragenlijstonderzoek als een focusgroep zijn kritische oorzaken gevonden die een significant effect hebben op de bouwkwaliteit. De gedetailleerde analyse van deze oorzaken in Noord-China laat zien dat “Onvolledige bouwplaats onderzoek” de meeste gevolgen heeft voor de kwaliteit en dat “Onvolledige bouwinformatie in projecten” de meest voorkomende oorzaak is. Om de oorzaken duidelijk te begrijpen, is het essentieel om ze te onderscheiden op basis van de inspanningen die nodig zijn om een oorzaak aan te pakken. De oorzaken ‘Werken onder hoge kostendruk’, ‘Ongunstige natuurlijke omstandigheden’ en ‘Fraude van bouwbedrijven’ zijn extern en vereisen een hoog niveau van maatregelen om ze op te lossen. Het aanpakken van deze externe oorzaken is essentieel om kwaliteitsverlies te verminderen. De afzonderlijke coördinatoren van renovatieprojecten kunnen deze factoren niet rechtstreeks beïnvloeden.

Na het identificeren en analyseren van de oorzaken in de eerste en tweede onderzoeksstap van dit proefschrift, zijn in **de derde stap** de diepere inzichten vanuit een kwaliteitsmanagementperspectief verkend. De meeste oorzaken van kwaliteitsgebreken beïnvloeden niet alleen direct de bouwkwaliteit, maar hangen ook onderling samen. Veel eerdere studies hebben oorzaken geïdentificeerd en gerangschikt zonder rekening te houden met dit netwerk van verschillende oorzaken. Er zijn zowel directe als indirecte / onderliggende invloedsfactoren te onderscheiden. Om de ingewikkelde relaties tussen de oorzaken in kaart te brengen, zijn de volgende onderzoekstechnieken toegepast: Interpretive Structural Modelling (ISM) en Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC). Met behulp van deze methodes is informatie gegenereerd over de afzonderlijke oorzaken van de kwaliteitsgebreken en hun onderlinge verbanden. Alle externe oorzaken zijn verbonden met alle interne oorzaken. Uit dit onderzoek blijkt dat de volgende vier factoren de hoofdoorzaken zijn: “Gebrek aan ervaren projectmanagers”, “Ongeautoriseerde wijzigingen in ontwerpdocumenten”, “Onvolledige gebouwinformatie in projecten” en “Slechte coördinatie ter plaatse”. Het verminderen of elimineren van deze oorzaken helpt bij het oplossen van verschillende andere interne oorzaken. Aan de andere kant zijn oorzaken zoals “Gebruik van slechte materialen”, “Onvoldoende prestaties van apparatuur” en “Onnauwkeurig ontwerpwerk” de meest voorkomende directe oorzaken. De implementatie van kwaliteitsmanagement kan ervoor zorgen dat kwaliteitsgebreken niet alleen preventief worden voorkomen maar ook kunnen worden opgelost. Door de hiërarchische structuur van de oorzaken te combineren, zijn strategieën voor kwaliteitsmanagement opgesteld in dit proefschrift . Voor de context van China zijn die strategieën, op basis van eerdere onderzoeks studies (Li 2014, Liu en Guo 2014). geïdentificeerd vanuit vijf perspectieven: mensen, materialen, machines, ontwerp en organisatie,

De vierde stap in dit proefschrift onderzoekt hoe de actoren en hun interacties het ontstaan van kwaliteitsgebreken beïnvloeden en veroorzaken tijdens het renovatieproces. De interactie tussen actoren is essentieel voor een goed begrip van beleidsprocessen en -resultaten, die de oorzaken van kwaliteitsgebreken bij energierenovatieprojecten van gebouwen mede helpen verklaren.. In bestaande studies lijken actoren en hun interacties tijdens het renovatieproces te vaak onderbelicht te zijn in de discussie over de oorzaken van kwaliteitsgebreken. Op basis van de beleidsnetwerktheorie zijn de belangen en middelen in kaart gebracht van de bij de renovatieprojecten betrokken actoren.. Een vergelijkende casestudy laat zien wat er tijdens het renovatieproject gebeurt en hoe en hoe de kwaliteitsgebreken in energie-renovatieprojecten worden veroorzaakt. Publiek-private samenwerking is een essentieel onderdeel van de bouwvoorbereiding en bouwprocessen in de Chinese renovatiepraktijk. Onvoldoende betrokkenheid van bewoners kan een belemmering vormen voor de uitvoering van de energie-renovatieprojecten en kan zo de bouwkwaliteit negatief beïnvloeden. De lokale overheden richten zich vooral op het bouwtijdschema in plaats van ervoor zorg te dragen dat de energiebesparende maatregelen conform de technische eisen worden uitgevoerd.

De conclusies van dit proefschrift hebben voornamelijk betrekking op de oorzaken van kwaliteitsgebreken in de energie-renovatieprojecten. In de eerste plaats kunnen de meeste kwaliteitsgebreken op managementniveau worden vermeden. De oorzaken van kwaliteitsgebreken zijn te vinden tijdens de managementprocessen, zoals onvolledig bouwplaats onderzoek, slechte controleprocedures van toezichthouders en slechte geschoolde arbeiders. Ten tweede zijn enkele externe oorzaken buiten de afzonderlijke projecten ontstaan op beleidsniveau , zoals werken onder hoge kosten en hoge tijdsdruk en fraude van bouwbedrijven.. De bijdrage van dit proefschrift is dat het een nieuw analysekader biedt om de oorzaken van kwaliteitsgebreken bij energiebesparende renovatieprojecten op management- en beleidsniveau in Noord-China te analyseren.

1 Introduction

1.1 Energy-saving targets of existing residential buildings in China

Energy conservation has become a priority in the effort to address environmental pollution and achieve low-carbon development (Lin and Liu 2015a; Shrestha and Kulkarni 2013). Currently, building energy use accounts for 40% of global energy consumption, and this proportion is expected to reach 50% by 2030 (Juaidi et al. 2016). In China, energy consumption has more than doubled in the past two decades (Zhao et al. 2014). China has become one of the world's largest energy consumers, accounting for 19% of global energy consumption (Zhao et al. 2014). China's energy consumption in the building sector accounts for nearly one-third of total PRC energy consumption, and keeps increasing rapidly (Lin and Liu 2015b). In an effort to achieve energy savings, the Chinese governments typically rely on energy policy tools, which can help conserve energy in thousands of existing buildings, such as the energy-saving renovation programme (Hou et al. 2016). The potential benefit of effective renovation in terms of energy savings is high (Baldwin et al. 2018).

Energy-saving renovations of existing residential buildings in Northern China have been promoted by the Chinese government since 2007 (Kong, Lu, and Wu 2012). The energy-saving renovation undertaken has shown that full-scale renovation can create a good indoor thermal environment. Moreover, energy-saving renovations need to meet a target, such that heating energy consumption is reduced by 40%-50% relative to the consumption during the early 1980s (Chen et al. 2015).

Overall control targets for the whole of the northern regions in China have been or will be published by national and local governments. For example, the goals of the 11th Five-Year period (2006-2010) were the energy-saving renovation of 150 million m^2 (building floor area) in residential buildings of Northern China. Moreover, the guidance and support of government policies play an important role, such as the target set for the renovation designated areas. During the 12th Five-Year period (2011-2015), building energy renovation in Northern China reached 1.17 billion m^2 of the building floor area. For the 13th Five-Year Plan (FYP) (2016-2020), according to Building Energy Conservation and Green Building Development, the central government intended to renovate 2.5 billion m^2 of building floor area. Thus, the large-scale energy-saving renovations are being realized in China. However, the execution of these plans has not always been successful. Indeed, some quality failures would be inevitable in renovation projects (Liu 2015, Lo 2015).

These quality failures can cause unexpected and significant losses, such as overrun time, safety hazards, and only a low-level energy performance after completion (far below expectations). In order to understand the reasons why actual performance fell so far short of expectations in China, previous research efforts have attempted to find the negative factors concerning the quality failures in building energy renovation projects, as well as their technical solutions to undertake rework (Hwang, Zhao, and Goh 2014; Wang 2012b). Yet, little attention has been paid towards analysing the causes of quality failures in building energy renovation projects in Chinese context (Wang 2012b; Yu 2013).

1.2 Quality failures and their causes in the energy-saving renovation projects of the existing residential buildings

1.2.1 Energy-saving Renovation Projects in Northern China

The amount of energy consumption of any particular building sector has a close relationship with different climate zones, including the Severe Cold Zone, Cold Zone, Hot Summer and Cold Winter Zone, Hot Summer and Warm Winter Zone, and Mild Zone. Of these climate zones, the Severe Cold Zone and Cold Zone are called '***heating zones***' and are located in Northern China, where building sectors receive district heating in winter. Two-thirds of areas in China are located in cold and severe cold zones (Zhao, Künzel et al. 2015), and 40% of the total energy consumption in residential buildings are consumed in Northern China (Zhou, Zhang et al. 2015).

Therefore, the energy saving potential in Northern China is high (Zhou, Wang et al. 2018). Based on the technical guidelines for building energy renovations in Northern China, the external envelope (including the external wall, roof, door, and window) remarkably affects building energy consumption. Therefore, energy-saving renovations usually include the external envelope structure ("Technical guidelines for heat supply meter and energy-saving renovation of existing residential buildings in northern heating areas" 2008).

In 2007, the Chinese national government made an energy-saving target in the government-led mode for the energy-saving renovation projects of the existing residential buildings. The current expectation is that the energy-saving renovation undertaken can achieve 40%-50% of the energy consumption compared to targets of the early 1980s from national governments. Energy-saving renovation projects can produce a good energy performance and also a more comfortable indoor thermal environment (Chen et al. 2015). However, this energy-saving target is negatively impacted by the quality failures when upgrading existing buildings, which frequently occur in energy-saving renovation projects. Quality failures during both the construction upgrading and even the usage process hinder the energy efficiency of the completed energy-saving renovation projects of the residential buildings (Lo 2015).

Responsibilities of Main Stakeholders

In China, both national and local governments, lead energy-saving renovation projects of existing residential buildings. The national government issues regulations and incentives on building energy renovation to promote the renovation of the existing residential buildings. Meanwhile, the responsibilities of implementing these energy policies are transferred to local governments (the provincial, municipal, and district governments) by the national government (Kong, Lu, and Wu 2012). Local governments implement the policies accordingly with organizing and planning the building energy renovation projects. The national and local governments also issue the applicable laws, regulations, and other policies for technical requirements. For example, the Chinese central government developed ***'Technical guidelines for heat supply meter and energy-saving renovation of existing residential buildings in Northern heating areas'*** (China 2008) at the national level.

Besides the governments, other stakeholders, including supervision companies, construction companies, and design companies, are fully involved in carrying out the building energy renovation within their respective localities. Supervision companies are the delegates of local governments to supervise the construction quality by doing on-site inspections and construction document checks. Furthermore, construction companies are also the main stakeholders to ensure quality standards are achieved, by constructing, organizing, arranging, and checking the construction processes of renovation projects. The responsibilities of design companies are to provide the design documents, including renovation specifications, design drawings, technical requirements, and other relevant documents. These design documents are used to guide construction methods and flows.

Renovation Processes

Based on the previous studies (Wu et al. 2012), eight process phases can be identified, namely: target setting, decision-making, tendering and bidding, survey and design, construction design, construction, acceptance, and usage, as shown in Figure 1.1. These are explained as follows.

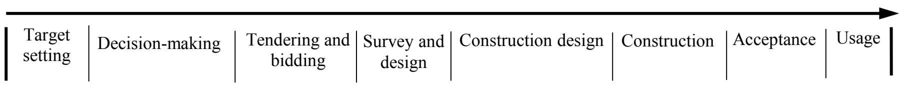

FIG. 1.1 The stages of renovation projects (Modified from (Wu et al. 2012))

In the **target setting phase**, national governments determine renovation targets and plans for local governments. During this phase, financial support is planned by the governments. Based on each renovation target, the feasibility of renovating existing buildings is judged by the municipal and district governments **during the decision-making phase**. After the building energy renovation projects are set up, **tendering and bidding** is the primary work of the municipal government in order to contract the task with the respective design and construction companies. In the **survey and design phase**, the design companies need to survey on-site situations, including the building structure, appearances, existing installation, and other information. The on-site survey information is the foundation for the design documents. Construction companies in the **construction design phase** make construction plans to arrange construction resources, such as men, materials, and machines before the project starts to construct. For the **construction phase**, the construction activities are complicated, and workers need to complete the main body of the building energy renovations. A significant impact on construction quality happens in the construction phase. Before the **usage** by the residents, **quality acceptance** must be carried out by specific stakeholders, including officers in local government, chief supervisors, designers, and project managers. Quality acceptance is the last procedure to manage construction quality within several stages of renovation projects.

1.2.2 Definition of quality and impact of the quality failures in the construction industry

ISO issued by the International Organization for Standardization, defines quality as the totality of characteristics of an entity that bear on its ability to satisfy stated or implied needs (ISO 2000). All constructions must meet the technical requirements set in the building regulations, and these requirements are minimum quality demands (Meijer and Visscher 2017b). According to the above definitions and expressions, this research defines quality as the fulfilment of the technical requirements as laid down (stated) by regulatory agencies.

The finished quality of construction projects has been one of the most significant factors to which the public pays increasing attention (Chen and Wang 2016). The incidence of quality failures is an unsettled issue in the construction markets because these quality failures have been common and frequently arising in construction projects (Hwang and Yang 2014; Subhi, Dinesh, and Resmi 2017). In the context of China, the existence of quality failures has a direct impact on the energy performance of the buildings (Gang et al. 2016). Quality failures cause a tremendous amount of energy to be wasted annually in construction and usage processes (Lo 2015). Furthermore, quality failures during construction processes are threats to the success of construction projects with their consequential overdue schedule and unexpected cost overruns (Liu 2015b). Owing to past quality failures, residents' dissatisfaction is acting as the dominant barrier for the implementation of the future building energy renovation (Lo 2015). Thus, overcoming these quality failures is necessary to promote and boost the successful accomplishment of building energy renovation projects (Wang 2012b). However, very few studies analysed the impacts of quality failures and their causes in the Chinese construction context.

Some international studies focused on their impacts and potential threats in construction projects (Forcada, Macarulla, and Love 2013; Aïssani et al. 2016; Alencastro, Fuertes, and de Wilde 2018). According to Forcada et al.'s studies, due to quality failures, a majority of the existing buildings that have been energy renovated do not save as much energy as the designs have predicted (Forcada, Macarulla, and Love 2012). Johnston et al. found that the heat-transfer coefficient is 1.6 times greater than predicted, caused by quality failures (Johnston, Miles-Shenton, and Farmer 2015). Based on previous research, the extent of quality failures mean that the overall heat loss is much higher than predicted in the existing residential buildings (Bell et al. 2010; Alencastro, Fuertes, and de Wilde 2018). In particular, in energy renovation projects, increasing quality failures are highly likely to cause extra energy consumption. Visscher (Visscher 2014) has shown that quality failure is one of the main causes of a large discrepancy between expected and real (actual) energy use.

Quality failures erase the projected benefits of development programmes (Ede 2011; Kakitahi, Landin, and Alinaitwe 2011). Much as this is notable, these quality failures during the construction processes result in material and labour wastage, requiring reworks, additional time, and other resources (Mahmood and Kureshi 2015). Furthermore, occurrences of quality failures can also lower the health and safety levels of residents (Georgiou, Love, and Smith). In short, these quality failures bring a project value loss and negative impacts on project time and cost (Forcada et al. 2014; Schultz et al. 2015). Potential fire hazards will be created due to quality failures in the construction stage and even the usage stage.

1.2.3 Quality Failures in the energy-saving renovation projects

Energy-saving renovations of residential buildings are one of the most challenging types of general construction projects to undertake, with a higher probability of schedule delays and worse quality performance than that of other constructions (Cattano et al. 2013). Unique quality failures in building energy renovations include physical constraints because of existing conditions, limited work sites, and limited knowledge of existing conditions (Cattano et al. 2013). In order to reach high-quality goals, more strict and supportive government regulations and quality control systems are needed (Meijer and Visscher 2016b). The current challenges are similar in the Chinese context.

China has become one of the most significant contributors to energy use, and the building sectors have drawn full attention due to their high energy consumption (Yuan et al. 2017). As shown in national statistics, in China, the building sector accounts for approximately 27.45% of the total energy consumption (Zhao et al. 2019). Thus, it is imperative to improve the energy conservation of existing buildings in China. The Chinese government is promoting the increasing amount of energy-saving renovation projects. However, the implementation of the energy-saving renovation programme involves a complex system related to various stakeholders and processes in the Chinese context. In this implementation system, the highest potential wastage for energy consumption is caused by the quality failures occurring in the energy renovation projects (Zhang 2010; Liu 2016). Thus, quality failures are the key concern of the renovation constructions (Chen and Wang 2016). Previous research efforts have shown that the quality failures in the context of China affect the building energy renovation projects negatively. Gang et al. (Gang et al. 2016) and Wang (Wang 2012b) considered that during the process of renovation of the external wall the quality failures are most likely to happen. Also, Chen et al. (Chen and Wang 2016) and Liu (Liu 2015b) surveyed that various quality failures exist in the existing building renovation, such as the invalid fill between the frame and window panes. The detailed quality failures are identified, such as ‘Incorrect installation of the steel nails,’ ‘Untreated wall around the new windows,’ ‘Missing rivets,’ and so on. Because of the novelty of the building energy renovation projects, the quality failures and their causes have not yet been studied. Therefore, quality failures still need to be resolved for the further development of building energy renovation projects in China.

1.2.4 Causes of Quality Failures

Quite few research papers are relevant to the causes of quality failures happened in the energy-saving renovation projects in Chinese context. Therefore, this thesis reviewed the papers in detail to identify the causes of quality failures in the building construction industry. Attention has begun to focus on the causes of quality failures in the construction industry in China, in order to understand the nature of quality failures and how they occur. These studies have identified different causes of quality failures. According to Zhang’s research (Zhang 2017), inaccurate on-site investigations will cause erroneous investigation reports, which result in quality failures in the construction site. Xu et al. (Xu et al. 2015) ranked poor communication and cooperation among the stakeholders as the top factors to hinder the acceptable quality of construction projects. Liu (Liu 2015b) researched the relationships between design documents and construction quality and concluded the errors during the design stage in design documents are more likely to cause subsequent quality failures. This finding is consistent with the conclusions of Jiao et al. (Jiao et al. 2011), who stated that checking the design documents is a significant procedure to control construction quality.

For an alternative view of different stakeholders in the Chinese construction industry, Liu found that construction companies are the main stakeholders to affect the construction quality (Liu 2010), and poor on-site management of construction companies may cause quality failures (Li 2014a). In Li’s studies (Li 2014a), the limitation of technical knowledge and lack of workers’ training are the main causes of quality failures in construction projects.

Previous studies in the international background have analysed the causes of quality failures; for example, Hughes and Thorpe (Hughes and Thorpe 2014a) studied that poor supervisor competency and incomplete design drawings are fundamental causes in the construction industry. Chong and Low (Chong and Low 2005) considered that poor craftsmanship is possible to cause quality failures. Love et al. (Love et al. 2010) investigated and considered that causes of quality failures are inefficient information exchange, excessive client involvement, and lack of clearly-defined working procedures. Also, Kakitahi et al. (Kakitahi et al. 2015) showed the three substantial causes of quality failures are inadequate communication, embezzlement, and dishonesty. Meanwhile, Aiyetan (Aiyetan 2013) ranked that the causes of quality failures are inadequate communication, incomplete construction planning, ineffective management skills, inexperience of personnel, and poor construction materials. Based on these causes identified, Aiyetan (Aiyetan 2013) provided some suggestions for quality improvements. Enshassi et al. (Enshassi, Sundermeier, and Zeiter 2017b) identified and ranked that the five main causes of quality failures are fraud, competitive pressure, poor management, time pressure, and the absence of work security. In sum, a set of causes was identified based on a thorough review of previous studies, as summarised in Table 1.1.

TABLE 1.1 List of identified causes from previous studies internationally

Causes	Descriptions	References
Incomplete construction site survey	Designers or construction companies ignore or make a deficient site survey.	(Aiyetan 2013)
Inaccurate design work	There are mistakes and discrepancies in design documentations	(Aiyetan 2013; Jingmond and Ågren 2015a; Hughes and Thorpe 2014a)
Unsettled plan or lack of construction plan	Construction companies ignore or make deficient construction planning	(Aiyetan 2013; Dixit et al. 2017)
Unauthorized changes in design documentations	Construction companies change design documentation without the agreement of designers	(Love et al. 2010)
Incomplete building information in projects	Technical information or original documentation are missing	(Ye et al. 2014; Aiyetan 2013; Jingmond and Ågren 2015a; Kakitahi et al. 2015; Love et al. 2010; Hughes and Thorpe 2014a; Xiang et al. 2012)
Poor operational skilled workers	Operational labour in construction processes lacks skill	(Jingmond and Ågren 2015a; Schultz et al. 2015; Oyedele et al. 2015; Aljassmi and Han 2014; Forcada et al. 2012; Forcada et al. 2014; Chong and Low 2005; Aiyetan 2013)
Use of poor materials	Quality of construction materials is non-specified	(Ye et al. 2014; Aiyetan 2013; Oyedele et al. 2015)
Inadequate equipment performance	Mechanical equipment is non-specified	(Jingmond and Ågren 2015a; Hughes and Thorpe 2014a)
Poor on-site coordination	The speed of communication on site between main stakeholders is low.	(Aiyetan 2013; Schultz et al. 2015; Dixit et al. 2017)
Poor site management	Workers, material, and equipment on site are not strictly managed and controlled	(Aiyetan 2013; Dixit et al. 2017)
Complex on-site environment	Site conditions are limited, such as narrow construction spaces	(Ye et al. 2014; Hughes and Thorpe 2014a)
Poor checking procedures of supervisors	Supervision and feedback processes make failures	(Ye et al. 2014; Aiyetan 2013; Love et al. 2010; Hughes and Thorpe 2014a; Oyedele et al. 2015)
Fraud of construction companies	Construction companies cut corners by cheating in work.	(Schultz et al. 2015; Enshassi, Sundermeier, and Zeiter 2017b)
Working under high-cost pressure	Budget and funding for renovation projects is insufficient	(Aiyetan 2013; Schultz et al. 2015; Kakitahi et al. 2015; Enshassi, Sundermeier, and Zeiter 2017b)
Working under high-time pressure	Design time and construction time is urgent	(Aiyetan 2013; Schultz et al. 2015; Enshassi, Sundermeier, and Zeiter 2017b)
Adverse natural conditions	The natural environment is an interference such as low temperature, inadequate solar energy, rain interference	(Ye et al. 2014)

Different construction projects will generate different types of quality failures depending on the specific technical measures, construction flows, responsibilities of stakeholders, as well as the implementation of the policies. Similarly, various construction projects have their own unique causes of quality failures (Kylili, Fokaides, and Jimenez 2016). In energy-saving renovation projects of residential buildings, the causes of quality failures, therefore, are required to be identified and studied based on the specific construction natures and characteristics.

1.3 Research Approach

1.3.1 Problem statement

It is significant to improve energy efficiency, in order to address the problems of climate change and resource scarcity (Alam et al. 2019). Buildings are major consumers of energy, contributing to a large proportion of the total energy-use globally (Jafari and Valentin 2017). The low energy-efficiency of the existing buildings has resulted in excessive energy consumption and the massive emission of greenhouse gas (Yuan et al. 2017). In Northern China, buildings are responsible for the majority of the energy consumption, and this increased by more than 10% annually (Liang, Peng, and Shen 2016; Xu, Chan, and Qian 2011). Energy-saving renovation projects for existing residential buildings in Northern China are emphasized by Chinese governments (Liang, Peng, and Shen 2016). During the 13^{th} Five-Year Plan (2016-2020), China targeted the building energy-saving by implementing renovation of more than 2.5 billion square meters (m2) floor area (Liu, Tan, and Li 2020). However, quality failures frequently occur during the construction processes in energy-saving renovation projects. The impact of these quality failures has resulted in unsatisfactory energy performance throughout the usage phase of the existing buildings. It seems that the challenge in the implementation of the energy renovation programme is in preventing quality failures repeatedly occurring in construction.

Reducing quality failures plays a critical role in energy renovation projects and has received increasing attention in order to better achieve the energy-saving goals (Paiho, Seppä, and Jimenez 2015). Several studies have documented the quality failures in general construction projects and their contributions in failing to reach accepted quality performance (Lin, Chang, and Su 2016; Lee et al. 2019). However, the reasons why quality failures in building energy renovation projects occur in the Chinese context were unknown. The analysis and understanding of the causes are a vital prerequisite to prevent and eliminate quality failures. A comprehensive review and commentary on the causes of quality failures occurring in building energy renovation projects are, however, still scant. The causes of quality failures in energy renovation projects have been identified and analysed incompletely. This results in a limited understanding of why quality failures occur and how these quality failures could be avoided (Xiang, Zhou et al. 2012).

The causes are not isolated but rather stem from complex correlations in impeding good quality performance (Tan et al. 2019). Due to their neglect of the causal relationships among these causes of quality failures, the project coordinators have actually failed to manage the quality of construction projects. Thus, a deeper insight into the intricate relationships among the causes is needed (Shen et al. 2016). Quality construction often depends on policy performance, which closely relates to actors and their interactions. Consequently, there is a need to upgrade actors' behaviour and provide political support for controlling the causes of quality failures. However, in the Chinese context, during the renovation implementation process, the ways in which the actors and their interactions affect and cause quality failures is barely even considered.

Given the limitations mentioned above, the in-depth study needs to explore how to reduce the causes of quality failures to facilitate the successful accomplishment of the building energy renovation projects. Accordingly, there is a need for identification and analysis of the causes: including the relationships among the causes and actors' interactions during the implementation of the renovation policies. Valuable information could be provided to help both project participants and policy-makers to better understand the causes of quality failures.

1.3.2 Aim & research questions

The main focus of this thesis is to deepen the understanding of the causes of quality failures in energy-saving renovation projects of the existing residential buildings. This aim is achieved by answering the main research question, which is formulated as follows:

What are the main causes of quality failures for the energy-saving renovation projects of existing residential buildings in Northern China?

The main question is further subdivided into four key questions, as follows:

1 **What are the quality failures and their characteristics in building energy renovation projects in Northern China? (Chapter 2)**

The research began with the initial idea to look into the extent and characteristics of quality failures in building energy renovation projects (Chapter 2). It became clear that quality failures can cause unexpected losses and repeatedly happen. This also meant it would be hard to achieve the goals of energy efficiency, and such failure would lead to conflicts with the aims of improving building energy performance. Therefore, the next logical step was to find out why the quality failures occur.

2 **What causes quality failures in building energy renovation projects in Northern China? (Chapter 3)**

This sub-question considered that the causes of quality failures are not only identified but also studied from two perspectives: the importance of a cause (related to impact and frequency) and the level of effort required to tackle a cause (related to origin and scale). The causes were evaluated in relation to the internal and external to the projects. The following two sub-questions explore what can be done to reduce these causes.

3 **What are the relationships among the causes of quality failures in building energy renovation projects in Northern China? (Chapter 4)**

The causes of quality failures in practice were analysed by the Interpretive Structural Model (ISM) in order to provide an assessment of the interrelationships of the causes. Based on the results, appropriate strategies were provided to improve quality performance. The solutions were categorised as people, material, equipment, design, and organization with a project level of the existing management actions.

4 **How do the actors and their interactions affect and cause quality failures during the renovation implementation process in Northern China? (Chapter 5)**

This key question was seen at the national and local level through the lens of a network among stakeholders in a policy network. By answering this sub-question, the causes of quality failures were explained by studying the interactions among actors and analysing how these interactions affect actors' resources exchange.

1.3.3 Research scope

A strict definition of the research scope is clarified in this section. The word "Quality" in this thesis is defined as the totality of elements and characteristics of a project with satisfying technical requirements issued by governments (see Fig. 1.2).

Three renovation items are contained in energy-saving renovation projects of the existing residential buildings in Northern China. These renovation items are envelope thermal insulation, heating system, and heat meters and regulation facilities. Extant studies reveal that there is a high energy loss in envelope thermal insulation (Zhao, Wu, and Zhu 2009; Shilei, Yong, and Jinying 2009; Li, Zhao, and Zhu 2013). Based on the technical guidelines, the envelope thermal insulation is described as three technological measurement categories, which are doors and windows, roof, and external walls (see Fig. 1.2). Since almost all quality failures occur in the energy-saving renovation of envelope thermal insulation based on the practical investigation, this thesis focuses on the renovation item of the ***envelope thermal insulation performance***.

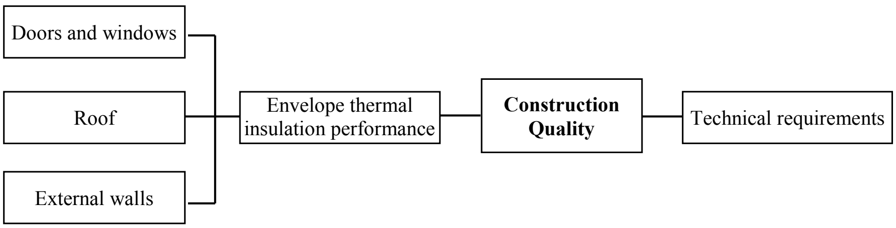

FIG. 1.2 Research Scope

1.3.4 Research methods

The main research method used in this thesis is through case studies of energy-saving renovation projects in residential existing buildings. The renovation project cases were selected on the basis of the following criteria. First, the cases are located with representative features, such as climate zones, temperature characteristics, etc. Second, renovation regulations and quality control are applied in the whole construction processes of case studies. Third, the main project stakeholders in cases projects of energy-saving renovation are involved, such as construction workers, supervisors, and designers. The case study approach was conducted to establish a foundation to support the development of the interviews with experts and survey questionnaires.

Hohhot is a representative city in the heating areas of Northern China in an energy-saving renovation context (Figure 1.3), so it was selected as the case city. In Hohhot, the coldest month is January with an average temperature of about −12 °C, and the hottest month is July with an average temperature of about 22 °C. Geographically, Hohhot is located in the northwest of the territory where winters are long and cold. Consequently, building heating is a significant energy demand in this city. As the centre in the Inner Mongolia Autonomous Region, Hohhot is one of the pilot cities in China. The energy-saving renovation of existing buildings started in Hohhot in 2008, and the administrative and technical regulations of building energy renovations issued by the national governments have been applied.

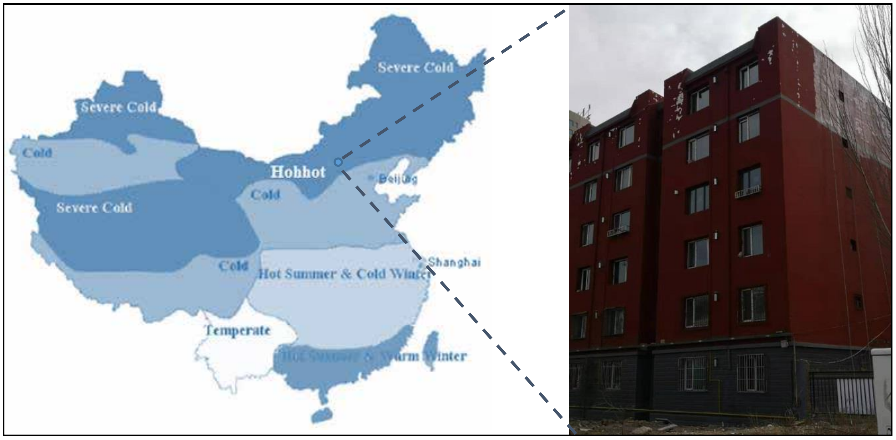

FIG. 1.3 Location of Hohhot

Data were collected by qualitative research methods, including site visits, review of project documents, interviews with experts, and focus groups. The interviews and questionnaires were held at two different points of time in this study. Two field visits were made to each renovation case in the periods: January to March 2018; and July 2019. In total, seven cases were selected by conducting interviews with the cooperative respondents. These respondents are representatives from different key backgrounds/roles in order to provide a comprehensive view of the research questions. Two questionnaire surveys were conducted in Northern China, and one focus group was organized in the case city. Table 1.2 shows what methods are used for which part of the research, and what aims are achieved by these methods.

TABLE 1.2 Research methods in this thesis

No.	Research methods	Chapters	Aims
1	The first interview and site visit	Chapter 2	Identify quality failures; Explore and test the construction steps, impacts, and causes of quality failures.
		Chapter 3	Confirm the causes if the causes were possible to appear during construction processes; Explore the relationships between quality failures and these causes.
		Chapter 4	Obtain the final list of identified causes; Establish the contextual relationships between causes.
2	The first-round questionnaire	Chapter 2	Evaluate the quality failures with respect to occurrence frequency.
3	The second-round questionnaire	Chapter 3	Evaluate the causes of quality failures with respect to the level of impact and frequency.
4	Focus group	Chapter 3	Discuss the origin and scale of the causes and obtain the classification of the causes.
		Chapter 4	Test if there are logical or conceptual contradictions in the structural model and classification; Provide some recommendations regarding the causes of quality failures at the quality management level.
5	The second interview	Chapter 5	Investigate the actors' interactions and their conflicts.

1 **The first research sub-question (Chapter 2)** was answered by identifying quality failures, evaluating the quality failures with respect to occurrence frequency, and exploring the construction steps, impacts, and causes of quality failures. The data was collected by the first interview, site visit, and the first-round questionnaire.

The causes of quality failures were reviewed based on previous studies, before the first interview and site visits. The first interview generated background information to identify and confirm the quality failures and their causes. A series of interviews with practitioner experts was undertaken to collect data relating to the quality failures and their causes. The following criteria formed the basis for the interviewer selection. First, the experts were from different key backgrounds/roles to provide a comprehensive understanding of the causes of quality failures. Second, the experts have sufficient working experience with engaging in the renovation field for over eight years. Separate interviews were conducted as the on-site fieldwork in January to March 2018 in the case study city with 22 experts, consisting of five quality supervisors from the supervision company, ten project managers, two designers, and five government officers.

In the first-round questionnaire, 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 first questionnaire survey was 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. 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%.

2 **For the second research sub-question (Chapter 3)** data from the first interview, site visit, the second-round questionnaire, and focus group were used to confirm the causes of quality failures, evaluating the causes of quality failures with respect to the level of impact and frequency, discussing the origin and scale of the causes, and obtaining the classification of the causes.

The purpose of the second-round questionnaire survey is to have a deeper understanding of the causes of the quality failures in energy-saving renovation projects. Throughout the second questionnaire survey, the data for analysing the importance (impact and frequency) of the causes were collected. The questionnaire was designed based on the literature review and confirmed by the interviews with experts. It comprised two parts: 1) questions relating to the respondents' background; and 2) their rating of the impact and frequency of each listed cause of the quality failures in energy-saving renovation projects. The questionnaire scoring system was sufficient to collect respondents' perceptions while ensuring a sufficiently large size sample for subsequent analysis. The target groups for this questionnaire are design companies, supervision companies, government, and construction companies to capture their current energy-saving renovation construction. In this way, a total of 280 questionnaires were dispatched to respondents. Finally, 113 fully completed questionnaires were received, giving a response rate of 40.4%. Of these, 22 (19.4%) were officers from governments, 49 (43.4%) were from construction companies, 27 (23.9%) were supervisors from supervision companies and 15 (13.3%) from design companies.

A focus group was used as the collection method of data. The focus group was chosen rather than other qualitative research methods because it can generate information on the collective views from the participants in the group. Ten participants are involved in the focus group. The criteria to select focus group participants were: a) must be at management level (i.e., project managers, construction supervisors, officers in government, designers); b) must have worked on energy-saving renovations for more than eight years, and c) must have rich experiences on project management and quality control. According to the relevant studies conducted by Yu et al. (Yu et al. 2018), these criteria can guarantee that the selected participants are qualified to discuss the topics pertaining to the building energy renovation projects.

3 **The third research sub-question (Chapter 4)** was an**s**wered by establishing the relationships among causes. The interview and site visit were used to establish the contextual relationships between causes. Before the interview and site visits, the researchers reviewed the causes of quality failures according to previous studies. The contextual relationships between causes were established after two rounds of discussion in the interview. In order to achieve more in-depth insights, the Interpretive Structural Model (ISM method) and Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC) technology were adopted to develop a structural model of these causes of quality failures. Then, according to the focus group, the logical or conceptual contradictions of the relationships of the causes were tested, and some recommendations are provided regarding the causes of quality failures.

4 **The fourth research sub-question (Chapter 5)** dealt with the data from a case study to investigate the actors' interactions and their conflicts in building energy-saving renovations. The framework of policy network theory was applied to design interviews, as this theory highlights the actors and their interactions in the policy implementation processes. The fieldwork was done, and the interviews were conducted in each of the two cases with representatives of involved actors.

The interview gathered detailed information about the actors' interactions during the renovation processes and their conflicts in the implementation of the building energy-saving renovation programme. In total, 14 persons have been interviewed, six of whom have been interviewed more than once. The Chinese contexts of building energy-saving renovation projects, such as renovation area targets and financial plans at a national level, the involved actors, their objectives, and resources, are firstly understood through the official websites and relevant literature in order to complement the interviews. The goals of the interviews have been to 1) describe the origin, official goals, and current situation of the project; 2) investigate the actors, their objectives, and resources; 3) build the actors' relations and conflicts.

1.4 Thesis structure

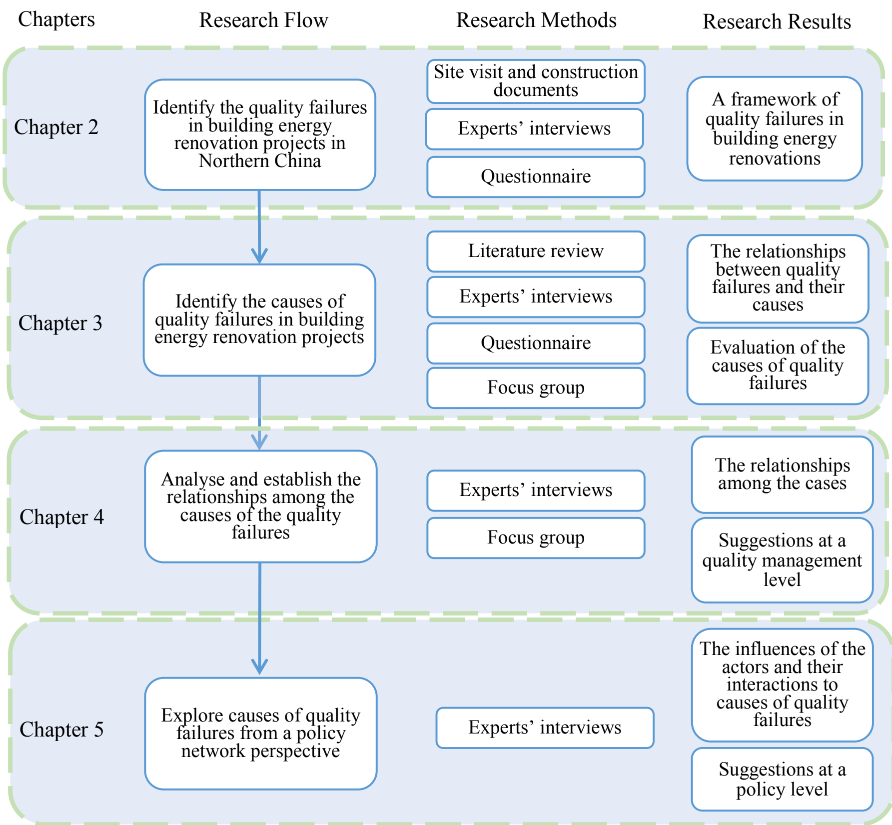

FIG. 1.4 The research method and structure of this thesis

A more logical structure of the thesis is depicted in Figure 1.4. The chapters of the thesis have been compiled chronologically, in terms of analytical work as well as their publishing timeline. Chapters 2 to 4 are essentially journal articles, either published or in process. Chapter 5 has been submitted for publication. Chapter 2 identified the nature of quality failures as a foundation for exploring the causes of quality failures. Chapter 3 explored the relationships between quality failures and their causes in energy-saving renovation projects. In Chapter 3, the causes have been classified and evaluated. In order to achieve a high-quality performance of building energy renovation projects, Chapters 4 and 5 deal with the solutions of these causes identified. Chapter 4 mapped the causes of quality failures and provided suggestions from a management perspective to solve the causes. Chapter 5 studied the formation of the causes from a policy perspective and tackled the causes through improving the actors' behaviour and their interactions in the building energy renovation projects. Highlight areas divide the content into four chapters of this thesis.

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

Published as: Yuting Qi, Queena K. Qian, Frits M. Meijer, and Henk J. Visscher. (2019). "Identification of quality failures in building energy renovation projects in northern china." Sustainability 11, no. 15, 4203.

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 the 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 survey; inaccurate design work; fraud of construction companies; and inefficient cooperation between different departments. Above all, the behaviours 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

2.1 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 (Yang, Yan, and Lam 2014). In China, the energy consumption in building stock accounted for about 24.1% of total national energy use in 1996, rising to 27.5% in 2001, and may increase to about 35% by 2020 (Lo 2014a). The building energy consumption is rising rapidly year by year in China (Lin and Liu 2015a; Qian, Chan, and Choy 2012).

In favour of developing 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 (Kong, Lu, and Wu 2012). For building energy renovation projects in Northern China, the central government planned and guided to renovate the existing residential buildings. A large number of existing buildings were renovated, and building energy renovations entered a large-scale implementation stage in Northern China (Liu et al. 2018). However, quality failures happen frequently in this type of building energy renovation projects, which do not meet the technical requirements (Liu 2015a). 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 (Hwang and Yang 2014). Forcada et al. (Forcada et al. 2014) defined quality failures as those in which construction product failed to fulfil the technical requirements and so needed the re-doing during the construction processes. The existence of quality failures has a direct impact on the energy performance of the buildings (Alencastro, Fuertes, and de Wilde 2018). 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 programmes (Ede 2011; Kakitahi, Landin, and Alinaitwe 2011). Owing to past quality failures, residents' dissatisfaction is acting as the dominant barrier for the implementation of the future building energy renovation (Lo 2015). Therefore, researching quality failures is necessary to achieve high-quality performance in the building energy renovation projects.

While quality failures are increasingly regarded as well-known problems and have been widely discussed in the literature (Kylili, Fokaides, and Jimenez 2016), the evaluations in existing studies have mainly focused on the impact of the quality failures (Alencastro, Fuertes, and de Wilde 2018). Quality failures repeatedly appear in construction (Devi and Chitra 2013; Jingmond and Ågren 2015a; Park et al. 2013), 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 the frequency distribution (Adenuga 2013; Hwang, Zhao, and Goh 2014; Jingmond and Ågren 2015a). 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 (Wang 2012b; Zhang and Song 2017). 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 (Wang 2012b; Yu 2013).

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 2.2 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 2.3 introduces the research method. In Section 2.4, 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 2.4. Section 2.5 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 conclusion in Section 2.6.

2.2 Literature review

2.2.1 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 (Battikha 2003). 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' (Battikha 2003; Jha and Iyer 2006). Sim and Putuhena (2015b) argued that the quality of construction can be guaranteed if quality standards and specifications have been earnestly implemented. Shanmugapriya and Subramanian (2015) 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. (2014) and Sommerville (2006), 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. (2009) defined quality failure as a "shortcoming or falling short in the performance of a building element." Watt (2009) and Alencastro (Alencastro, Fuertes, and de Wilde 2018) 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 fulfil 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 (Forcada et al. 2014). The quality of construction is essential for occupants (Meijer and Visscher 2017b). For construction companies and other stakeholders, quality failures cause rework, repair, and other losses, and even the impact on poor construction performance and energy-saving inefficiency (Heravi and Jafari 2014; Kakitahi, Landin, and Alinaitwe 2011). At the project level, time, money, and other resources are wasted because of reworks and poor construction performance caused by quality failures (Aljassmi and Han 2012; Heravi and Jafari 2014; Love and Li 2000). The quality of both energy performance and the cost optimality is necessary to promote and analyse in construction projects, as stated in several (D'Agostino et al. 2017; Congedo et al. 2016; Ferreira et al. 2016; Ballarini, Corgnati, and Corrado 2014). Hence, there is an urgent need to avoid quality failures in construction projects.

2.2.2 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 (Chong and Low 2005), locations (Forcada, Macarulla, and Love 2012), trades (such as bricklayer and carpenter) (Georgiou 2010), and building areas (such as bathrooms, kitchens, lounges, bedrooms) (Forcada et al. 2011).

Quality failures were identified and analysed according to two major categories: the impact and frequency of quality failures. In terms of the impact on cost, Mills, Love, and Williams (2009) found quality failures deplete construction projects with

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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 (Alencastro, Fuertes, and de Wilde 2018).

Some studies were conducted that evaluated and ranked quality failures from the frequency perspective. Forcada et al. (2012) identified common quality failures in new building construction like incorrect fixtures and incomplete tile grouting. Georgiou (2010) 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. (2010) 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. (Dixit et al. 2017) introduced one of the leading causes is poor coordination between various trades in construction projects. Additionally, Shanmugapriya and Subramanian (Shanmugapriya and Subramanian 2015) indicated the non-conformance to codes and standards in the process was ranked first, which influences quality negatively in India. In Spain, Forcada et al. (Forcada, Macarulla, and Love 2012) attempted to show bad craftsmanship is the typical cause for the quality failures. Also, Forcada et al. (Forcada et al. 2014) continued to show that poor craftsmanship is more likely to cause technical faults than non-conformance materials or products used. Kakitahi et al. (Kakitahi, Landin, and Alinaitwe 2011) described inadequate communication, graft, and 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. (Gang et al. 2016) claimed that the inappropriate treatment of the external wall is most likely to happen. Chen et al. (Chen and Wang 2016) and Liu (Liu 2015a) 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 (Qiao A. (2014). Quality management of exterior insulation construction of civil buildings. Doctoral dissertation 2014) regarded the cracks as universal quality failures during the external wall renovations. Wang (Wang 2012b) 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 the building energy renovation projects, the 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.

2.2.3 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 about 96 million km^2 from subtropical zones in the south to cold zones in the north (Li and Yao 2012). 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 the building energy renovation projects, the Chinese government issued a set of administrative regulations and technical specifications (Zhou, Levine, and Price 2010). 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).

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 (“Regulations on quality control of construction projects”).

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 (“Regulations on quality control of construction projects”). 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 (“Regulations on quality control of construction projects”). The obligations of Design companies are to provide a site survey and design documents (“Regulations on quality control of construction projects”).

Renovation processes

According to previous studies, the complete building energy renovation processes are arranged with three stages, renovation preparation stages, renovation stages, and post-renovation stages (Wu et al. 2012). These stages are divided into particular sub-stages, including 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 2.1 (Wu et al. 2012).

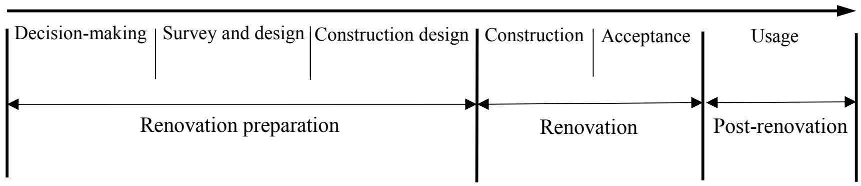

FIG. 2.1 The stages of renovation projects (Modified from Wu et al. (Wu et al. 2012))

In the ***decision-making*** phase, the feasibility with renovating existing buildings is studied before building energy renovation projects are set up (Zhou, Zhou, and Liu 2017). 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 (China 2004). Based on the survey information, the design is necessary for the renovation projects and use of construction work. Thedesign 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 (Ye et al. 2014). 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. Achievement of a high-quality performance depends on the assurance of 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 (Zhang 2015).

Construction steps

The implementation of the building renovation programme 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 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 ("Technical guidelines for heat supply meter and energy-saving renovation of existing residential buildings in northern heating areas" 2008). 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'*** ("Technical guidelines for Energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region" 2015). 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 Figure 2.2, Figure 2.3, Figure 2.4 for details) ("Technical guidelines for Energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region" 2015). In three different categories, all of them started with preparation and ended with site cleaning. According to the 'Technical guidelines for Energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region,' required the compulsory use of expanded polystyrene insulation (EPS), which was a type of thermal insulation materials and could have a huge effect on the long-term performance.

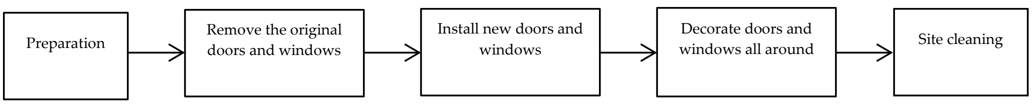

FIG. 2.2 Construction flow in door and window renovation

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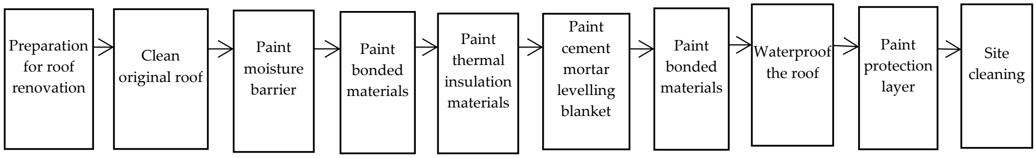

FIG. 2.3 Construction flow in roof renovation

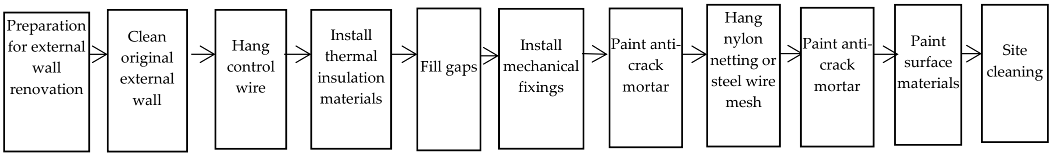

FIG. 2.4 Construction flow in external wall renovation

2.3 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 the building energy renovation projects. Finally, the quality failures were evaluated to be further analysed by a survey questionnaire (Figure 2.5).

	Step 1	Step 2	Step 3
Methods	Case studies	Expert interviews	Questionnaires
Aim	Identify quality failures Explore the construction steps, impacts and causes of quality failures	Confirm if the quality failures and the causes were possible to appear during construction processes Test if the description of quality failures, impacts and causes were clear	Evaluate the quality failures with respect to occurrence frequency

FIG. 2.5 Research methodology

2.3.1 Step 1 - Case studies

A case study approach was undertaken to identify 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 centre in the Inner Mongolia Autonomous Region, Hohhot city has developed rapidly in China. In Hohhot, the coldest month is January with an average temperature of about −12 °C, and the hottest month is July with an average temperature of about 22 °C (Figure 2.6). 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.

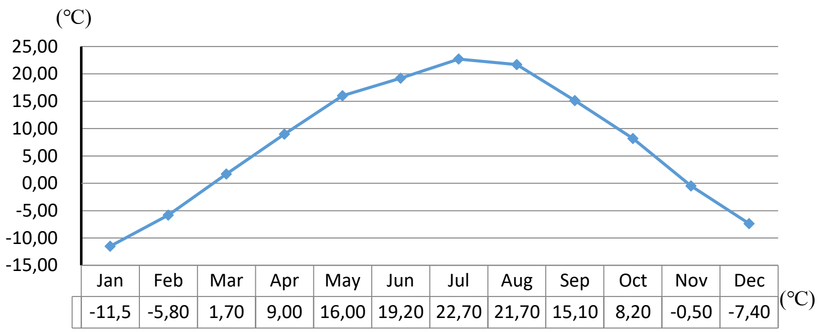

FIG. 2.6 Average temperature in Hohhot (Source: (Lv, Du et al. 2010))

The five cases of building renovation projects were selected to be representative of the residential building renovation situations (Figure 2.7). 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 2.1). The diversity of project characteristics is intended to know what and how quality failures occurred, based on their particular context and conditions.

FIG. 2.7 The residential building renovated in the case study (by the authors)

TABLE 2.1 Five cases: context 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)	45800	2006-2008	300	Window: install double glass windows; Roof: install EPS; External wall: install EPS	Ongoing
2	11 million RMB (1.3 million Euros)	52086	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)	24900	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)	77738	1996-1999	320	Window: install double glass windows; Roof: install EPS; External wall: install EPS	Completed
5	12 million RMB (1.5 million Euros)	55620	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 around 77738 m^2 and the smallest covers around 24900 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 2.7). 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 the 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 and technical requirements (see the key technical specifications in Table 2.2) of the 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.

TABLE 2.2 Technical specification of building energy renovation projects in Hohhot

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

(Source: 'Technical guidelines for Energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region')

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 government officials (Table 2.3).

TABLE 2.3 Background of the Interviewees in 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	1	/
	14	Project manager of a Construction company
	15	Supervisor of a Supervision Company
	16	Designer of a Design Company

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 Figure 2.2, Figure 2.3, Figure 2.4), and then explain the causes of the quality failures by reference to the construction quality reports and on-site documents.

2.3.2 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, 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 are shown in Table 2.1.

2.3.3 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 (Zimmermann 2010), the linguistic values were designed, involving “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%.

2.3.4 Fuzzy-set evaluation method

Several studies have used Likert scales in their questionnaire surveys and adopted parametric statistical methods, such as the t-test (Hwang, Zhao, and Gay 2013; Zhao, Hwang, and Low 2013). In this traditional method, human judgments were represented as exact numbers (Kahraman et al. 2014). 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 (Tseng et al. 2008). 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 (Vafadarnikjoo et al. 2015).

Fuzzy set evaluation is often used to incorporate the linguistic information (Arunraj, Mandal, and Maiti 2013; Kulak, Durmuşoğlu, and Kahraman 2005; Vafadarnikjoo et al. 2015). 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 (Arunraj, Mandal, and Maiti 2013). In previous studies, Fu (Fu 2008) and Kar (Kar 2015) applied 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.

2.4 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.

2.4.1 Identified quality failures in building energy renovations in Northern China

Table 2.4 presents the quality failures identified from five cases and the distribution of quality failures within the five cases. Various quality failures occurred need to 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,’ these rework and repair of the quality failures must be recorded by construction companies during the construction period. Recording as 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 2.4. 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 2.4 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.

2.4.2 Sources of quality failures

Table 2.5 presents the distribution of quality failures in construction steps and identification of the main construction steps where quality failures arose.

TABLE 2.5 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

The results reveal that the first three quality failures appear in installing process of new doors and windows for the doors and windows renovations, so installing is a key construction step to control quality.

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.'

2.4.3 Occurrence frequency of quality failures

Table 2.6 and Figure 2.8 show the percentage of the respondents' evaluation of the quality failures concerning the occurrence frequency according to the different linguistic variables.

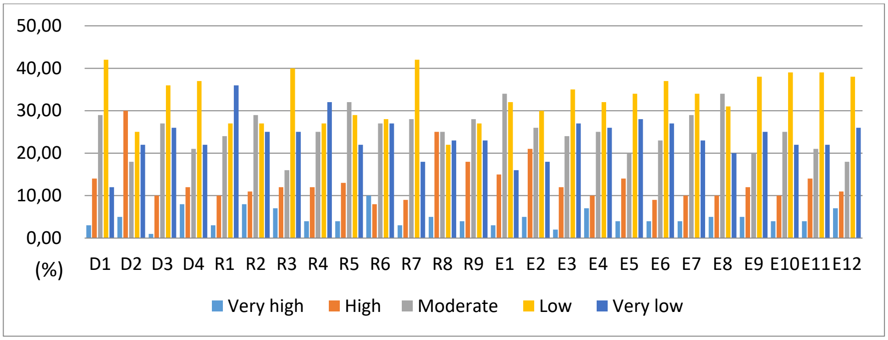

FIG. 2.8 The percentage graph of respondent evaluation of the quality failures

TABLE 2.6 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

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,…x_n}, the fuzzy set (S,n) is often denoted by { n(x_1)/x_1,…, 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) (Zhang, Skitmore, and Peng 2014; Peng Xu, Chan, and Qian 2012). 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(Zimmermann 2001), the degree of membership for each indicator can be described as follows:

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

where V_{xi} is a popular variable above 2 for the quality failure x_i, and $f(V_{xi})$ 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 (Peng Xu, Chan, and Qian 2012).

The means and standard deviations of the variable of the frequency are shown in table 2.7. Moreover, according to equation 1, means and the value of standard deviation, the degree of membership n of each quality failure can be calculated. The results are shown in Table 2.7.

TABLE 2.7 The degree of membership of indicators for common quality failures

No.	Quality failures	Mean	SD	$n(x_i)$
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. Theλ-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 $\lambda=0$, all indicators belong to the common quality failures set, while if $\lambda=1$, 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, $\lambda=0.65$ is a commonly used threshold in fuzzy set theory (e.g. (T. A. Tsiligiridis 2004)). Therefore,$\lambda=0.65$ is adopted as the criterion to select common quality failures in this study. Adopting this criterion in conjunction with Table 2.7 results in D1, D2, D4, R2, R5, R8, R9, E1, E2, and E8 being identified as common quality failures.

2.4.4 Causes of Quality failures

Table 2.8 presents the causes of quality failures within the 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.

TABLE 2.8 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.

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TABLE 2.8 Causes of the quality failures (by the authors)

Quality failures	Causes			
	Code	Stakeholders	Renovation processes	Explanations
Misalignment of the waterproof roof layer (R8)	R8-1	Workers	Construction design	The workers lack experience on waterproof the roof in the 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.

2.4.5 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)*.

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 within the workers skipping 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.

2.5 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 (Ashokkumar 2014; Ede 2011), the participant causes are direct factors to affect construction quality. According to Table 2.8, the employment of inexperienced / untrained workers and project managers in construction companies are 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 contribute the quality failures, in line with Jingmond and Ågren (Jingmond and Ågren 2015a).

2.5.1 Worker's default

The possible reason for quality failures provided by Yong (Yong 2016) and Mydin (Mydin, Othman, and Sani 2014) 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', '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.

2.5.2 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 (Tang 2014b), 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. (Doloi et al. 2012) 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 the 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 little quantitative indicators for the specific descriptions of construction preparation are issued in the administrative regulations (Geng et al. 2012). Consequently, uncompleted construction plans increase the number of quality failures. Therefore, enforcement of a specific construction plan could be considered by policymakers in building energy renovation projects in Northern China.

2.5.3 Inadequate checking procedures by Supervisors

As can be seen from the results (see Table 2.5), 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 of 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 et al.

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. (Ye et al. 2014) 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 2.5), there has been a tendency for the causes of quality failures to be induced at the construction design period (Hwang, Zhao, and Goh 2014). Supervisors only focus on quality inspection and management at the construction stage, whereas construction preparation is ignored (Wu et al. 2012). Therefore, the supervising of construction activities during construction design stages need 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 construction design stages of building energy renovation projects.

2.5.4 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 the errors or changes of design documents such as ‘the size of door and windows.’ These errors probably cause quality failures (D2-1) hindering the goals of the 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.

2.5.5 Fraud of construction companies

The quality failures may occur contributed by organizations as a whole, rather than individual contributions from workers, project managers, supervisors, and designers in isolation. Jingmond and Ågren (Jingmond and Ågren 2015a) highlighted that the organizational routine rather than individual behaviour 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 the building energy renovation need to understand the importance of construction quality and regard construction quality as a critical factor to affect project value.

2.5.6 Inefficient cooperation in different departments

The building energy renovation project involves multiple departments of the 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 (Li, Ng, and Skitmore 2012; Zhao et al. 2012). 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 (Shang and Sui Pheng 2014).

2.6 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, the prevention and possible eradication of quality failures are possible through the identification and evaluation of them.

The detailed analysis of quality failures identified in five cases in Northern China concluded that the ten most common quality failures including *'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*

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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 are ranging 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 a 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 behaviours, 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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3 Causes of Quality Failures in Building Energy Renovation Projects of Northern China

A Review and Empirical Study

Published as: Yuting Qi, Queena K. Qian, Frits Meijer, and Henk J. Visscher. (2020) "Causes of Quality Failures in Building Energy Renovation Projects of Northern China: A Review and Empirical Study." Energies 13, no. 10, 2442.

ABSTRACT

Building energy renovations can effectively improve the environmental performance and energy sustainability of the existing buildings. From 2007 onwards, the Chinese government has promoted energy-saving renovations of existing urban residential buildings. Nevertheless, various quality failures happen during the construction period in energy-saving renovation projects of residential buildings. Yet, the causes and their characters remain largely unknown. Through a literature review, this paper investigates the causes of quality failures. Validated through experts' interviews, a total of 18 causes were identified in building energy renovation projects. These causes were analysed from two main aspects: the importance of a cause (related to impact and frequency), and the level of effort required to address a cause (related to origin and scale), using both a questionnaire survey and a focus group. The results indicate that the critical causes of quality failures are working under high-cost and high-time pressure, adverse natural conditions, fraud of construction companies, incomplete construction site survey, poor checking procedures of supervisors, poor operational skilled workers, inadequate equipment performance, lack of experienced project managers, and incomplete building information in projects. The causes were classified as external and internal causes of building energy renovation projects. The outcome of this paper should aid policy-makers and project coordinators to focus on critical causes of quality failures and develop effective actions and policy interventions to achieve successful renovation projects with high-quality performance.

KEYWORDS causes; quality failures; building energy renovation projects; Northern China

3.1 Introduction

Energy problems and carbon emissions have become worldwide issues, so there has been growing consciousness regarding energy consumption and carbon emission reductions. Based on past statistics, about a 28% increase in the energy demand may occur until 2024 in the world (Sieminski 2014). More specifically, in terms of the building sector, energy consumption has remarkably increased in the last several decades (Cho et al. 2019). In China, the energy consumption the existing buildings is far larger than that of the total energy consumption (Yang, Yan, and Lam 2014). Specifically, the poor energy efficiency of existing residential buildings wastes a large amount of energy (Qian, Chan, and Choy 2012). To improve energy performance, the Chinese government focuses on the energy efficiency renovations of existing residential buildings in Northern China (Liu et al. 2018). For example, doors, windows, roofs, and external walls are renovated. However, various quality failures happened and resulted in construction repair and even rework (Liu 2015a; Qi et al. 2019). Additionally, some quality failures were repeated in the building energy renovation projects (Love, Edwards, and Irani 2008; Kakitahi, Landin, and Alinaitwe 2011), which brought losses to stakeholders (Sellés, Rubio, and Mullor 2008; Mitropoulos and Nichita 2009).

These quality failures would hinder energy efficiency during the construction and even usage processes of building energy renovation projects (Lo 2015). Moreover, due to quality failures, a tremendous amount of energy is wasted annually in construction and usage processes, and hereby the high-quality performance of the constructions can reduce energy wastage (Qi et al. 2019). According to Forcada et al.'s studies, due to quality failures, a majority of the existing buildings that have been energy renovated do not save as much energy as the designs have predicted (Forcada, Macarulla, and Love 2012). Johnston et al. found that the heat-transfer coefficient is 1.6 greater than predicted, caused by quality failures (Johnston, Miles-

Shenton, and Farmer). Similarly, based on Bell et al.'s research, the quality failures cause that the overall heat loss is 54% higher than predicted in the residential buildings (Bell et al. 2010). Furthermore, occurrences of quality failures can lower the health as well as safety levels of residents (Georgiou, Love, and Smith). Thus, overcoming these quality failures is necessary to promote and boost the successful accomplishment of the building energy renovation projects.

Building energy renovation projects lie at the heart of the implementation of energy-saving and low-carbon policies (Lo 2014b). Quality control and management in the building energy renovation projects are challenging because of the presence of the different technologies and government roles, which makes building energy renovation projects significantly different in scope from other construction projects (Cattano et al. 2013). More precisely, building energy renovation projects have their own unique causes of quality failures (Kylili, Fokaides, and Jimenez 2016). Definitely, the mere identification of the causes alone is insufficient for understanding reasons for the quality failures during renovation construction. Therefore, it is important not only to identify but also to study the root causes to avoid quality failures happening in energy-saving renovations of residential buildings in the future.

In spite of building energy renovation projects' significance, there are limited detailed studies that investigate the causes of quality failures (Adabre and Chan 2019). Therefore, this study took empirical cases and made field visits in Hohhot, the provincial capital of Inner Mongolia, in Northern China. The city was selected as the case site for research based on the threefold selection criteria. First, Hohhot is located in the 'heating areas' in Northern China, and it is well known as a building energy renovation city. Second, this city is supported by central and local governments to be an exemplar for building energy renovations. Third, as part of the energy renovation program in Hohhot, there is a requirement to record the occurrence of quality failures, and construction quality is controlled and managed strictly. These selection criteria ensure the renovation projects in Hohhot cover a broad diversity of the characteristics of the causes of quality failures, which aims to know what and how the causes of quality failures occurred.

Fortunately, it is possible to find enough cooperative respondents for the building energy renovation projects in Hohhot. The authors have been there twice to organize the experts' interviews and a focus group in 2018 and 2019. The respondents are representative of the stakeholders involved in the building energy renovation projects, including government officials, project managers, supervisors, and designers. The questionnaire survey was conducted in Northern China, and 113 valid questionnaires were received with a representative sample of the stakeholders playing different roles in energy building renovation projects.

Our research departs from previous studies. Some of these studies have identified and analysed according to the impact or severity of the causes of quality failures (e.g. (Auchterlounie and Tony ; Hoonakker, Carayon, and Loushine ; Schultz et al. 2015; Mills, Love, and Williams 2009)). Others paid attention to ranking the causes of the quality failures from the frequency angle (e.g. (Forcada et al. 2014; Shanmugapriya and Subramanian 2015; Aljassmi and Han 2014; Mills, Love, and Williams 2009)). However, these previous studies have predominantly evaluated only one particular area, especially the impact of these factors affecting the construction quality. Hence, they are only offering limited information about the causes of the quality failures in practice, combining both their importance and levels of effort required to tackle a cause (Mosannenzadeh, Di Nucci, and Vettorato 2017). Tackling a cause means to address the consequences of the causes after a cause occurs.

In the Chinese energy renovation context, the specific causes have not yet been treated in the academic literature in a systematic way. The importance and the level of effort required to tackle a cause are proposed as key indicators.. As a result, there is a need for systematic identification and analysis of the causes: the importance of a cause (related to impact and frequency), and the level of effort required to tackle a cause (related to origin and scale). In this paper, the evaluation indicators adopted are the combination of the importance, origin, and scale for building energy renovation projects. The “importance of a cause” in this context refers to the impact and frequency of the causes before the causes occur. “The origin and scale” refer to the level of the consequences of the causes after they occur. The combination of four evaluation indicators provides a comprehensive comparison of different causes throughout the whole process of the causes occurring. Furthermore, this combination would be novel and meaningful for the main stakeholders, whose main priorities might tend to avoid and address the causes of quality failures in building energy renovation projects. This paper is the first one to make sense of the evaluation of the causes of these four perspectives jointly.

The objectives of this paper are: 1) to identify the causes associated with quality failures in building energy renovation; 2) to determine their importance (related to impact and frequency); 3) to classify the causes based on their levels of effort required to tackle a cause (related to origin and scale).

The paper is organised as follows. A review of related studies on quality failures and the framework of their causes from global experiences are contained in Section 3.2. Section 3.3 presents the research methods to collect data. Section 3.4 presents thetthe interrelationships of the quality failures and their causes, the cause analysis of the importance (impacts and frequency), and efforts required to address a cause (origins and scales).). Section 3.5 discusses the critical causes and gives implications for policy-makers and project coordinators. Finally, the main findings and recommendations for future research are concluded in Section 3.6.

In more details, first, the causes were identified based on a literature review, validated through experts' interviews. The experts were interviewed to confirm if the causes were possible to appear in empirical cases, and the relationships between quality failures and causes were obtained. Second, the questionnaire survey was carried out to collect data for analysing the importance of the causes (impact and frequency) by using a five-point Likert scale. Finally, the levels of effort required to tackle causes (origin and scale) were evaluated based on a focus group (see Fig 3.1).

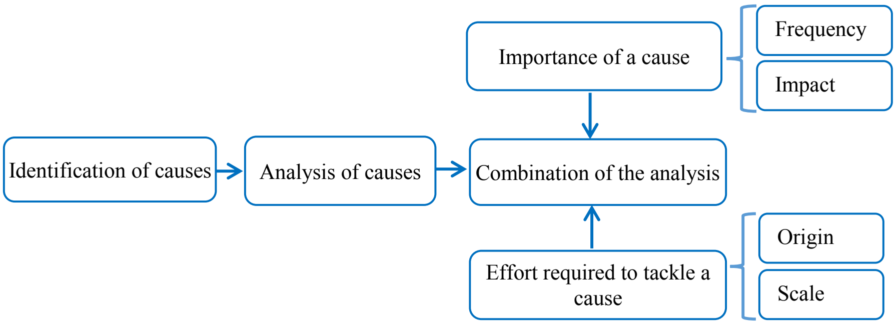

FIG. 3.1 The research process and indicators

3.2 Literature Review

3.2.1 Quality and Quality failures

Over the last few decades, there have been various expressions adopted to define construction quality(Battikha 2003). The International Standards Organization (ISO) defined quality in the construction industry as the sum of elements and features of a product or service with satisfying given needs. According to the American Society of Civil Engineers (ASCE), quality is the consistency to predetermined requirements..

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Also, the Construction Industry Institute (CII) published the definition of quality as the conformance with established requirements. Jha and Iyer (Jha and Iyer 2006) defined quality as 'compliance with customer's specification and customer's expectations.' As defined by Qi et al. (Qi et al. 2019), the definition of quality in construction projects is to meet the technical requirements of regulatory agencies.

In the building construction industry, various interchangeable terms are used to refer to 'quality failures' to describe imperfections, including error,' 'non-conformance,' 'defect,' 'fault,' and 'quality deviation' (Sommerville and McCosh 2006; Forcada et al. 2014). Also, Shanmugapriya and Subramanian (2015) came up with quality failure as one of the main shortcomings in the means output that technical requirements and specifications. As defined by ISO 9000: 2005, quality failure is that quality cannot fulfil a requirement. According to Mills et al.'s studies (2009), quality failure is a "shortcoming in the building performance." Watt (2009) and Alencastro (2018) defined quality failure as "inadequacy or user requirements of a building." Sim and Putuhena (2015b) considered that construction quality fails because quality standards and requirements are not earnestly implemented. In this paper, the authors define a quality failure as "the nonfulfillment or the implementation gap of the technical requirements as laid down (stated) by regulatory agencies."

3.2.2 Causes of Quality Failures

There have been studies to identify the causes of quality failures; for example, Chong and Low (2005) investigated and considered that poor craftsmanship is the fundamental cause. Hughes and Thorpe (2014a) identified that causes are poor supervisor competency and incomplete drawings. Love et al. (2010) advocated causes of quality failures, including inefficient use of information technologies, excessive client involvement in the project, lack of clearly defined working procedures, insufficient changes. Aiyetan (2013) investigated the causes of quality failures and suggestions for quality improvements. Meanwhile, inadequate communication, incomplete construction planning, ineffective management, the inexperience of personnel, and weak quality concrete are identified as the causes of quality failures. Kakitahi et al. (2015) ranked inadequate communication, embezzlement, and dishonesty as the three significant causality factors to cause quality failures. Enshassi et al. (2017b) studied the five leading causes of quality failures, including fraud, competitive pressure, poor management, time pressure, and the absence of work security. As shown in Table 3.1, a provisional set of causes was identified based on a thorough review of previous studies.

TABLE 3.1 List of identified causes from a literature review

Causes	Descriptions	References
Incomplete construction site survey	Designers or construction companies ignore or make a deficient site survey.	(Aiyetan 2013)
Inaccurate design work	There are mistakes and discrepancies in design documentations	(Aiyetan 2013; Jingmond and Ågren 2015a; Hughes and Thorpe 2014a)
Unsettled plan or lack of construction plan	Construction companies ignore or make deficient construction planning	(Aiyetan 2013; Dixit et al. 2017)
Unauthorized changes in design documentations	Construction companies change design documentation without the agreement of designers	(Love et al. 2010)
Incomplete building information in projects	Technical information or original documentation are missing	(Ye et al. 2014; Aiyetan 2013; Jingmond and Ågren 2015a; Kakitahi et al. 2015; Love et al. 2010; Hughes and Thorpe 2014a; Xiang et al. 2012)
Poor operational skilled workers	Operational skilled labour in construction processes lacks	(Jingmond and Ågren 2015a; Schultz et al. 2015; Oyedele et al. 2015; Aljassmi and Han 2014; Forcada et al. 2012; Forcada et al. 2014; Chong and Low 2005; Aiyetan 2013)
Use of poor materials	Quality of construction materials is non-specified	(Ye et al. 2014; Aiyetan 2013; Oyedele et al. 2015)
Inadequate equipment performance	Mechanical equipment is non-specified	(Jingmond and Ågren 2015a; Hughes and Thorpe 2014a)
Poor on-site coordination	The speed of communication on-site between main stakeholders is low.	(Aiyetan 2013; Schultz et al. 2015; Dixit et al. 2017)
Poor site management	Workers, material, and equipment on site are not strictly managed and controlled	(Aiyetan 2013; Dixit et al. 2017)
Complex on-site environment	Site conditions are limited such as narrow construction spaces	(Ye et al. 2014; Hughes and Thorpe 2014a)
Poor checking procedures of supervisors	Supervision and feedback processes make failures	(Ye et al. 2014; Aiyetan 2013; Love et al. 2010; Hughes and Thorpe 2014a; Oyedele et al. 2015)
Fraud of construction companies	Construction companies cut corners by cheating in work.	(Schultz et al. 2015; Enshassi, Sundermeier, and Zeiter 2017b)
Working under high-cost pressure	Budget and funding for renovation projects is insufficient	(Aiyetan 2013; Schultz et al. 2015; Kakitahi et al. 2015; Enshassi, Sundermeier, and Zeiter 2017b)
Working under high-time pressure	Design time and construction time is urgent	(Aiyetan 2013; Schultz et al. 2015; Enshassi, Sundermeier, and Zeiter 2017b)
Adverse natural conditions	The natural environment is an interference such as low temperature, inadequate solar energy, rain interference	(Ye et al. 2014)

3.2.3 Previous Studies on the Analysis of the Causes

In order to avoid quality failures, the analysis of the causes is crucial. In previous studies, two main aspects (four sub-aspects) have been considered: the importance of a cause (related to frequency and impact), and efforts required to tackle a cause (related to scale and origin) (as explained below).

Some researches were carried out to rank causes from the frequency angle. For studying the current situation of the construction markets and existing causes of quality failures, Forcada et al. (2012; 2014) carried out a series of research projects. They concluded that poor craft is more likely to cause quality failures than non-specified materials or equipment used. Aljassmi and Han (Aljassmi and Han 2014) identified the majority of quality failures related to a violation of operation or poor workers' skills.

Various causes were analysed according to their impact on construction quality. Schultz et al. (2015) identified the most significant influences on quality failures in Denmark. These causes include 'budgetary conditions,' 'schedule pressure,' and 'discontinuous quality control.' Dixit et al.(2017) studied and ranked the causes based on the responses affecting construction productivity in India. The causes are improper planning, poor site coordination lack of commitment, lack of organization competency, and inefficient site. Oyedele et al. (2015) proposed the five most substantial causes, including non-specified materials, lack of skill and labour experience, inadequate inspection, poor site installation process, as well as incomplete quality assurance. In the context of China, Ye at al. (2014) investigated a total of 39 causes of quality failures through the in-depth literature review and an interview of practice and experience. Also, they conducted a questionnaire survey to rank these causes, in which poor project process management, non-specified construction technology, and the inferior construction materials were the highest.

In terms of the scale of causes, Reddy (2013) classified the causes into three categories: micro, meso, and macro, to analyse the circumstances under which different causes arise. Iqbal et al. (2015) explained the causes were taking place in micro, meso, and macro environments. Following this way to categorize the causes, this paper evaluates causes based on the micro and macro scales.

The studies of the origin of the causes can be used to prevent these causes occurring before the start of a project. According to Page's study (2010), a framework of the causes was presented according to the internal and external to the projects. Also, Chaplin and O' Rourke (2014) analysed and concluded that it was necessary to study some internal causes of projects and focus on the communications and messages in external projects. This paper also groups the causes as external and internal to the renovation projects.

Taking into account the previous researches worldwide, a systematic cause analysis from all these four aspects (including impacts, frequency, scales, and origins) has not yet been investigated.

3.2.4 Main Characteristics of Energy-saving Renovations of Existing Residential Buildings in Northern China

Background of Building Energy Renovations in Northern China

In China, the energy consumption of buildings is influenced by a variety of regional climates. China covers a land area of about 96 million km^2 with different climate zones (Li and Yao 2012). According to the Standard of Thermal Design Code for Civil Building (GB50176-93), five climate zones are classified, including Severe Cold Zone (SCZ), Cold Zone (CZ), Hot Summer and Cold Winter Zone (HSCWZ), Hot Summer and Warm Winter Zone (HSWWZ), and Mild Zone (MZ). Of these, urban residential buildings in the SCZ and CZ receive district heating in winter, and they are called heating zones.

The Chinese governments have carried out the energy-saving renovation to improve building energy efficiency of heating zones since 2007 (Kong, Lu, and Wu 2012). According to the technical guidelines for the energy-saving renovation of existing residential buildings in Northern China, energy-saving renovations usually include external envelope structure (including the external wall, roof, door, and window), outdoor pipe network and heat source balance, indoor heating system and heating meter(Li, Zhao, and Zhu 2013). Additionally, the current situation is that a large number of existing buildings were renovated in the large-scale implementation stage(Liu et al. 2018). Meanwhile, the energy-saving renovations undertaken have shown that renovation can achieve the 50% energy efficiency target from central governments and produce a good thermal performance and indoor environment (Chen et al. 2015).

Empirical cases in this paper were selected in Hohhot, which is a northern city of the centre in the Inner Mongolia Autonomous Region. It is a typical city of the heating areas in a building energy renovation context. Based on technical guidelines for building energy-saving renovation in Northern heating areas ("Technical guidelines for heat supply meter and energy-saving renovation of existing residential buildings in northern heating areas" 2008) at the national level, the provincial government has the potential autonomy to issue their own technical requirements with consideration of different regional circumstances. Thus, the provincial government in Inner

Mongolia (where Hohhot is located) issued technical guidelines for the energy-saving renovation of existing residential buildings in the Inner Mongolia Autonomous Region. In these technical specifications, the main three construction technology categories are described, including door and window, roof, and the external wall. Meanwhile, the compulsory use of expanded polystyrene insulation (EPS) is required by technical guidelines at the local level ("Technical guidelines for Energy-saving renovation of existing residential buildings in Inner Mongolia Autonomous Region" 2015). EPS is a type of insulation materials, which have a significant effect on long-term thermal performance.

Responsibilities of Main Stakeholders in Building Renovation Projects

As a standard mode, the government leads building energy renovation projects. That is, the governments planned and guided to renovate the existing residential buildings. In 2000, in order to ensure the construction participant's compliance with their responsibilities, the national government published Regulations on quality control of construction projects ("Regulations on quality control of construction projects"). The provincial governments transfer the policies to local government (the municipal government and district government), and then the local governments implement the policies accordingly (Kong, Lu, and Wu 2012). Besides the local governments, other stakeholders, including construction companies, supervision companies, and design companies, share in carrying out the building energy renovation projects. Since the local government, supervision construction and design companies are fully involved in renovation projects, they are naturally the main stakeholders.

In most building energy renovation projects, local governments (the municipal government and district government) guide and lead the whole renovation processes. Correspondingly, they organize the activities in renovation projects and contract the tasks with the other stakeholders. As the delegates of local governments, supervision companies are required to manage the construction quality and to do on-site inspections, evidential tests, and final checks. Construction companies are the main body to complete the renovation construction processes. They affect quality by organizing workers, materials, and other necessities for construction. Construction companies are responsible for organizing, arranging, and checking the construction scheme in construction preparation. A site survey and design documents are provided by design companies. Design documents include renovation specifications, technical drawings, and other relevant documents, which guide construction methods and materials.

3.3 Research Method

This research is intended to identify the causes of quality failures and study the importance of the causes (impact and frequency), origin, and scale.. First, a comprehensive literature review was conducted to establish a foundation (see Section 3.2.2). Second, experts' interviews supported and validated the findings from the literature review. Third, the final causes based on the experts' interviews were prioritized to be further analysed by a questionnaire survey. Finally, a focus group was carried out to evaluate the effort requires to address these causes (Fig. 3.2).

Method	Literature review (see Section 2.2)	Interviews with practitioner experts	Questionnaires	Focus group
Number of participants		22 experts	113 respondents	10 participants
Aim	Identify causes of quality failures based on the previous studies.	Confirm the causes if the causes were possible to appear during construction processes. Explore the relationships between quality failures and these causes.	Evaluate the causes of quality failures with respect to the level of impact and frequency.	Discuss the origin and scale of the causes and obtain the causes classification.
Result	An initial list of causes of quality failures	A final list of causes of quality failures; The relationships between quality failures and their causes	The ranking of causes: impact and frequency	The categories of causes: origin and scale

FIG. 3.2 The research method, objective and results

3.3.1 Interviews with Practitioner Experts

A literature review was first conducted to identify an initial list of causes of quality failures. ItIt is to understand the likely causes of quality failures from a global view and to prepare for data collection relating to the causes of quality failures of construction projects

A series of interviews with practitioner experts was undertaken to formulate the final list of causes, which are based on a literature review and construction documents. The causes of quality failures were provided for reference in order to elicit the opinions of experts. The following criteria formed the basis for the interviewer selection. First, the experts were from different key backgrounds/roles to provide a comprehensive understanding of the causes of quality failures. Second, the experts have sufficient working experience with engaging in the renovation field for over eight years. Separate interviews were conducted as the on-site fieldwork in January and March 2018 in the case study city with 22 experts, consisting of five quality supervisors from the supervision company, ten project managers, two designers, and five government officers (the details are illustrated in Table 3.2). they were requested to take into consideration the characteristics of building renovation projects in the Chinese context. Additionally, in order to make the data on causes more complete, they were asked to identify the relationships between quality failures and their causes.

TABLE 3.2 The position and number of experts in the interview

Position of the stakeholders	Profiles	Number of the experts
Supervisors	Supervision company	5
Project managers	Construction company	10
Designers	Design company	2
Officers	Government	5
Total		22

All these experts in the interviews were asked to inspect the list of causes and to remove those causes if they have not experienced those under conditions of building energy renovations in Northern China. Likewise, they were requested to add some 'new' causes, which have not been referred to in other studies. The final list of identified causes from the aggregation of expert views has been provided(see Section in 3.4.1). From the literature, 16 causes were taken, and after discussion with industrial experts, two causes are included. These are 'lack of experienced project managers' and 'wrong construction flow,' both of which were added to the preliminary list. Consequently, 18 causes are considered, and they form the main content of the questionnaire design and the focus group. In addition, in order to ensure the data on causes more reliable, all experts in the interviews were requested to relate these causes to the quality failures (see in Section 3.4.1).

3.3.2 Questionnaire

The purpose of the questionnaire survey is to have a deeper understanding of the causes of the quality failures in energy-saving renovation projects in Northern China. The data for analysing the importance (impact and frequency) of the causes were obtained via a questionnaire survey. The questionnaire was designed based on the inputs of the 18 causal factors identified in the literature review and confirmed by the interviews with experts.. It comprised two parts: 1) questions relating to the respondents' background; and 2) their rating of the impact and frequency of each listed cause of the quality failures in energy-saving renovation projects. The questionnaire scoring system was sufficient to collect respondent's perceptions while ensuring a sufficiently large size sample for subsequent analysis. The target groups for this questionnaire are design companies, supervision companies, government, and construction companies to capture their current energy-saving renovation practices. The impact of a cause was defined as the extra cost to repair the quality failures associated with this cause divided by the budget. A five-point Likert scale was used, delimited from 1 (0< impact <5%) to 5 (impact >=20%) (Mills, Love, and Williams 2009; Ye et al. 2014). Meanwhile, the frequency was defined as the number of projects in which the cause of quality failures occurred divided by the number of all renovation projects participated in by respondents, based on a five-point Likert scale ranging from 1 (0 < frequency < 20%) to 5 (80% < frequency < 100%).

In this way, a total of 280 questionnaires were dispatched to respondents. All respondents were familiar with building energy renovations with sufficient management knowledge. Finally, 113 fully completed questionnaires were received, giving a response rate of 40.4%. Of these, 22 (19%) were officers from governments, 49 (43.4%) were from construction companies, 27 (23.9%) were supervisors from supervision companies and 15 (13.3%) from design companies (Table 3.3).

TABLE 3.3 The summary of responses in the questionnaire survey

Type of group	Number of respondents	Percentage (%)
Government	22	19.5
Construction companies	49	43.4
Supervision companies	27	23.9
Design companies	15	13.3
Total	113	100

3.3.3 Focus Group

A focus group was used as the collection method of data regarding the effort required to tackle a cause (related to origin and scale) to classify and analyse the causes of quality failures. The focus group was chosen rather than other qualitative research methods, because it can generate information on the collective views from the participants in the group. Thus, data from focus groups are useful to provide a rich understanding of participants' experiences and knowledge regarding causes and their origin and scale.

In this study, a focus group was conducted in Hohhot, where the energy-saving renovation of existing buildings has been carried out since 2008. Ten participants involved in the focus group are shown in Table 3.4. The criteria to select focus group participants were: 1) must be at management level (i.e. project managers, construction supervisors, officers in government, designers); 2) must have worked on energy-saving renovations for more than eight years; and 3) must have rich experiences on project management and quality control. According to the relevant studies conducted by Yu et al. (2018), these criteria can guarantee that the selected participants are qualified to discuss the topics pertaining to the building energy renovation projects.

The focus group meeting started with a presentation to introduce the objectives and definitions of the causes. This was followed by a session, including interactive thematic discussions. During the discussion session, each participant was requested to give their expert opinion about the origin and scale of each cause of the quality failures in energy-saving renovation projects from their perspective.

TABLE 3.4 Position and number of focus group participants

Position description	Type of group	Number of focus group participants
Project manager	Construction company	2
Technical engineer	Construction company	2
Supervisor	Supervision company	2
Officer	Government	3
Designer	Design company	1

3.4 Results

3.4.1 Causes of Quality Failures

Table 3.5 presents various quality failures recorded in documents and identified from the experts' interviews. The nature of the quality failures, needing rework or repair with extra cost and time, are shown. 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 3.5 The quality failures that occurred in renovation projects

Technology measurements	No.	Quality failures
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 vapour 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 levelling 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

Table 3.6 presents the distribution of quality failures contributed by 18 causes. The results show the relationships between 25 quality failures that occurred during the construction processes and their causes in energy-saving renovation projects.

TABLE 3.6 The quality failures contributed by the causes

Causes (18)	Quality failures (25)																								
	D1	D2	D3	D4	R1	R2	R3	R4	R5	R6	R7	R8	R9	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
Poor operational skilled workers	√	√	√					√		√	√	√	√	√	√	√			√				√		
Fraud of construction companies						√	√							√	√		√	√			√	√		√	√
Incomplete building information in projects					√						√	√			√										
Lack of experienced project managers	√							√			√	√		√	√				√	√					
Working under high-time pressure			√	√					√					√	√								√		
Working under high-cost pressure						√	√								√		√	√			√				√
Use of poor materials								√		√			√						√				√	√	√
Inadequate equipment performance																							√		
Complex on-site environment, such as limited construction spaces	√															√									
Adverse natural conditions, such as low temperature, inadequate solar energy, rain interference										√	√		√			√			√					√	
Inaccurate design work					√																				

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TABLE 3.6 The quality failures contributed by the causes

Causes (18)	Quality failures (25)																								
	D1	D2	D3	D4	R1	R2	R3	R4	R5	R6	R7	R8	R9	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
Unauthorized changes in design documents																					√				
Incomplete construction site survey		√			√																				
Wrong construction flow										√			√											√	
Poor checking procedures of supervisors						√	√						√				√	√			√	√		√	
Unsettled plan or lack of construction plan		√	√	√										√						√					
Poor site management				√								√								√					
Poor on-site coordination		√																							

3.4.2 The Importance of the Causes (Impact and Frequency)

The data from the questionnaire survey were analysed using SPSS. The Likert five-point scale was used in the survey, and its reliability was determined using Cronbach's coefficient alpha, which measures the internal consistency among the elements. Values elements of Cronbach's alpha of 0.7 or above normally indicate a reliable set of items (Xu, Xu, and Shen 2013). The value of this test was 0.871, which was greater than 0.7, indicating that the five-point scale was reliable at the 5% significance level. Thus, the collected sample can be treated as a whole and is suitable for further ranking analysis in this section.

The mean score method was adopted in previous quality management studies to prioritize the relative importance among the factors (Mao et al. 2013). In this study, the mean score is used to determine the relative ranking, as perceived by the respondents, in descending order of their impacts and frequency. If two or more causes occurred to have the same score, the one with a lower standard deviation (SD) was assigned a higher rank.

Table 3.7 presents the ranking of the mean score of the respondents' evaluation of the causes concerning their impacts on construction quality (the column impacts). The findings show that 11 out of the initial 18 causes of quality failures have mean scores greater than the average total value (3.49). The cause of the greatest impacts on construction quality is the "Incomplete construction site survey" (mean=3.65). Both "Inadequate equipment performance" and "Lack of experienced project managers" have the same mean scores. Yet, the standard deviation of "Inadequate equipment performance" is 1.167, which is lower than that of "Lack of experienced project managers" (std. deviation=1.276).

TABLE 3.7 Impact rankings, frequency rankings, origin, and scale of causes

Origin	Code	Causes	Impacts (n=113)			Frequency (n=113)			Scale	
			Mean	Std. Devia-tion	rank	Mean	Std. Devia-tion	rank	Micro	Macro
External	E1	Working under high-cost pressure	3,55	1,323	5	3,51	1,344	4		√
	E2	Working under high-time pressure	3,52	1,247	6	3,49	1,196	5		√
	E3	Adverse natural conditions	3,56	1,488	4	3,38	1,358	9		√
	E4	Complex on-site environment	3,46	1,316	13	3,33	1,442	12	√	
	E5	Fraud of construction companies	3,44	1,224	14	3,53	1,261	2		√
Internal	I1	Incomplete construction site survey	3,65	1,274	1	3,27	1,459	15	√	
	I2	Poor checking procedures of supervisors	3,62	1,325	2	3,42	1,334	7	√	
	I3	Poor operational skilled workers	3,58	1,287	3	3,45	1,356	6	√	
	I4	Inadequate equipment performance	3,50	1,166	7	3,41	1,431	8	√	
	I5	Lack of experienced project managers	3,50	1,276	8	3,51	1,247	3	√	
	I6	Incomplete building information in projects	3,49	1,204	9	3,58	1,321	1	√	
	I7	Unauthorized changes in design documents	3,49	1,240	10	3,32	1,441	13	√	
	I8	Wrong construction flow	3,49	1,337	11	3,36	1,303	10	√	
	I9	Inaccurate design work	3,48	1,268	12	3,20	1,428	16	√	
	I10	Use of poor materials	3,43	1,322	15	3,33	1,372	11	√	
	I11	Unsettled plan or lack of construction plan	3,43	1,274	16	3,18	1,297	17	√	
	I12	Poor on-site coordination	3,37	1,364	17	3,18	1,397	18	√	
	I13	Poor site management	3,31	1,211	18	3,30	1,295	14	√	

Similarly, because a total of 10 causes have mean scores higher than the average total value (3.38), they were identified as the common causes resulting from the quality failures. Table 3.7 presents the ranking of the respondents' evaluation of the causes concerning their frequency in energy-saving renovation projects (the column frequency). The first in rank is "Incomplete building information in projects" (mean=3.58), which is thus most frequent in Chinese energy-saving renovation projects.

3.4.3 The Origin and Scale of the Causes

As for the level of effort to solve a cause, two possible approaches are combined (Xia and Chen 2011): avoiding the emergence of the cause, and reducing the influences of an already emerged cause of quality failures. The former is strongly related to the origin of the causes, which can be internal or external to the project (Cagno et al. 2013). External causes are those that originated outside the project. The origin of the causes was adopted from (Cagno et al. 2013; Mosannenzadeh, Di Nucci, and Vettorato 2017). The latter is related to the cause scale, for which this research applied the micro-meso-macro scale model (Reddy 2013). Micro causes can be addressed at the project management level. Macro causes are difficult to be dealt with by the project. The scale of the causes was adopted from Mosannenzadeh et al. (2017).

The origin and scale of the causes are illustrated in Table 3.7. The results show that the external causes include: "Working under high-cost pressure" (E1), "Working under high-time pressure"(E2), "Adverse natural conditions"(E3), "Complex on-site environment"(E4), and "Fraud of construction companies"(E5). Of these, "Working under high-cost pressure" (E1), "Working under high-time pressure"(E2), "Adverse natural conditions"(E3), and "Fraud of construction companies"(E5) are macro causes with a high level of required action for tackling. Also, the "Complex on-site environment"(E4) is a micro-scale. Regarding the internal origins of the causes, these include: "Incomplete construction site survey"(I1), "Poor checking procedures of supervisors"(I2), "Poor operational skilled workers"(I3), "Inadequate equipment performance"(I4), "Lack of experienced project managers"(I5), "Incomplete building information in projects"(I6), "Unauthorized changes in design documents"(I7), "Wrong construction flow"(I8), "Inaccurate design work"(I9), "Use of poor materials"(I10), "Unsettled plan or lack of construction plan"(I11), "Poor on-site coordination"(I12), and "Poor site management"(I13), and are all micro scale.

3.5 Discussion of Critical Causes

Although the awareness of the construction quality has increased during recent years, there are various causes to contribute the quality failures during construction stages. According to Table 7, ten causes extracted from a total of 18 selected causes were based on the responses from experts' views and the literature review. All the ten causes (E1, E2, E3, E5, I1, I2, I3, I4, I5, I6) obtained mean scores of impacts or/ and frequency above the average total value.

The applications of renovation technologies play a fundamental role in the achievement of successful programme goals. Various causes are closely related to the technical aspects. According to the technical guidelines in Inner Mongolia Autonomous Region, the distributions of the quality failures and their causes in technical procedures are 'installation of new doors and windows,' installation of thermal insulation materials,' 'waterproofing the roof,' 'painting the protection layer.' In short, the inadequate equipment, use of poor materials, and similar technical causes occur in these procedures. The advice for technical procedures is to strengthen the standardizations and technical design standards, both of which fall behind the actual work practices. Furthermore, from technical perspectives, thermal insulation materials have significant influences on the energy consumption of existing buildings, so more attention needs to be paid when selecting new thermal insulation materials coming to the market.. Also, various technical solutions are significant to reduce the causes of quality failures, like developing and applying online tools to share information efficiently in the building energy renovation projects. Meijer and Visscher (2017b) also advised applying online systems further through the construction process. In contrast, Jingmond and Ågren (2015a) considered that the organizational solutions rather than technical advice need further attention to solving the causes of quality failures. Their solution is proposed to focus on training the workers with appropriate technical knowledge and hands-on skills.

To clearly understand the causes, it is essential to precisely separate all the causes. Based on the origin in the empirical investigation, this paper classifies the causes into external and internal to the renovation projects, in line with Mosannenzadeh (2017) and Balasubramanian (2012).

The origin of the critical cause of quality failures is external if the cause is originated outside the project, including policy implementation gap (E1, E2), adverse natural environment (E3), and fraud of construction companies (E5).

Although particular organizations are established for quality supervision to achieve the performance of high quality in the renovation projects of this nature (Kong, Lu, and Wu 2012), there are still various causes that are internal to projects. These causes are possible to bring quality failures during the construction processes, which even affect the overall quality and energy performance. In this study, the results reveal that 13 causes have internal origin to the project, and they all are at a micro-scale. In terms of impacts and frequency (see Table 7), there are six top internal causes (I1, I2, I3, I4, I5, I6) to contribute to the quality failures during construction stages, all of which are greater than the average total value. It means that these causes can be avoided or reduced through better project organization, and so these causes need action from project stakeholders and policy-makers. In line with previous findings (Schultz et al. 2015; Dixit et al. 2017), overcoming these internal causes can remarkably reduce quality failures and improve countries' performance through improvements in construction behaviour and management procedures.

In light of the analysis above, these findings help policy-makers and project coordinators to understand the allocations of their responsibilities better and to develop their proper actions in the future building energy renovation context in Northern China.

3.5.1 External causes

3.5.1.1 Policy implementation gap (E1, E2)

The Chinese national government has published various policies and targets on energy-saving renovation (Wu et al. 2017). Ran (Ran 2013) illustrated there is a gap between the national government's energy-saving renovation policy and the outcomes of its implementation at empirical levels. Actually, high-time and high-cost pressure factors are related to the energy policy implementation gap (Lo 2014a). Moreover, these two causes are regarded as the dominant causes regarding the aspects of impacts and frequency (see Table 3.7).

The government-led model is established in building energy renovation projects in the Chinese context. Indeed, the top-down mandatory targets for renovating magnitude are set according to national energy policies from the national government. National policy targets can then be translated to lower levels of governments through the allocation of the renovation targets. Accordingly, the

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municipal government releases its implementation plan, which establishes the objective of renovating building areas. However, local governments are under intense pressure to complete the targets from upper levels of governments. The priorities of local governments in achieving energy conservation and climate change targets are different, and in practice they focus on construction time more. Thus, the local governments reduced attention to the goal of energy conservation and climate change (Lo 2014a). From the viewpoint of the local government, their task is significantly more difficult to achieve than those of the national government. Hence, construction time pressure (E2) in building energy renovations is higher than that in other constructions.

On the other hand, the building energy renovation belongs to government investment projects. In order to complete targets, the governments have to provide renovation fee, and so they minimize renovation costs as much as possible. However, the renovation cost is limited and fixed. The high-cost pressure (E1) exists in building renovation projects resulting in other levels of causes of quality failures.

3.5.1.2 Adverse natural environment (E3)

In Northern China, in the SCZ and CZ, the natural environment is an interference element of energy-saving renovation projects, such as inadequate solar energy, low temperature, high humidity wind, rain interference, et al. It is apparent that these natural environment elements would affect energy-saving renovation construction adversely and cause the quality failures in Northern China.

3.5.1.3 Fraud of construction companies (E5)

The construction companies always aim to maximize income and minimize their cost to achieve their company profits because of the nature of the private companies. Thus, construction companies may tend to procure the construction material at a lower price in order to reduce material costs. Due to this, quality failures appear, including non-specified fire resistance of EPS boards, non-specified volume-weight, and thickness of EPS boards, non-specified nylon net, missing rivets, non-specified rivets, non-specified anti-crack mortar, and other similar types of quality failures (see Table 3.6). Wu et al. (Wu et al. 2012) also stated that the fraud of construction companies is the primary cause of quality failures in construction projects. In the results of this study, the fraud of construction companies (E5) was ranked as the second cause for the impact on construction quality (Table 3.7) and regarded as the macro cause, which is likely the most difficult to be dealt with and requires action mainly from policy-makers. In the Chinese context, the provision of monetary incentives is insufficient for triggering substantial behavioural changes of construction companies leading toward more sincerity in building energy renovation projects (Xu, Xu, and Shen 2013). Several solutions for policy-makers are proposed to issue the incentives to drive the construction companies' awareness of construction quality and the connection between construction quality and project value.

3.5.2 Internal causes

3.5.2.1 Incomplete construction site survey (I1)

The errors in the on-site survey are ranked the first in consideration of the level of the impact. Indeed, an incomplete or even incorrect construction site survey will make errors such as 'incorrect size of the new window frame and door frame.' In building energy renovation projects, a construction site survey could impact on the implementation steps of the projects directly, but it is always paid too little attention by the main stakeholders. Clearly, it would seem that a practical task would be to supervise the on-site survey allocated by the local government in the Chinese situation.

3.5.2.2 Poor checking procedures of supervisors (I2)

Supervisors in energy-saving renovation projects co-supervise with local government.. Inadequate supervision of materials and equipment are the main reasons for quality failures, for example, 'non-specified fire resistance of expanded polystyrene (EPS) boards', 'non-specified anti-crack mortar', and 'non-specified nylon net', et al. The obligations of on-site supervisors are material and equipment supervision. However, some on-site supervisors do not strictly check the quality of raw materials, semi-finished products, or mix-components. They fail to apply enforced inspection (Ye et al. 2014).Moreover,, administrative supervisors responsible for checking construction documents ignore checking the construction plans. On the other hand, there has been a tendency for the causes to be induced at the construction design stage (Hwang, Zhao, and Goh 2014). Supervisors only focus on the construction stage, whereas the inspection and management of construction preparation are ignored (Wu et al. 2012). Therefore, the supervision during the construction preparation period needs to pay more attention to material and equipment preparation stage.

3.5.2.3 Poor operational skilled workers (I3)

Due to the novelty of the energy-saving renovation projects, the specific technologies and operations are challenges to meet construction quality requirements for workers lacking operation skills. In most projects, construction work is the preferred occupation of migrant workers with low labour costs (Zhang, Skitmore, and Peng 2014). Therefore, workers who have little knowledge and experience are more likely to make errors in operational processes. As a result, many quality failures arose, such as “incorrect installation of the steel nails” and “cracks of concrete”.

In an actual situation, “poor operational skilled workers” have a closer relationship with “inaccurate design work”. Because of incomplete design documents, workers probably make errors during their operational processes. In building energy renovation projects, it is so difficult to remedy workers’ mistakes. Therefore, workers and other project participants need to be trained to identify incorrect design documents. According to the renovation policies in the context of China, it is not mandatory requirements to train the construction workers and other participants with design information and technical knowledge. Meanwhile, construction companies failed to train and manage on-site workers. Thus, to establish an internal training system is a necessary and urgent issue now. Furthermore, mandatory requirements regarding training and educating workers and other construction participants could be needed in the renovation policy framework.

3.5.2.4 Inadequate equipment performance (I4)

Incorrect selection and usage of equipment are hindrances to the high-quality performance of energy-saving projects (Francom and El Asmar 2015). According to Ashokkumar’s study (Ashokkumar 2014), some construction activities might use the wrong equipment, which is more likely to cause quality failures. In this empirical investigation during the processes of installing mechanical fixings, ‘incorrect drilling’ occurs when the power of the electric drill is too low, or the drill bit is selected incorrectly. The selection and usage of equipment need to be checked and recorded strictly by construction management authorities. If the equipment performance does not meet the technical requirements, it is impossible to achieve the high-quality performance of renovation projects.

3.5.2.5 Lack of experienced project managers (I5)

As is well known, various activities in construction work are heavily dependent on the organization of the project managers. In the current situation, the project managers' lack of experience of energy-saving renovation results in quality failures. For the empirical investigation, some project managers ignore to emphasize to workers the knowledge of the waterproofing techniques, and other technical requirements. Often, project managers cannot clarify the scope of personnel responsibility due to a lack of experience in renovation construction. The 'Lack of experienced project managers (I5)' in renovation projects is considered as one of the most frequent causes in the Chinese context (shown in Table 3.7).

Additionally, the chances for professional experience and training are very limited. It is meaningful that the local governments establish the education and training system for project managers in the energy-saving renovation, and introduce a scheme mandating the employment certification of renovation projects for project managers.

3.5.2.6 Incomplete building information in projects (I6)

Incomplete building information appears most frequently (see in Table 3.7). This is because all renovated buildings were built before 2007, and thus it is hard to find details of old building documents. Furthermore, the delay in information update is a reason for 'Incomplete building information in projects (I6)'. For example, the size of enclosure components (include: windows and doors et al.) reinstalled by the homeowners and other the information different from the original design drawings are missing in renovation projects. Therefore, the building information suitable for site operations needs to be updated and then shared among the participants during the stages of survey, design, and construction.

3.6 Concluding remarks

The energy renovation of existing residential buildings is increasingly influential in reducing energy consumption in the building sector. Undoubtedly, building energy renovations are failing the challenge to meet their goals of high-quality performance due to quality failures. Despite various statutory requirements to ensure high-quality performance on energy-saving renovation projects, quality failures frequently occur during the construction processes in energy-saving renovation projects. The impact of these quality failures has resulted in unsatisfactory energy performance throughout the usage phase of the existing buildings. Until this research study, the reasons for quality failures in building energy renovation projects were unknown about why this happens in the Chinese context.

The causes of quality failures in energy renovation projects have, however, been identified and analysed incompletely. This results in a limited understanding of why quality failures occur and how these quality failures could be avoided. In this paper, the novelty lies in the fact that it has explored and analysed the causes systematically from two main aspects: the importance of a cause and the level of effort required to address a cause in the context of China.

The analysis and understanding of the causes are a vital prerequisite in order to prevent and eliminate quality failures. So, this research study first identified the 18 causes of quality failures based on the literature review and expert opinions. Then, the detailed analysis of these causes in Northern China concluded that the "Incomplete construction site survey" (I1) was ranked as the highest level of the impacts on quality, and the most common cause was "Incomplete building information in projects"(I6). The level of action required for tackling a cause of quality failures combined their origin and scale. The "Working under high-cost pressure" (E1), "Working under high-time pressure" (E2), "Adverse natural conditions"(E3), and "Fraud of construction companies"(E5) are external to projects at macro-scale with a high level of required action for tackling the challenge. Based on the evidence in this paper, they are more likely to be influenced at the policy level from the focus group. The Chinese framework of the causes of quality failures could provide a reference for improving the construction quality of energy-saving renovations in the world.

Strategies of reducing the causes of quality failures were provided at the policy level and project level, respectively, which are different previous studies in building energy renovations. At the policy level, there is a need for a common political interest in the

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implementation of renovation projects among different levels of governments. In terms of the project level, the government should establish an inspection system to track and inspect the project's implementation. An effective inspection mechanism is necessary to avoid quality failures occurring.

This paper specified how the quality failures happened, and the causes of quality failures were to be identified and analysed. Meanwhile, it confirmed that the appraisal method was applied as a means of assessing the causes in the building energy renovation projects. On the one hand, in this paper, the applicability of the recommendations for the policy-makers at a policy level refers to improve the top-down mandatory implementations of the energy renovation policies. On the other hand, the suggestions at a project level are applied to the quality management processes of the energy renovation construction.

The outcomes of this research may help both project participants and policy-makers to better understand the causes of quality failures. Thus, the findings would be valuable for policy-makers and project coordinators both for predicting and avoiding the quality failures and for developing proper action and policy interventions to ensure successful building energy renovations with high-quality performance in the future.

A few limitations should be acknowledged for future studies. The case city was only chosen in the Chinese context so that the situation may be different from the other countries. Moreover, this research did not address relationships of the causes for energy-saving renovations. Future research should be wider and include the interactions of these causes as well as the international experience indicating that placing more stringent requirements on details in the project documentation including the work sentencing, may reduce some sources of the quality failures on the construction and allow shorter construction time.

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4 Unravelling Causes of Quality Failures in Building Energy Renovation Projects of Northern China

A Quality Management Perspective

Published as: Yuting Qi, Queena K. Qian, Frits Meijer, and Henk J. Visscher. (2021) "Unravelling Causes of Quality Failures in Building Energy Renovation Projects of Northern China: Quality Management Perspective." Journal of Management in Engineering, 37(3), 04021017.

ABSTRACT

Both a proper understanding of the causes of quality failures and the development of coping strategies for renovating existing residential buildings for energy saving are essential for the success of building energy renovation programmes in Northern China. It is surprising, however, that although in recent years there has been more attention to studying the 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 in impeding high-quality performance. Due to their neglect of the causal relationships among these causes of quality failures, the project coordinators have actually failed to manage the quality of construction projects. Considering a network of different causes, the authors report on efforts to identify and manage the causes of quality failures in construction processes in this paper. This new understanding of the nature of causes has been achieved by considering all four sources of data: the literature review, opinions of experts, interpretive structural modelling (ISM), and focus groups. Our analysis shows that, not only do many causes directly influence the construction quality in building energy renovation projects, but also they interact. It is noticeable that external causes remain associated with all internal causes. The “lack of experienced project managers,” “unauthorized changes in design documents,” “incomplete building information in projects,” and “poor on-site coordination” are driving causes , and their elimination allows the solving of several other internal causes. Finally, the solutions are proposed to improve the current situation and categorised as people, material, equipment, design, and organization based on the quality management processes. The findings of this paper provide valuable references for helping both policy-makers and practitioners to adopt effective policies and measures to manage the construction quality of building energy renovation projects.

KEYWORDS Causes, Quality failures, Quality management, Building energy renovation, Interpretive structural model (ISM)

4.1 Introduction

Energy consumption and carbon emission reductions 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 becoming higher (Qi et al. 2020). Especially, in China, the existing building stock is responsible for approximately one-third of the total energy consumption (Hong et al. 2016). The total area of existing buildings in China was about 48.6 billion square meters, 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 Chinese existing building stock. Building energy renovations can effectively 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, from 2007 onwards, building energy renovations have entered a large-scale implementation stage in Northern China (Liu et al. 2018). The national government

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started to renovate the 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 renovate 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. 2013b).

However, in the energy-saving renovation projects, quality failures, which cannot meet the established technical requirements, would frequently arise during the construction processes (Qi et al. 2019). Based on the previous studies, the existence of quality failures have a significant negative impact on the energy performance of buildings (Alencastro, Fuertes, and de Wilde 2018). Furthermore, the impact of these quality failures covers energy performance throughout the usage phase of the existing buildings, over a period of many years. Due to quality failures, the building U-value is 1.6 times greater than predicted (Johnston, Miles-Shenton, and Farmer 2015) and even these quality failures erase the energy benefits of renovation programmes (Ede 2011; Kakitahi, Landin, and Alinaitwe 2011). In China, it is hard to achieve the goals of energy efficiency rates because of quality failures, and such failure leads to conflicts with the aims of building energy performance (Qi et al. 2019). Consequently, these resulted in residents' dissatisfaction and the negative reputation of building energy renovation sector (Lo 2015). Therefore, it is critical to identify and manage the causes of quality failures in construction processes in order to avoid quality failures and improve construction quality, and in turn, save energy.

Energy-saving renovation programme adopts the same management models as traditional construction projects, so the roles and responsibilities of the construction participants remain during the project management processes. As building energy renovation belongs to government's investment projects, the government plays an investor in the management of energy renovation projects. Ideally, the construction participants (include construction companies, supervision companies, government, and design companies) in renovation construction projects should be able to collaborate in implementing five areas of management actions: people, material, equipment, design, and organisation.

This paper focuses on building energy renovation projects in the Chinese situation. Although slight differences exist in quality management of different countries, most models of quality management consider these five categories: people (Zhang, Skitmore, and Peng 2014; Safapour and Kermanshachi 2019), material (Gschoesser, Wallbaum, and Boesch 2012; Inyim, Zhu, and Orabi 2016), equipment (Eteifa and El-adaway 2018; Mahamid, Bruland, and Dmaidi 2012), design (Wang, Li, and Tam 2015; Wang, Li, and Tam 2014; Dehghan, Hazini, and Ruwanpura 2015; Safapour and Kermanshachi 2019), and organization (Li, Ng, and Skitmore 2012) (Oppong, Chan, and Dansoh

2017; Liu and Guo 2014; Li 2014b). The suggestions based on five areas of quality management actions can be useful for reducing the internal causes of problems and so 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 on managing quality.

In practice, the causes 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 causes of quality failures, the project coordinators have actually failed to manage the quality of construction projects. Thus, it is important to conduct a deep insight into the intricate relationships among the causes (Shen et al. 2016).

Although there has been a huge amount of studies that tried to identify and analyse the causes of quality failures (e.g. (Hughes and Thorpe 2014a; 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 recognising a whole network of different causes working together (Hwang, Zhao, and Goh 2014). Hence, based on their limited understanding, information was offered about how quality is influenced by separate causes that, in reality, have interactive relationships.

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

According to the previous studies (Mathiyazhagan et al. 2013; Dubey et al. 2015), the interpretive structural modelling (ISM) and Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC) techniques are typical methods to structure and find the root factors, and they have also been used in other construction projects more recently.

Therefore, these objectives are achieved by devising a mixed-method approach, by combining the ISM method and the MICMAC technique. The ISM method is a system analysis method to establish a hierarchy structure among causes (see Section 4.2). The MICMAC technique is employed to analyse the driving-power and dependence-power for each cause (see Section 4.3). The analysis serves to identify which causes are behaving as the driving causes in energy renovation projects, and which causes are performing as the 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 as the site 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 since 2008, and the administrative and technical regulations of building energy renovations issued by the national governments have been applied.

Next, in Section 4.2, 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. The methodology is introduced in Section 4.3, which tests the validity of these causes, identifies relationships of the causes affecting the construction quality as well as classifies the causes based on their driving-power and dependence-power. In Section 4.4, the ISM maps the relationship between the causes, and subsequently, MICMAC groups the causes. The results of the analyses of the relationships and grouping of causes are then presented. In Section 4.5, there is a discussion on the causal maps and classifications. The authors' recommendations are provided and grounded from a quality management perspective, where we argue for the implementation of a renovation policy as well as for the roles of the stakeholders in renovation projects. Finally, Section 4.6 summarizes the findings of the paper and the main contributions upon achieving high-quality performance in building energy renovation projects.

4.2 Literature review

4.2.1 Quality, Quality Failures and Quality Management in Construction Projects

The different concepts of quality were introduced by previous studies. According to the International Standards Organization (ISO), the 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 surpass expectations. Meanwhile, quality is also defined as meeting the customer's expectations or compliance with customer's specification (Battikha 2003; Jha and Iyer 2006). Sim and Putuhena (2015b) came up with a definition of quality as the '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).

The success of a construction project found in the literature 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, using terms such as: 'non-conformance,' 'error,' 'fault,' 'defect,' and 'quality deviation' (Forcada et al. 2014; Sommerville and McCosh 2006). According to Alencastro (2018), the definition of quality failure is: " *failing or shortcoming in the function, performance, statutory, or user requirements of a building*".

In line with Qi (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 situation of the building energy renovation projects (Qi et al. 2019). Firstly, numerous quality failures were identified, such as 'Cracks of roof concrete,' 'Misalignment of the waterproof roof layer,' or 'Missing rivets.' Secondly, 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 tackle a cause (for more details about the study, see (Qi et al. 2019)). This paper contributes to the solutions of 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, Madu, and Lin 2008; Jraisat, Jreisat, and Hattar 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) where quality management is broadly defined as an umbrella term for a number of quality improvement programmes, such as quality assurance, quality control, total quality management, Six Sigma, and integrated management system. All these programmes share a core focus on systematic attention to improve quality in projects (Niu and Fan 2015).

4.2.2 Quality Management Actions in Building Energy Renovations in China

It is important to state that most of the quality failures can be avoided at management level when quality management actions provide sufficient dedication and attention to details (Kuei and Lu 2013; Abdul-Rahman et al. 2014; Brinkhoff et al. 2015). The success of quality management depends heavily on management actions. Thus, proper quality management actions must be adopted (Othman and Azman 2011).

In the context of China, the quality management actions are identified from five perspectives, including people, materials, machines, design, and organization, based on previous research studies (Liu and Guo 2014; Li 2014b; Wu, Li, and Liu 2013).

4.2.2.1 People

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

Project managers and chief supervisors play a critical role in construction projects (Zhang, Skitmore, and Peng 2014). They need to emphasize the key technical points, supervise quality during the construction stage, organize workers, and manage construction sites (Wang 2016; Wang 2012a). Moreover, a specific construction plan implemented by project managers could help control the various steps of the projects directly (Tang 2014a). Thus, project managers, who are required to provide the certification, must have rich management experience and renovation knowledge in building renovation projects ("Regulations on quality control of construction projects").

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; or to (4) sign the quality report (Zhang and Yu 2016). The site supervisors are delegated to the governments, and they need to implement the management of the on-site conditions that are adverse to quality and record the quality failures records (Ye et al. 2014).

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

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

4.2.2.2 Material and equipment

Quality of construction materials and equipment is the critical management factor in contributing success, which determines the level of construction quality (Liu and Guo 2014). Material concerns raw materials, auxiliary materials, semi-finished products, components, and fittings, among others (Cui 2017). Meanwhile, construction machinery, construction tools, facility, and instruments belong to equipment(Li 2018). The construction companies procure the material (like 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 Sui Pheng 2014). Officers in the government and supervisors must check the certifications of construction materials and equipment ("Regulations on quality control of construction projects"). During the construction stage, project managers need to do the evidential tests and on-site inspections supervised by the on-site supervisors ("Regulations on quality control of construction projects").

4.2.2.3 Design

Based on the site survey and original building information, the design is necessary for the renovation projects and the use of 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 ("Regulations on quality control of construction projects"). Design companies need first to check their own design documents completed ("Regulations on quality control of construction projects"). At the construction preparation stage, local governments and supervision companies organize the meetings for the construction companies to check and discuss the design documents (Wang, Li, and Tam 2014). During construction processes, if there are errors found in design documents, the changes must be approved by the chief supervisors ("Regulations on quality control of construction projects").

4.2.2.4 Organization

In the Chinese quality management model, quality must be supervised by the internal organizations of private companies (Shang and Sui Pheng 2014; Zou, Zillante, and Coffey 2009). For example, design companies also manage design processes in order to avoid quality failures caused by design mistakes. Construction companies build their own rules and quality responsibility system to manage the quality, such as the examination of materials and equipment before installation ("Regulations on quality control of construction projects"). Whereas, the interactions and interrelationships between main stakeholders largely determine the quality management of the construction projects (Jraisat, Jreisat, and Hattar 2016).

Quality management in building energy renovation projects involves multiple main stakeholders. The efficient cooperation between different stakeholders is supported by the high speed of communication (Wang 2012a). For example, construction companies must provide construction information to supervision companies effectively, and supervision companies need to report the construction schedule and cost every month to local government.

4.2.3 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, Jreisat, and Hattar 2016). The Chinese quality management model is implemented through a mixed management system (Wu et al. 2012). The main stakeholders during quality management processes are classified into two categories, namely, public parties and private parties (see Fig.4.1.).

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

Local governments (including provincial governments, municipal governments, and district governments) are responsible for implementing the renovation projects to match the 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 ("Regulations on quality control of construction projects").

On the other hand, private companies usually are 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, et al. The construction company is a direct participant during the construction process, in which the activities are the most complicated and have a significant impact on construction quality. In particular, construction companies prepare the necessary resources for construction (workers, materials, and machines) and provide construction time-scheme and information. Construction companies are required to test the quality of the materials and machines, doing evidential tests and on-site inspections. Construction companies also are responsible for checking design documents within construction processes.

Supervision service is provided by supervision companies to assist the local governments in managing the construction quality. The local governments and supervision companies oversee the work processes of design companies and construction companies. The supervision actions include plan approval, site inspection, evidential tests, and final check before the delivery of the renovation projects. Supervisors must check covert projects by on-site inspection. Otherwise, construction procedures cannot continue.

The obligations of design companies are to check the original documents of the existing buildings, do an on-site survey, and provide design documents.

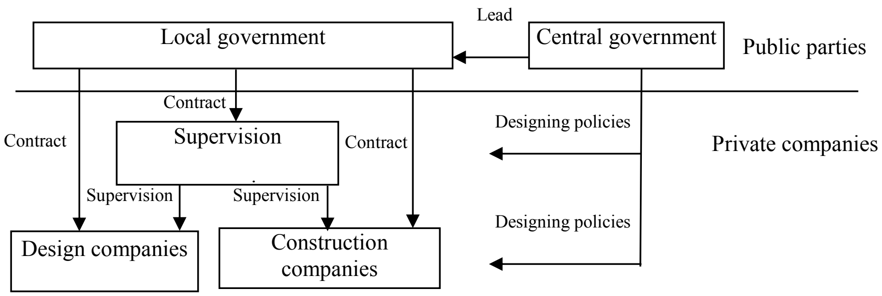

FIG. 4.1 The relationships between the main stakeholders in renovation construction projects

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4.2.4 ISM Method and MICMAC Technique

In order to achieve more in-depth insights, the ISM method and MICMAC technology were adopted to develop a structural model of these critical factors.

ISM method 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, it is used for examining the effect of each cause on others as well as for measuring relationships to achieve the objectives of the research. According to Valmohammadi and Dashti (2016), ISM provides an effective tool to investigate the inter-relationships among specific causes.

This method can be applied for many purposes including identification and analysis of internal relationships between the barriers for the implementation of green supply chain management (Mathiyazhagan et al. 2013; Al Zaabi, Al Dhaheri, and Diabat 2013), identification of the critical for adoption of green supply chain management (Mathiyazhagan and 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 organisation (Alawamleh and Popplewell 2011), the analysis of the interactive networks of the risks in green building projects (Yang, Zou, and Wang 2016), identification and analysis of the internal relationships between supply chain management enablers (Gorane and Kant 2013), identification of the root barriers in the development of renewable resources (Rezaee, Yousefi, and Hayati 2019), prioritization and categorisation of the principles for total quality management implementation (Mehta, Verma, and Seth 2014).

The theoretical foundation of ISM is systems science, while the majority of 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, Hone, and Liu 2014; Qureshi and Kang 2015), Bayesian network model (Leu and Chang 2013; Zhang et al. 2014) and Fault tree analysis (Aljassmi and Han 2014; Cheng and Li 2015). Comparing with these methods, ISM did not have strict statistical constraints on the sample size. Furthermore, the topic regarding quality failures is sensitive, and a database of quality failures is lacking in construction projects. It is, therefore, difficult to approach a sufficient sample of valid respondents for data surveys. However, the application of the ISM method 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, Luthra, and Haleem 2013).

In using the ISM method, the emphasis is given to the quality of respondents instead of quantity. Therefore, ISM was more appropriate for this paper compared with other methods.

MICMAC technique 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 between causes. Also, the MICMAC technique is a standard method to identify and analyse the factors in a complex system.

4.3 Research Studies on the 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 internal or external to the projects (Balasubramanian 2012). Internal causes are originated inside the project, and these causes can be solved from a quality management perspective at a project level. Therefore, this paper focuses on the internal causes and reduces these causes by quality management.

The authors have conducted a global search and examination of relevant scholarly literature. Given the vast number of articles on the causes of quality failures in general, in order to develop our initial list of identified causes, we build upon 18 articles (see Table 4.1 and Table 4.2) 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 the renovation projects and new building projects. In order to have 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.

4.3.1 Review on 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 labour skills (Adenuga 2013; Enshassi, Sundermeier, and Zeiter 2017b), inferior materials (Janipha and Ismail 2013), lack of clear instructions given by site supervisors (Jingmond and Ågren 2015a), et al. These internal causes of weakness could be reduced or completely avoided or through better attention to quality management at a project site level, which provides the light for reducing the causes of quality failures from a quality management perspective.

A literature survey has thrown light on various kinds of causes that hinder quality performance from going better. Most of the internal causes are associated with lack of operational workforce (Jingmond and Ågren 2015a), 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 2014a; 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 related to a 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 situation of the construction markets. They found that poor craft skills, non-specified 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 are: poor supervisor competency; and incomplete drawings. Love et al. (2010) summarized that primary causes are ineffective information technologies, lack of clear working procedures, and insufficient changes.

Dixit (2017) mentioned that the causes are poor site coordination, lack of competency, fragmented supply chain, lack of commitment, improper construction planning, and inefficient site management. Meanwhile, Aiyetan (2013) investigated the causes of quality failures and came up with management suggestions for quality improvements. In his study, poor communication, the inexperience of personnel, and non-specified concrete are identified as the causes of quality failures. Oyedele (2015) identified and ranked causes. The five most important causes are the poor quality of materials, low level of skill and labour experience, inadequate inspection and testing, poor site installation procedure, as well as lack of quality assurance.

In Kakitahi et al.'s study (2015), inadequate communication is described as a substantial factor to cause quality failures. Based on an interview and questionnaire survey, Ye at al. (2014) investigated and prioritized a total of 39 causes of quality failures, in which unclear project process management, poor quality of construction technology, and the use of inferior construction materials ranked the first three causes.

TABLE 4.1 List of identified internal causes from a literature review

Causes	Description of causes	References
Poor operational skilled workers	Operational skilled labour in construction processes lacks.	(Jingmond and Ågren 2015a; Schultz et al. 2015; Oyedele et al. 2015; Aljassmi and Han 2014) (Forcada et al. 2012; Forcada et al. 2014; Chong and Low 2005; Aiyetan 2013; Ashokkumar 2014; Yong 2016)
Poor checking procedures of site supervisors	On-site supervision and feedback processes make failures.	(Ye et al. 2014; Aiyetan 2013; Love et al. 2010) (Hughes and Thorpe 2014a; Oyedele et al. 2015)
Use of poor materials	The quality of construction materials is non-specified.	(Ye et al. 2014) (Aiyetan 2013; Oyedele et al. 2015) (Janipha and Ismail 2013)
Inadequate equipment performance	Mechanical equipment is non-specified.	(Jingmond and Ågren 2015a; Hughes and Thorpe 2014a)
Inaccurate design work	There are mistakes and discrepancies in design documentation.	(Aiyetan 2013; Jingmond and Ågren 2015a; Hughes and Thorpe 2014a) (Ahzahar et al. 2011)
Incomplete construction site survey	Designers or construction companies ignore or make 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 2015a; Kakitahi et al. 2015; Love et al. 2010; Hughes and Thorpe 2014a)
Unsettled plan or lack of construction plan	Construction companies ignore or make deficient construction planning.	(Aiyetan 2013; Dixit et al. 2017)
Poor site management	Workers, material, and equipment on site are not strictly managed and controlled.	(Aiyetan 2013; Dixit et al. 2017)
Poor on-site coordination	The speed of communication on-site between main stakeholders is low.	(Aiyetan 2013; Schultz et al. 2015; Dixit et al. 2017)

This paper collected 11 internal causes from the international literature. Table 4.1 shows the sources and descriptions of these internal causes. In order to identify representative causes affecting the quality of renovation construction in the Chinese context, an interview survey was conducted, which is illustrated in section 4.4.1.

4.3.2 Review on External Causes

The origin of some causes is outside the projects, such as regulation environment, culture environment, natural environment (see Table 4.2). Therefore, quality management at a project level cannot be used to prevent these external causes occurring. From a global view, Schultz et al. (Schultz et al. 2015) identified two significant external influences on quality failures. These external causes include 'planning of budgetary conditions,' and 'time schedules.' Kakitahi et al. (Kakitahi et al. 2015) identified that graft and dishonesty of private companies are the external causes of the quality failures. On a similar line, Enshassi et al. (Enshassi, Sundermeier, and Zeiter 2017b) studied the three external causes of quality failures, including fraud, competitive pressure, and schedule pressure.

TABLE 4.2 List of identified external causes of quality failures (from a literature review)

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

In building energy renovation projects of the Chinese context, a government-led approach is a standard mode. In the government-led model, the top-down mandatory requirements for renovating technology are set from the central government. As the unique features in building renovation projects, a set of strong legal energy targets and the financial support from the government may bring the external causes also to be strong, such as working under high-cost and high-time pressure in China.

4.4 Methodology

As described in Fig. 4.2., the inter-relationships of causes and their classifications include three methods: ISM method, Matrix Impact Cross-reference Multiplication Applied to a Classification (MICMAC) technique, and focus group.

Methods	ISM method		MICMAC technology	Focus group
Aim	Obtain the final list of identified causes; Establish the contextual relationships between causes.	Establish a structural model for causes based on ISM analysis	Classify the causes based on their driving-power and dependence-power	Test if there are logical or conceptual contradictions in the structural model and classification; Provide some recommendations regarding the causes of quality failures at quality management level.

FIG. 4.2 Research methodology

The step by step procedure involved in the ISM method and MICMAC technique is as follows in this paper. The schematic approach of the present study is shown in Fig. 4.3.

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 semi-structured 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. Warfied (1974) defined the contextual relationship as conceptual links between the system components matched with the system objectives.

The Structural Self-Interaction Matrix (SSIM) is developed as a binary matrix and indicates pairwise relationships among the factors of the system under consideration. Therefore, SSIM is developed for 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. It states that if a 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 analyse 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 method and MICMAC technique.

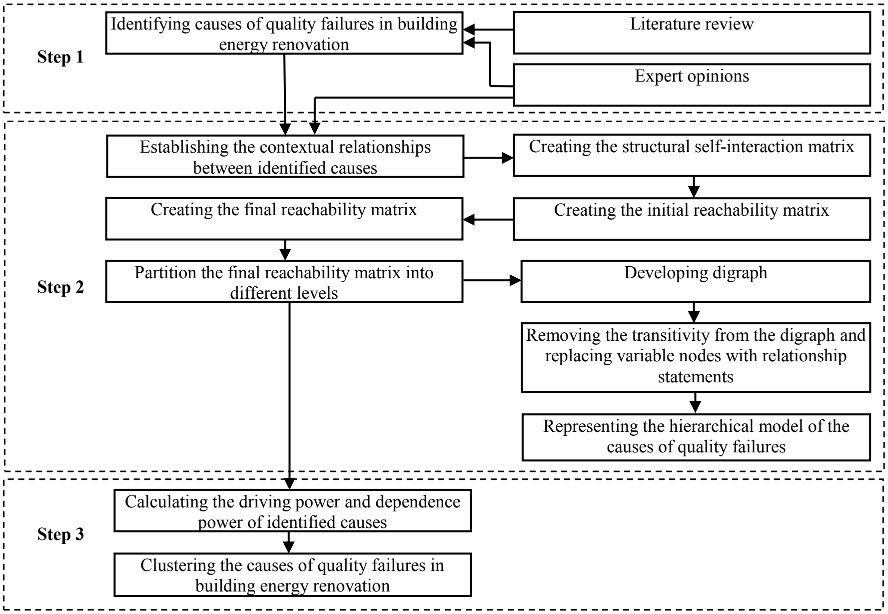

FIG. 4.3 Flow diagram to identify and analyse the internal relationships of the causes of quality failure for building energy renovation (modified from (Rezaee, Yousefi, and Hayati 2019)

4.4.1 Identifying Causes of Quality Failures

In international scholarly literature (see Table 4.1), 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 is important to ensure that the interviewees are knowledgeable about both building energy renovations and quality management. In order to find effective interviewees, all experts were selected based on their working resumé in the renovation projects. They are with sufficient knowledge regarding building energy renovations and more than eight years of quality management experience. It is considered that their opinions are effective for analysis in this paper. In using the ISM method, the emphasis is not given to the number of experts, so the quantity of the experts does not have so big an influence (Shen et al. 2016). So, 22 experts were invited, and their opinions were collected. Based on the opinions of these experts, the final list of causes of quality failures is obtained, and the contextual relationships between causes are established. The profile of the interviewees is present in Table 4.3.

TABLE 4.3 The 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	On-site supervisor	Face to face, phone
	12	On-site 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

>>>

TABLE 4.3 The profile of experts and interview method

Group	No.	Profile	Interview method (first round, second round)
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

The experts' group consist of ten project managers working in construction companies, five supervisors from the supervision companies, two designers and five government officials in the fields of building energy renovation whose opinions have been used in two sections, including providing a final list of causes and building causal relationships between these causes.

In this paper, 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 the agreement for all causes and their relationships. The 18 causes are listed in Table 4.10 based on literature and discussions with 22 experts. From the literature, 16 causes are taken, and after discussion with the experts, two causes are included.

In the building energy renovation projects of the Chinese context, the project managers' lack of management experience and renovation knowledge may result in quality failures. Additionally, due to wrong flows of construction processes, some quality failures may occur, such as concrete cracks. Consequently, 18 causes are considered (see Table 4.10).

4.4.2 Establishing the structure model for the causes of quality failures

The internal causes can be avoided or reduced through better project management, and overcoming these internal causes can remarkably reduce quality failures through improvements in management procedures (Qi et al. 2020). Thus, the 13 internal causes for analysing the management of energy renovation projects were studied in this section.

In order to establish the structure of the internal causes, the causes' level partitions between causes need to be identified first. The results of identifying the level partitions of the causes are shown in Table 4.6 , with each table including the columns of reachability set, antecedent set, intersection set, and level. The process of partition analysis can be analysed 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.

TABLE 4.4 Structural self-interaction matrix

Causes	1	2	3	4	5	6	7	8	9	10	11	12	13
1	-	A	O	O	O	O	O	O	A	V	O	O	O
2		-	O	V	V	O	V	O	X	V	V	V	V
3			-	V	V	O	O	O	A	O	O	O	O
4				-	O	O	O	O	O	A	O	A	O
5					-	O	O	O	O	O	A	A	O
6						-	A	O	A	O	O	O	O
7							-	O	A	O	V	O	O
8								-	O	O	O	O	X
9									-	V	V	O	X
10										-	A	A	O
11											-	V	O
12												-	O
13													-

The resulting matrix is called Structural Self-Interaction Matrix (SSIM) (see Table 4.4). 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 (Appendix A). On the other hand, the final reachability matrix shows indirect relationships and direct relationships. So that, in the final reachability matrix, if cause 1 influences cause 2, and cause 2 influences cause 3, cause 1 necessarily influences cause 3. The final reachability matrix is obtained by incorporating the transitivity (see Table 4.5.). The reachability and antecedent sets are obtained from the final reachability matrix.

TABLE 4.5 Final reachability matrix

Causes	1	2	3	4	5	6	7	8	9	10	11	12	13	DP*	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		

DP = Driving Power

2 Reachability set and Antecedent set

The reachability and antecedent set 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 4.5. For example, concerning cause 1, its reachable causes include cause 4 and 10. So the reachability set for cause 1 consists of cause 1, 4, and 10. As a result, the reachability sets for all causes can be obtained, as shown in the column "Reachability set" in Table 4.6.

The antecedent set for a particular cause consists of the cause itself and the other causes which 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 4.5. For example, concerning cause 1, its reached cause include cause 2, 8, 9, and 13. So the antecedent set for cause 1 consists of cause 1, 2, 8, 9, and 13. As a result, the antecedent sets for all causes are obtained, as shown in the column "Antecedent set" in Table 4.6.

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 4.6. As a result, the intersection sets for all causes are obtained, as shown in the column "Intersection set" in Table 4.6.

TABLE 4.6 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	
6	6	2,6-9,13	6	
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	

4 Identification of level partition between causes

The cause of which the reachability sets equal their intersection sets are the same is given the top-level cause. For example, it can be seen in Table 4.6, cause 4, 5, and 6 have the same reachability set and intersection set. These three causes are partition as top-level. According to the principle of ISM, eliminating these cause (cause 4, 5, and 6) and repeating the same procedure for other causes, different cause levels are created in Table 4.7. 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 6 iterations shown in Table 4.7.

TABLE 4.7 Level partition-iteration 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 4.8 presents the final results obtained from 6 iterations.

TABLE 4.8 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 on-site coordination	

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 between 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. 4.4 as an ISM model.

4.4.3 Analysing the causes' driving-power and dependence-power

In general, a cause with a higher dependence power indicates that several other causes should be addressed before this cause can be eliminated. A cause with a higher driving power means that its elimination allows solving several other causes (Attri, Dev, and Sharma 2013; Tan et al. 2019). Following the classification adopted by previous researchers (Mandal and Deshmukh 1994), the causes are divided into four groups. Namely (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 analysing and categorizing the driving and dependence powers of causes, the MICMAC analysis has been used. In the final reachability matrix (see Table 4.5), 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 the MICMAC technique gives an insight into the relative importance and interdependencies between 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 (see Fig. 4.5).

4.4.4 Validating the causes' map and classification

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

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

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

In the focus group, ten participants were involved to be representative of all departments at management level with consisting of three officers 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 above principles (their details are in Table 4.9). The goals of the focus group have been to 1) test if there are logical or conceptual contradictions in the structural model and classification; 2) provide some recommendations regarding the causes of quality failures. As for these participants, all experts in the focus group are considered to be 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 the 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 come up with their 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 4.9 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	On-site 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

4.5 Results

4.5.1 Causes of quality failures

Table 4.10 presents the 18 causes identified from the literature review and experts' interviews. A focus group classified the internal causes from four management perspectives: people, material and equipment, design, and organization.

TABLE 4.10 Identified causes from a 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 on-site coordination
External		14	Complex on-site environment
		15	Fraud of construction companies
		16	Working under high-cost pressure
		17	Working under high-time pressure
		18	Adverse natural conditions

4.5.2 Structural Model for the Internal Causes of Quality Failures based on ISM Analysis

According to Fig. 4.4, all the 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 on-site coordination (13)”. These causes act as dominant roles for hindering the high-quality performance in building renovation projects. Also, “Incomplete building information in projects (9)” is experienced 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. The “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 an education level of junior middle school or

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below, the site management is not clear to workers causing 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)”.

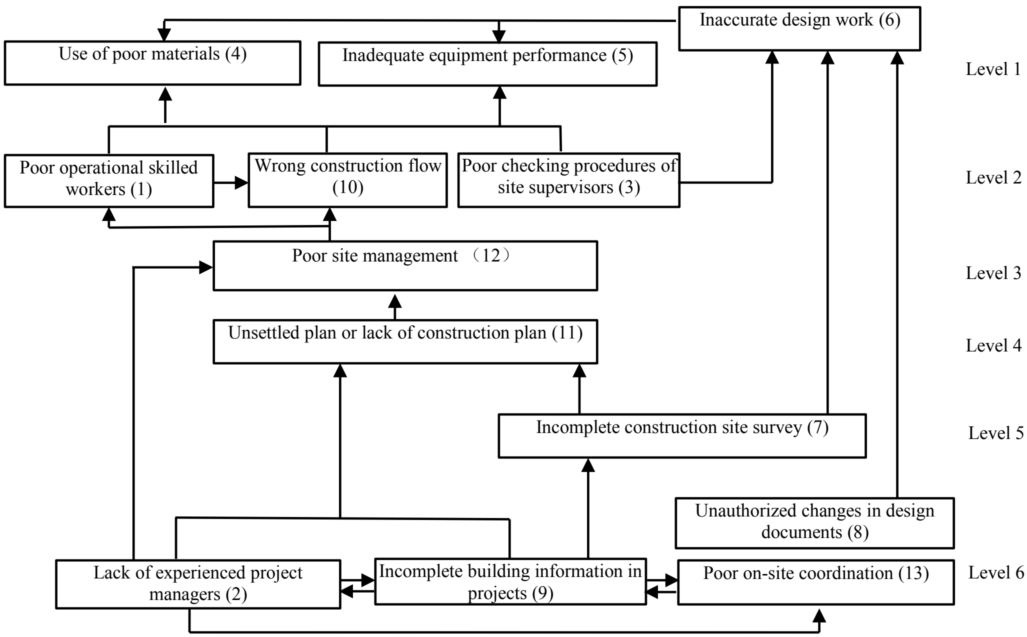

FIG. 4.4 ISM model of the causes of the quality failures

4.5.3 Driving and Dependence Powers of Causes

According to Fig. 4.5, the first cluster includes autonomous causes with low driving and dependence power. Causes “Poor operational skilled workers”(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 with high dependence-power in the second cluster.

No cause is situated in the third cluster, which includes linkage causes with high driving and dependence-power. Causes "Lack of experienced project managers"(2), "Unauthorized changes in design documents"(8), "Incomplete building information in projects"(9) and "Poor on-site 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 placed on the linkage-cause cluster or independent-cause cluster. According to the obtained results, causes 2, 8, 9, and 13 are the primary ones, due to their high driving-power.

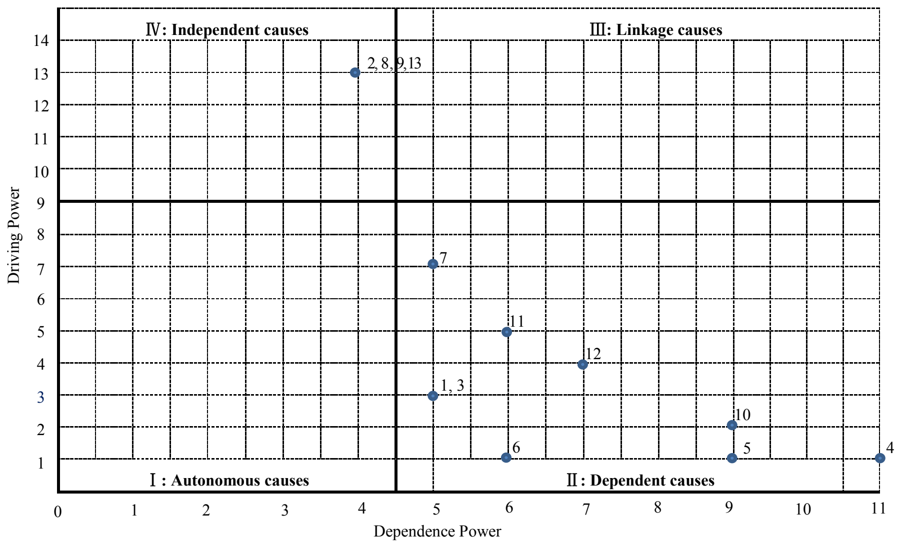

FIG. 4.5 Clustering the causes of the construction quality

In the labour category, there are three causes, namely: "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)" at level 2, and it is listed as dependent causes. "Poor operational skilled workers (1)" also has low driving 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 the causes at the 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 on-site coordination (13)” are considered top priorities, which have strong driving-power. Five causes come under the organizational category. “Incomplete building information in projects (9)” and “Poor on-site coordination (13)” are considered top priorities, which 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)”.

4.6 Discussion

4.6.1 Inter-relationship among internal causes

It should be re-stated that the causes of quality failures do not occur in isolation but are interrelated with other causes. The ISM model diagram (see Fig. 4.4) shows the interaction among the causes, and maps several processes feeding forward to the occurrence of the causes. The causes “Lack of experienced project managers,” “Unauthorized changes in design documents,” “Inefficient information transfer,” and “Poor on-site coordination” are very significant causes as they form the base of the ISM hierarchy. Not only do these four causes negatively impact the construction quality in building energy renovation projects, but also 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 they are known as the most directive 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 2015a). In contrast, Aljassmi and Han (2012) pointed out that inferior construction materials, workers’ competence limitations, and inadequate supervision are the priority consideration to reduce 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 the reduction of quality failures have emerged and are provided from a quality management perspective. These are presented under the following four headings, relating to: People; Material & Equipment; Design; and Organisation.

4.6.1.1 People

Project managers in all of the site staff play a vital role in driving the entire project. The results indicate that project managers could significantly affect other causes of quality failures in China. Taking two Asian counterparts, Malaysia and Iran, as examples, the major contribution 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. The implications are suggested to formalize the delineation of project managers' responsibilities in building energy renovation projects. The project managers should be responsible for the following functions:

- Defining general quality management practices;
- Managing the on-site construction;
- Verifying the efficiency and effectiveness of quality management;
- Informing the supervisors and local governments of some quality failures.

The advice for local government is to increase investment to educate project managers upon their responsibilities and organize the meetings to share their experiences.

"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 profoundly and frequently (Fang, Wu, and Wu 2015).

However, there was no work procedure to check each batch of material and equipment, for example, concrete, windows, and expanded polystyrene insulation (EPS). Attar et al. (2012) illustrated that the incompetent supervisor is a top factor affecting

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construction projects. In Poland, Głuszak and Leśniak (2015) also stated that there is poor supervision of construction works.

Key-work checklists are designed by the chief supervisors based on the technical requirements of the government. Nonetheless, it was found that project managers and site supervisors were not supporting the implementation of the key-work checklists because the completion of these checklists would slow down their work. Additionally, without proper supervision on the workers' construction behaviour, workers may ignore some construction steps in order to speed up. Moreover, the site supervisors do not check for themselves but proceed to call for an inspection by other site staff.

In order to resolve the causes above, local governments would check the reports upon specific supervision flows from on-site supervisors and build a systematic and practical checklist system to avoid missing inspection for site supervisors.

As a result of the shortage of skilled labour, a large number of semi-skilled and poorly trained workers were used in renovation projects (Zhang, Skitmore, and Peng 2014). The project managers had instructed the workers to specify the key points, but the workers themselves were unsure as to how the key points might 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 following the technical requirements from the governments. From a policy perspective, Visscher and Meijer (2014) considered that mandatory certification of different parties will become more useful for construction processes.

4.6.1.2 Material and Equipment

"Use of poor materials" and "Inadequate equipment performance" may represent the main indicators to reflect the final quality performance of the building energy renovation projects. This result is in line with Francom and Asmar's studies (2015). In an investigation of Indian construction projects, Thomas and Sudhakumar (2014) demonstrated there is a need to adopt effective material management practices at construction sites. The project manager had first set up a centralized laboratory at the worksite to take material samples before this kind of material was used.

Then, the procedures, on-site quality management of materials and equipment, are described:

- Material and equipment ordering;

- Certification checking;
- Material and equipment delivery to the site;
- Material and equipment sampling and testing;
- Batching of material and equipment

Non-specified material and equipment must be rejected during the inspection by the project manager or site supervisor. The rejection report can be sent to the chief supervisor and recorded. According to Hwang and Ng (Hwang and Ng 2013), most of the material and equipment do not have proven track records in Singapore. Therefore, the material and equipment checklist can be used to avoid the project manager and site supervisor's missing any inspections.

4.6.1.3 Design

"Unauthorized changes in design documents" has more capability to influence other causes. According to the nature of the construction companies, the primary interest of construction companies is to reduce their costs and increase company income. In order to reduce the cost, construction companies change the design documents without authorized by designers. Juszczyk et al. (2014) in Poland described that the modification of the design documentation often occurs during the execution of construction, which is a reason for quality failures. Policies and regulations can be designed to increase punishment so that construction companies do not have the motivation to change the design documents.

Globally, design errors can significantly affect quality in construction projects (Han, Love, and Peña-Mora 2013; Rafindadi et al. 2014). However, in the result of this paper, "Incomplete construction site survey" makes errors or changes in the design work. So, the effectiveness in addressing the "Incomplete construction site survey" will influence, to a large extent, the design work of building energy renovation projects.

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

4.6.1.4 Organisation

The efficient organisation of the construction team is essential for the construction processes (Głuszak and Leśniak 2015). "Incomplete building information in projects" and "Poor on-site coordination" are more significant to affect others and need to be given the highest priority for attention and avoidance. As stated by Janipha and Ismail (2013), information is important to ensure the right decisions are made, and appropriate action can be taken in 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 on-site coordination, Doloi et al. (2012) and Doumbouya et al. (2016) proposed effective cooperation between the stakeholders of the projects has a relationship with the sharing of project information. In China, the standard practice is that when key work is to be completed by the construction companies, the latter would inform the site supervisors. However, in order to speed up, project managers do not inform the site supervisor to check. Some of the site supervisors are asked to fill up the checklist, even though the works have not been completed. The solutions are that an efficient information-sharing system, such as the Building Information Model (BIM), should be applied in building energy renovation projects to improve communications between on-site participants. Meijer and Visscher (2017b) also advise governments to develop some online tools further to guide and organize the on-site participants through the construction process.

"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 will be addressed accordingly. So, 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.

4.6.2 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 are originated outside the project, such as working under high-cost and high-time pressure. These external causes can hardly 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 high-cost pressures have a commanding driving force to change construction coordinators' behaviour to tend to save the construction time and cost. These behaviours, such as making unauthorized changes in design documents, cause possible quality failures during renovation processes. Han et al. (2013) studied that time-schedule pressure can propagate the negative impact on numerous construction activities.

In order to solve 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 the current renovation regulatory structures, approaches and attitudes.

4.7 Summary and Conclusions

The process of building energy renovation is part of an essential strategy for achieving the 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 assured. These quality failures hinder the completion of the renovation projects on time, and even the poor airtightness and energy efficiency performance is the consequences of quality failures in the usage stage. Thus, it is hard to achieve the predicted energy efficiency rates due to quality failures, which conflicts with the aims of building energy performance.

Various causal factors affect construction quality, some of which are internal to the projects. In order to make decisions for managing resource allocation and mitigate the quality failures, the 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 paper thoroughly analyses the interrelationships of the internal causes in renovation projects and their driving and dependence power by using ISM and MICMAC techniques. The results obtained from these methods show the structural relationship between the FOUR main causes affecting construction quality. These are: the "***lack of experienced project managers*** (2)"; "***unauthorized changes in design documents*** (8)"; "***incomplete building information in projects*** (9)"; and "***poor on-site coordination*** (13)"; which are the driving causes with high driving-power. Efforts to address these four factors would mean that their elimination allows the solving of several other internal causes. Consequently, these causes of quality failures should be prioritized, and where more attention should be paid.

Combining the obtained results, this paper provides appropriate strategies to improve the quality performance within a broad perspective of the project level of the existing management actions. The solutions were categorised in terms of people; material and equipment; design; and organization, based on the quality management processes. It should also be highlighted that, since external causes remain associated with all internal causes, there is a need for upgrading the policies and regulations of building energy renovations, in order to mitigate and solve the external causes.

In conclusion, an understanding these interactive causes and their solutions may help project practitioners to make better-informed management actions, and so avoid the continuing quality failures, in order 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, which are contemplating the implementation of quality management for building energy renovation projects.

A possible limitation of the study as reported in this paper, is that the focus has been to explore the causes which are of internal origin to the project. 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 a policy level. Additionally, the scope of this research is the building energy renovation projects of Northern China. Cases were only chosen in the Chinese context. Further representative cases could be considered from a global view. Finally, although the empirical base could be improved, the data gives insight is a topic that has been hardly studied so far in China and that it hopefully forms a basis for substantial further data gathering.

Appendix A

INITIAL REACHABILITY MATRIX

	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 on-site coordination	0	0	0	0	0	0	0	1	1	0	0	0	0

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5 Exploring the Causes of Quality Failures for Energy-saving Renovation projects of Residential Buildings in Northern China

A Policy Network Perspective

Submitted for review.

ABSTRACT In recent years, China has seen a steep rise in energy-saving renovation projects of residential buildings. However, quality failures, that is, completed work that does not meet the technical requirements, too often occur during construction processes. Attention has begun to focus on the perceived causes of quality failures in building energy-saving renovation programme practical implementations.

During the implementation processes of the renovation policies, actors and their interactions triggered the external causes of quality failures. To probe this further, this study assesses and explores how the actors and their interaction affect and cause quality failures during the renovation implementation process. The policy network theory is used to map the resources actors have in different two energy-saving renovation projects. The results of the analysis show that the implementation of the energy-saving renovation programme should be further improved. A comparative case study shows that some causes of quality failures exist in the implementation of building energy-saving renovation programmes. Inefficient cooperation of public-private partnerships is responsible for demoting the involvement of private actors. Additionally, to some extent the involvement of residents is an unsatisfactory impact because some of them believe that the benefits of energy renovation do not outweigh their costs. During the energy-saving renovation programme implementation, local governments just focus on the construction time schedule rather than ensuring the technical conformance for energy-saving and thus addressing climate change. The moral hazard of lax supervision is much more probable to occur than in other types of construction projects, which is a critical cause of quality failures in building energy-saving renovation projects in the context of China.

KEYWORDS Causes, Quality failures, Energy-saving renovation projects, Residential buildings, Policy network theory

5.1 Introduction

Building sectors worldwide are currently estimated to use about 32% of the world's energy and contribute to nearly 20% of the global energy-related greenhouse gas emissions (IPCC 2014). Indeed, the largest energy-saving potential lies in the existing building stock (Visscher 2014). As illustrated by China's example, the energy consumption of existing buildings accounts for nearly one-third of China's total primary energy consumption (Qian, Chan, and Choy 2013). There is a huge stock of existing buildings in China, and the total floor area of existing buildings has approached almost twice that in the European Union during recent years (Li and Shui 2015). Moreover, the energy consumption in the building sector is rising rapidly year by year in China with increasing living standards (Liu, Li, et al. 2020). Therefore, the energy-saving renovation of existing residential buildings is one of the most vital developments in recent years for reducing energy consumption (Kong, Lu, and Wu 2012).

In response to the pressures brought by the strong energy demand, the Chinese central government has set ambitious area targets to complete energy-saving renovation in existing residential buildings of 1.2 billion m^2 in Northern China by 2020 (Chen et al. 2013a). As the primary policy objective, the energy-efficiency target is such that the heating energy consumption should be reduced by 40%-65% relative to the consumption during the early 1980s (Zhou et al. 2018). However, during the construction stages in energy-saving renovation projects of residential buildings, quality failures frequently occur. These can cause inefficient energy performance, safety hazards, overall cost increases, and other unexpected losses (Qi et al. 2019).

Quality is defined in this paper as meaning that the completed construction work has to meet the technical requirements set in the building regulations (Meijer and Visscher 2017a). Based on the previous studies (Qi et al. 2019), the common quality failures of energy-saving renovation projects of residential buildings in China include: *'Unqualified fire resistance of EPS boards,' 'Misalignment of the waterproof roof layer,'* and *'Cracks of roof concrete'.* These quality failures result in poor thermal insulation and so are threats to the high energy-efficient performance. Moreover, owing to these quality failures, there are consequential overdue schedules, and unexpected cost overruns, all of which become as the dominant barriers to implementing future building energy renovation. In order to satisfy the requirements in the construction processes, the causes of these quality failures need to be studied, and so improve construction quality.

In terms of the causes of quality failures, this paper departs from previous studies. Some of these studies identified the causes of quality failures (Chong and Low 2005; Forcada, Macarulla, and Love 2012; Georgiou 2010; Forcada et al. 2011). Others paid attention to interpreting the significance of the different causes (Aljassmi and Han 2014; Forcada et al. 2014; Hughes and Thorpe 2014b). Furthermore, these studies focused on studying and managing the causes of quality failures without the consideration of interactions of actors in the regulatory environment. In building energy-saving renovation projects, the main actors include governments, construction companies, supervision companies, and design companies. And yet, actors and their interactions during the implementation of the renovation policy seem too often neglected in the discussion about why quality failures occur, and specifically within Chinese contexts. Also, there is continuing academic interest in researching how to improve quality in building energy renovations.

Several theories are used by the researchers when studying the causes of the failures in energy renovations. Liang et al. (2016) studied decision-making for energy-saving renovation projects for residential buildings using game theory.

The option pricing theory has been used to understand the economic factors of renovation technology options (Menassa 2011). Sim and Putuhena (2015a) studied that the causes affecting the construction quality are HEMMC models from humans, equipment, materials, methods, and other conditions. In a similar study, Kuei and Lu (Kuei and Lu 2013) applied quality management to deal with the causes of quality failures. From the political and governance perspective in China, some scholars have emphasised the overarching situation with Multi-level Governance theory (Westman, Broto, and Huang 2019; Lo and Broto 2019). Some focus on the strategic-relational approach (Hu et al. 2020), and transition management theories (He, Lu, and Qian 2019). However, these theories only weakly explain the relationships of the actors in the causes of quality failures and focus too much on managing quality at the project level.

Policy network theory has become an important framework applied to the energy-saving policy field in western countries to analyse the actors and their interactions (Bache 2000). Using the policy network theory, Gonzalez (2012) argued that actors' behaviour towards energy-saving policy goals is important. Likewise, in Europe, Czischke (2007) drew on network theory to examine the housing policy implementations in the context of a rapidly-changing policy environment. However, in China, the implementation of the energy-saving renovation using policy network theory is barely even considered. This research study has chosen to adopt the Policy Network theory (Van Bueren, Klijn, and Koppenjan 2003), as it highlights the actors and their interactions in the policy process.

High-quality construction often depends on policy performance, which closely relates to actors and their interactions. Consequently, there is a need for upgrading actors' behaviour and providing political support for controlling the causes of quality failures (Mosannenzadeh, Di Nucci, and Vettorato 2017). In the implementation processes of the renovation policies, complex positions and relationships among actors also triggered the external causes of quality failures. One way to explore the interaction among actors and their impact of the quality failure is from the analysis of actors and their relationship in the building process. **Therefore, the study, as reported in this paper, uses the policy network theory to explore how the actors and their interactions affect and cause quality failures during the renovation implementation process.**

The remainder of this paper is organized as follows. Section 5.2 summarizes the Chinese policies for building energy renovations and explains the main actors and their interdependency in different arenas during energy renovation processes. The next Section outlines key definitions and applications based on the policy network theory, explaining how this helps explore the causes of quality failures in building energy renovations. Section 5.4 introduces the methods adopted in this study. Section 5.5 then presents and analyses two cases of building energy-saving renovation projects. There is a discussion about the actor interdependencies in Section 5.6, where we argue the causes of quality failures by applying the policy network approach. Finally, in the final Section, the conclusions are presented, and some suggestions are offered for future high-quality renovation construction and successful policy implementation.

5.2 Energy-saving renovation projects of Residential Buildings in Northern China

According to the Standard of Thermal Design Code for Civil Building (GB50176-93), China has five climate regions: Severe Cold, Cold, Hot Summer and Cold Winter (HSCW), Hot Summer and Warm Winter (HSWW) and Mild. More specifically, severe cold and cold climate zones combined constitute the so-called northern heating zone. The heating zone covers roughly the territory north of the Chinese Huai River (Chen et al. 2013a). The following Section mainly reviews the current renovation situation, main actors, and the arenas in existing buildings in Northern China.

5.2.1 Energy-saving renovation projects of Residential Buildings in general

The building energy use of heating zones accounts for more than 40% of the country's total urban building energy consumption (Li and Shui 2015). The building energy consumption has increased by more than 10% annually (Xu, Chan, and Qian 2011). The majority of existing buildings in Northern China have a low energy performance, and this result poses a pressing challenge for the coming years (Li and Shui 2015). For existing residential buildings built before 2007, the energy efficiency rate is around 40%, which falls behind the current design standard (Zhou et al. 2018). Thus, there is still great energy saving potential by renovating the existing residential buildings.

In Northern China, most old buildings do not feature building envelopes that are equipped with thermal insulation measures, so the indoor temperature in winter is low, and the level of comfort is likewise relatively weak. Therefore, the residential renovation that has taken place in Northern China has not only played an essential role in building energy-saving but has also been a significant means by which to improve the living environment.

Building energy renovation can effectively promote energy mitigation in the existing building sectors (Liu et al. 2018). Since 2007, the Chinese government has implemented energy-saving renovation projects in existing buildings in 13 provinces of Northern China (Zhou, Levine, and Price 2010). However, quality failures in energy-saving renovation projects are increasingly regarded as barriers to hinder high-quality and energy efficient performance.

The building renovation programme is a new energy policy in China. Its performance needs to be researched to improve construction quality. The energy-saving renovation of the existing residential buildings is through diversified instruments covering administrative regulations and technical specifications issued by governments to improve the energy performance of residential existing buildings (Liu, Tan, and Li 2020). The administrative regulations establish the relationships of the main stakeholders in the energy-saving renovation projects. On the other hand, technical specifications are set at a minimum quality level for achieving high-quality construction (Qi et al. 2020).

In building energy-saving renovation projects in the Chinese context, the government-led model is well established. Due to the government-led mode, a number of top-down mandatory energy policies are introduced by the national and local governments (Qi et al. 2019). Various levels of the Chinese government (including the central government, the provincial government, municipal government, and district government) make a renovation plan and provide financial support. Furthermore, the renovation plan and financial support mechanisms in the building energy-saving renovation projects are challenging, because these two are novel for the general energy policies. The renovation plan and financial support mechanisms establish particular actors' roles and relationships. Thus, the different actors' roles and relationships make building energy-saving renovation projects significantly different from other construction projects. Meanwhile, the renovation plan and financial support related to building energy-saving renovation projects reflect the current focus and future directions (Yuan et al. 2017).

The implementation and attainment of renovation area targets are compulsory at a local level and are steered top-down by the central government. The strict renovation area targets and financial support mechanism thus far to push with force regarding implementation have resulted in a significant breakthrough and are causes of the quality failures. The authors aim to examine the outcomes by analysing two cases of energy-saving renovation projects based on Five-Year Plan periods and financial support mechanisms in Northern China. The two different renovation area targets and two types of funding systems are covered by these cases, and these are held to be representative of energy renovation policies in Northern China. The following section describes the renovation plan and financial support mechanism in energy-saving renovation projects of the existing residential buildings.

5.2.1.1 Renovation plan

The Chinese national government aims to reduce heating energy consumption by 40%-65% compared to the early 1980s. Compared with the energy-efficiency target, Chinese specific energy conservation plans stipulated that the floor areas are planned to be renovated in the 11th, 12th, and 13th Five-Year Plan periods.

During the “11th Five-Year Plan” period (2006-2010), the government started to renovate the existing building stock on a large-scale. The goals of the 11th FYP were the energy-saving renovation of 150 million m^2 (building floor area) in residential buildings of Northern China. Indeed, from 2006 to 2010, China completed a building energy renovation of 183 million m^2, 18% higher than the expected 150 million m^2 (Li and Shui 2015).

In January 2011, the Chinese central government issued guidelines to emphasize the targets of the renovation area in heating zones. During the 12th Five-Year Plan (2011-2015), the area target was that 400 million m^2 of building floor area in existing residential buildings must be renovated. Additionally, the 13 provinces must complete the implementation of building energy renovation of at least 35% of all existing residential buildings. Consequently, by the end of the 12th Five-Year Plan, the energy renovation for existing buildings has achieved all renovation targets, and 1.17 billion m^2 of building floor area was renovated.

According to the “13th Five-Year Plan” period (2016-2020), the central government plans to renovate 2.5 billion m^2 of building floor area.

5.2.1.2 Financial support

One huge significant challenge to the renovation projects is financing (Zhang and Wang 2013). In order to address this issue, an efficient and government-sponsored funding mechanism has been established. Two primary sources of financial incentives are considered in building energy renovations. For most building energy-saving renovation projects, financial support from the Chinese central government is combined with local funding from local governments. In some cases, the residents also need to provide small financial shares (about 5%-10% of the total investment per household) for renovating the old windows.

During the period of the 11th Five-Year Plan (2006-2010), 4.47 billion RMB (0.57 billion Euros) was allocated by the Ministry of Finance (MOF) of China to implement the building energy-saving renovation projects. In the period of the 12th Five-Year Plan (2011-2015), the Chinese central government further assisted in increasing financial support. The central government provided 55 RMB/M^2 (7.01 Euros/M^2) and 45 RMB/M^2 (5.74 Euros/M^2) of energy-saving renovation projects in the Severe Cold and Cold regions, respectively. In the 13th Five-Year Plan, the central government has fulfilled the investment and encouraged local governments to provide local financial support for the renovations.

The general renovation plan and financial support in building energy-saving renovation projects are summarized above. The specific renovation policies in each case of the two cases make a difference to the project processes and outcomes in Section 5.4.

5.2.2 Main actors

The actors involved in the implementation of energy-saving renovation projects in Northern China are the central and local levels of governments, construction companies, supervision companies, and design companies.

In the Chinese context, most building energy-saving renovation projects are led and funded by the central and local governments. However, the central government is often not directly involved in managing the building energy-saving renovation projects. Generally, the central government develops the top-down mandatory requirements for intensity targets for renovation areas of energy-saving renovation projects. In order to complete the intensity targets for renovation areas, provincial governments coordinate with municipal governments and district governments to prepare and organize the project from start to finish (from preparation to completion).

The following private companies include design companies, construction companies, and supervision companies to maximize income and minimize their cost because of their nature. During the building energy renovation processes, design companies provide the design service. Construction companies are responsible for construction activities, including making the construction plan, arranging construction resources, and managing the construction processes. Supervision companies are required to co-supervise the construction quality, cost, and time with local governments.

5.2.3 Actor interdependency in different arenas

The paper does not focus only on the responsibilities and roles of individual actors, but on how the actors are affected by the other actors for matching their respective goals and resources. Actors need the resources to attain their own goals, so they often need to cooperate with other actors. Therefore, interdependencies in a network originate from the fragmentation of resources among these actors (van Bortel 2009).

Different from general construction projects, renovating the existing residential buildings is a complicated process. The different levels of government and private companies are both involved. The projects start with energy-saving renovation area targets, which are set from top to down. The complexity and uncertainty of the context for building energy-saving renovation projects require the local governments' organization and preparation. Subsequently, private companies are involved in the renovation construction processes. This paper focuses on the interactions among actors in three arenas: (1) target setting; (2) project preparation; and (3) project construction (see Fig. 5.1). The resources controlled by the actors are connected with their positions within the different arenas.

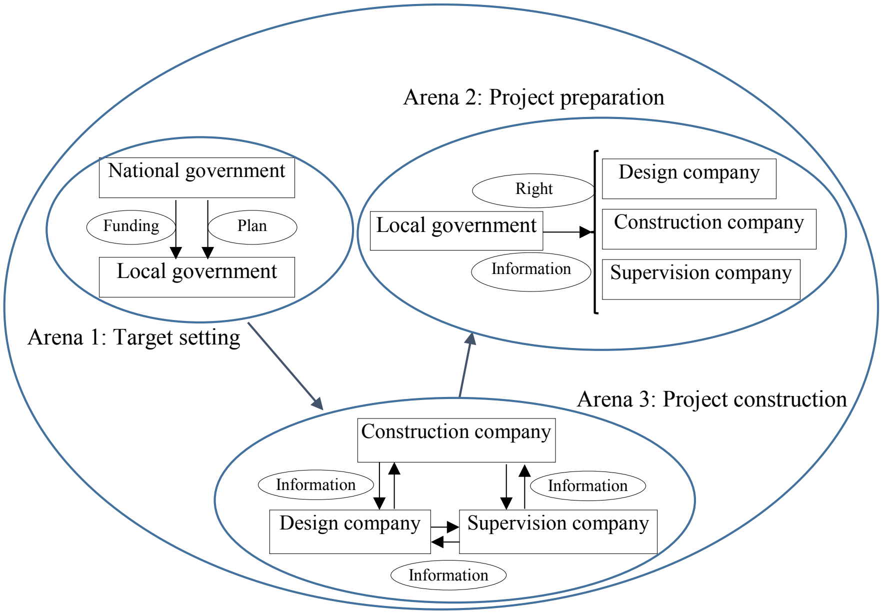

FIG. 5.1 The arenas of building energy-saving renovation projects

In the ***target setting arena***, local governments receive renovation area targets from national governments and make renovation plans from top to down. The governments fund the building energy-saving renovation projects in Northern China. Thus, the financial support mechanism is planned by national and local governments in this arena. In the ***project preparation arena***, for the choices available for the existing buildings, it is necessary to know the information about the building age, building floor area, and so on (Zhou, Zhou, and Liu 2017). According to the renovation area and distribution, the municipal governments select construction companies, supervision companies, and design companies by tendering and bidding, which, in turn, will be responsible for the tasks in building energy-saving renovation projects. The major activities in the ***project construction arena*** are to do a site survey and make construction plans to arrange construction resources, such as staff, materials, and machines (Ye et al. 2014). In this arena, the most complicated construction activities occur, which have a significant impact on quality.

5.3 Literature review

5.3.1 Policy network theory

Policy network theory (PNT) is a cluster of concepts, rather than one single theory, in which the making and implementation of the policy are considered as a process (de Jong et al. 2016; Lu, de Jong, and ten Heuvelhof 2018). These share a common emphasis on how the relationship between multiple actors jointly affect and depend on the behaviour of each other (van Bortel 2009). PNT explains why policy concepts often fail to be realized on the ground, or to put it more mildly, why good policy intentions are often diluted or twisted during implementation (Hudson et al. 2007; Klijn and Koppenjan 2000). One way to understand the policy network is through the distinction between the Anglo-Saxon school and the German-Dutch school (Marsh and Smith, 2000). The Anglo-Saxon school has embraced a stronger micro and meso-perspective, emphasizing the interactions among organizations, even individual actors, which is more suitable for our research purpose, and so has been adopted.

The policy network theory builds on the result of an interaction between multiple actors (see Fig. 5.2). So, it focuses on the interaction processes between interdependent actors and their conflicting interests Fawcett (Fawcett and Daugbjerg 2012; Sohn 2014). In this paper, some basic conceptual terms are explained, such as 'goals,' 'perceptions,' 'arenas,' 'resources,' 'interactions,' and 'conflicts.'

First, policy actors are assumed to have goals they aim to see realized as if in a game-like network setting, and this includes a perception of the problem situation at hand van (Van Bueren, Klijn, and Koppenjan 2003). These perceptions have generally evolved based on earlier learning experiences. Both the goals and strategies are derived from their perceptions. Goals are concrete (partial) translations of perceptions (Koppenjan, Koppenjan, and Klijn 2004). The actors' strategy refers to the tacit knowledge or routines of actors, which can impact decision-making and implementation (Koffijberg, de Bruijn, and Priemus 2012).

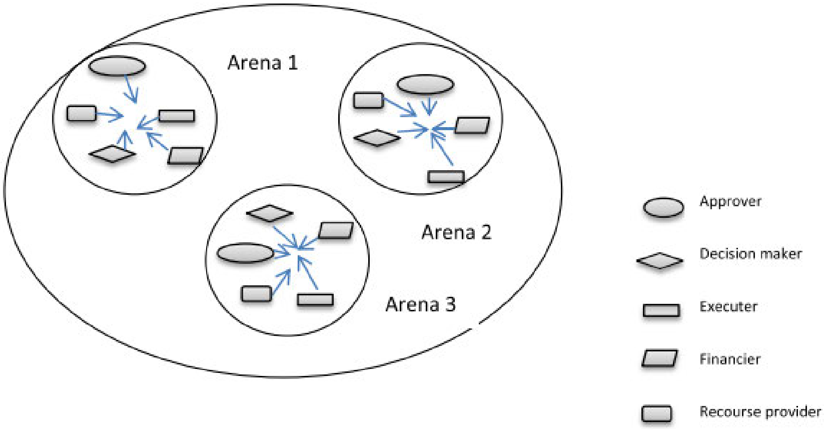

FIG. 5.2 The actors and their interactions according to policy network theory

Additionally, the actors are dependable on resources owned by other actors, and this dependence determines their position in the arena. This resource-dependence also forms power dependence among actors, which is different from the 'rational choice' approach to form the network by actors' bargaining and evaluation (Milhorance, Bursztyn, and Sabourin 2020). Furthermore, the actors have to operate resources strategically in order to create the dependencies in the interactions so that they can reach their objectives (Klijn and Koppenjan 2000). These resources include a range of political, legal, financial, organizational, physical, and informational instruments or tools that jointly flesh out policy concepts into visible concrete action (Milhorance *et al.*, 2020). Through swapping objectives/needs and resources/instruments, involved actors develop interactions through which they aim at impacting the behaviours of other actors, thus hoping to solve their own problem as well as those of society at large.

Besides the above attributes of actors (goals, perception, strategies, and resources), it is possible to understand further the interactions and conflicts among actors in the policy process. Interactions are played in one or more arenas, where specific groups of actors interact on an issue and make choices (Zheng, De Jong, and Koppenjan 2010). Arenas are places where specific groups of actors interact on an issue and make choices on specific aspects of the issue (Van Bueren, Klijn, and Koppenjan 2003). Networks have complex interactions because each of the actors is autonomous and has its own perception of problems, solutions, and strategies (McGuire and Agranoff 2011). This leads to substantial differences in perceptions, value conflicts, and disagreement about implementing policies (Klijn and Koppenjan 2015).

Conflicts in the arenas make the policy process and outcome dynamic and unpredictable. Conflicts in problem perception, goals, and adopted strategies are important explanations for the failure of concerted policy. Differences and disagreement in perceptions between actors may cause conflicts and block the interaction, which demands trust and shared motivation from actors to solve problems (Raynor and Whitzman 2020). The divergence in perceptions and goals of involved actors can be found often in energy-saving studies, as the pursuit of economic development is still the priority of governments in many countries (Mu, de Jong, and Koppenjan 2019). These problems are related to actors' values or ideology on certain issues, such as energy use, environment protection, and economic development.

These actors' activities take place in arenas not only guided by conflicting perceptions and goals but also conflicting strategies (Klijn and Koppenjan, 2015). As the government is still the main actor in the energy-saving field, institutional factors can also strengthen the conflicting strategies, such as governance styles. Although there are differences of emphases in governance modes in energy-saving, three classical types emerge, namely hierarchical, market, and network governance modes (Lo 2014b). A common cause of governance-style conflicts is that the government is still dominated by hierarchical governance, whereas private actors press increasingly for informal forms of governance.

Policy network theory deals with the formal and informal relationship between public and private actors, which is different from market and hierarchy governments (Sohn and Giffinger, 2014). In energy-saving studies, these relationships between public and private actors are often neglected, such as the poor relationship in a public-private partnership is always resulted from misunderstanding and conflicting interests (Tang, Shen, and Cheng 2010). Additionally, a reinvention of public participation in energy-saving projects is emphasised by scholars to mediate conflicts with residents (van Aalderen and Horlings 2020). However, other studies also show that bringing additional actors into the arena can increase conflicting relationships and detract from an agreed solution (Scott and Thomas 2017).
In the debate of policy network theory, conflict does not necessarily undermine governance, where it is 'divisible' or amenable to compromise perhaps through strong leadership, compensating losers, and removing difficult actors or introducing new ones (Davies 2005).

5.3.2 Policy network theory in the construction industry

Construction actors (e.g., supervisors, engineers, project managers, and designers) bear the overall responsibility to complete a high-quality construction, and their behaviours have to meet the policies and regulations (Meijer and Visscher 2016a). In policy network theory, these actors' interactions are essential concepts and elements. According to the previous studies, numerous causes of quality failures related to the actors' network in the energy renovation program. Jingmond and Ågren (2015b) highlighted that the actors' interactions need further attention to improve quality in construction projects. Also, Enshassi et al. (2017) considered that actors of construction projects are like a game network, and the actors' objectives may conflict with others, which directly causes dishonesty and competitive pressure. According to Kakitahi et al.'s study (2015), weaknesses in actors' network negatively impact on high-quality of constructions. On a similar line, Aiyetan (2013) and Schultz et al. (2015) have shown that the types of actors' structures may give high pressure on construction schedule and budget.

Moreover, working under high-cost and high-time pressure are the main causes of quality failures at a policy level. Thus, actors' network and interactions need to be analysed, and improve energy-saving renovation projects. Meanwhile, the policy network theory is an efficient tool to research the actors' interactions. In this paper, the policy network theory is used to analyse how actors and their interactions affect and cause quality failures during the renovation process.

5.3.3 Application of policy network theory in China

More recently, the adoption of policy network theory in energy-saving policy can be traced in China (Li et al. 2018). Feng (2016) explored institutional relationships in the energy-saving policies and observed that actors' networks gradually evolved into more complex ones, from a policy network perspective. Also, based on the policy network, Song (2012b) identified some issues in Chinese building policy, such as the lack of communication and the wrong understanding of actors' roles. She also revealed that these issues might be the root causes of quality failures in building energy renovations. In Song's research (2012a), the policy network theory breaks through the traditional analysis model and is conducive to explain the policies of building energy renovation process.

Tian and Wei (2014) studied the applicability of the policy network theory in the Chinese construction situation from three perspectives. These three perspectives are policy network structure, policy network interaction, and policy implementations. As far as the policy implementation is concerned, Tan and Lou (2012) analysed the relationships between owners and occupiers in housing rental policies at the national and local government levels. Liu and Yang (2010) researched the real-estate market using the policy network theory. The main actors, including national and local government, developers, and residents, formed a "government-market-society" policy network. In this policy network, it is necessary to clarify all actors' roles and interactions to promote the cooperative governance model. In summary, policy network theory can be applied to analyse the relationships among actors in the Chinese context. It is conducive to finding and studying the barriers that occur during policy implementation.

Jia (2020) reviewed the previous studies upon the policy network theory and noted that the Chinese government is the main resource provider. Thus, the effectiveness of the policy network could be stimulated by supporting the authority and legitimacy of the Chinese government. From the policy network perspectives, Liu (2013) commented, that for policy-makers in China, the preferences and actual demands of all relevant actors are key factors to be considered. Meanwhile, a productive communication platform of all parties would avoid the conflicts in the actors' interactions.

5.4 Method

5.4.1 Case study

This Section presents the reasons for the case study method and the two cases selected. The cases both reside in the Inner Mongolia Autonomous Region, which is a typical representative of a heating area for Northern China. Although regional differences of building energy renovations within Northern China exist (e.g., differences in organizational culture and technology routines), some generic features are similar across all heating areas in Northern China. These features include a collaborative model, funding support systems, and the hierarchical nature of administrative systems. Therefore, it is assumed that the findings in this paper are largely representative for the external factors likely to cause quality failures at the local level in China.

Building energy renovation is a relatively new policy issue in China. The investors are the governments rather than other actors. Meanwhile, the actors' interactions, the renovation plans, and financial support mechanisms in energy-saving renovation projects in the existing residential buildings are different from those in the other construction projects. Thus, building energy renovation construction is different from general construction. As such, it would not be suitable to use population-wide questionnaire surveys. Instead, a case-study-based approach is the preferred choice. Case-based data collection and case study analysis are preferred methods when 'how' and 'why' questions are considered (Yang, Zou, and Wang 2016).

This paper investigates the rationale and method of implementation of building energy-saving renovation projects in the 11th, 12th, and 13th Five-Year Plan periods. The survey aims to obtain an in-depth understanding of the actors' interactions outlined in Section 4. Therefore, the case selection was not random but based on selective sampling. **The authors chose two cases as the case study subject for the following reasons:**

First, the cases are supported by the national and local governments to be typical building energy-saving renovation projects, which ensure the cases are representative of not only the renovation regulations but also other energy-saving specifications.

Second, these two cases are selected to be representative of the policy implementation of the residential building renovations in different periods. In more detail, in November 2015, the end of the 12th Five-Year Plan, Case 1 was completed. During this period, governments issued specific renovation area targets to accelerate the implementation progress of the building energy-saving renovation projects. Case 2 was developed in 2016, during the 13th Five-Year Plan period. Thus, Case 2 provided an overview of the series of renovation area targets issued by central and local governments in the 13th Five-Year Plan periods.

Third, the different types of financial support mechanisms have different fund source characteristics and influences on construction quality. Considering the governments' investment capacity, the two cases cover two main financing mechanisms for residential building energy renovations in Northern China. In Case 1, the financing mechanism is a multi-source, including the central government, provincial government, and municipal governments' funds. In 2015, the financial contributions of the central, provincial, and municipal governments were 21.60 million RMB (2.75 million Euros), 21.60 million RMB (2.75 million Euros), 102.72 million RMB (13.10 million Euros), respectively. On the other hand, the financial source in Case 2 is from the residents and the local governments, only including the provincial government and municipal government. In 2016, the Inner Mongolia government invested 68.13 million RMB (8.69 million Euros) to renovate existing buildings in Hohhot city. In case 2, residents also contributed 5%-10% of the total investment per household. Table 5.1 presents the basic information on the two cases.

TABLE 5.1 Basic information on the two cases

No.	Location	Renovation period	Renovation area targets at the national level	Financial supporters
Case 1	Saihan district	12^{th} Five-Year Plan	400 million m2	National and local governments
Case 2	Xincheng district	13^{th} Five-Year Plan	2.5 billion m2	Local government and residents

5.4.2 Introduction to case projects

5.4.2.1 Case 1

Case 1 is a building energy renovation project located in Hohhot, which is a typical northern city in China. It concerns a five-story residential building renovation project located in Saihan District, on the south-east coast of Hohhot. The project was chosen to be representative of the building energy renovation project in Northern China due to the climate zone where it is located, its renovation technology measure, and energy performance. The total building floor area of energy renovation is 9925 m^2 in case 1. It was built in the 1990s before the first Chinese thermal regulations came into effect. Typically, the building has a brick concrete structure. The building envelope is not insulated, as was common practice at that time. The windows are double glazed with steel frames, and the floors are lightweight slabs. The renovation project was carried out between September and December 2015 in the 12^{th} Five-Year Plan (2011-2015).

The renovation included various technical measures to realise energy-saving. The goal was to cut the energy use almost in half (47.0%). The different energy-saving technology measures were to windows, roofs, and external walls. Windows are critical components because they control solar gains, heat losses, and thermal bridges. The PVC frames and double-glazing were used to reduce heat transfer. The floor and external walls have a significant impact on the energy performance of a building. In detail, as shown in Table 5.2, the insulation thicknesses were considered about 50 mm expanded polystyrene insulation (EPS) in floor renovation and external wall renovation. In case 1, the renovation indicators in terms of the U-values of the different envelope elements are summarized in Table 5.2.

TABLE 5.2 Renovation technology and thermal performance in Case 1

Item	Material	U-value (W/m²·K)	
		Before renovation	After renovation
Windows replacement	PVC frames and double-glazing	3.26	2.60
Roof thermal insulation	50mm EPS	1.10	0.60
External wall thermal insulation	50mm EPS	1.52	0.50

5.4.2.2 Case 2

The total building floor area of case 2 covers 12,756 m^2. The contract value is 1.01 million RMB (0.13 million Euros). This building energy renovation project includes four existing buildings built in the 1990s in Xincheng District. The renovation period of case 2 was 180 days from May 2016 to December 2016 in the 13th Five-Year Plan (2016-2020).

Table 5.3 summarizes the renovation scenarios considered in case 2 to improve the building envelope. For the window frames, polyvinylchloride (PVC) was chosen as material due to its cost-effectiveness, always with double-glazing. For the roof, the renovation measure consisted of placing 50 mm EPS boards on the roof slab. For the external wall, the renovation measures consisted of the application of 50 mm EPS. In this case, heating energy consumption was reduced by 43% relative to consumption before energy-saving renovations.

According to the other studies (Ferreira et al. 2016), the most important indicator for building energy-saving renovation projects are U-values (the details in case 2 see Table 5.3).

TABLE 5.3 Renovation technology and thermal performance in Case 2

Item	Material	U-value (W/m²·K)	
		Before renovation	After renovation
Windows replacement	PVC frames and double-glazing	3.26	2.60
Roof thermal insulation	50mm EPS	1.10	0.60
External wall thermal insulation	50mm EPS	1.52	0.48

5.4.3 Data collection

The fieldwork was carried out in Hohhot. Geographically, Hohhot is the provincial capital of Inner Mongolia, which is located in the northwest of the territory where winters are long and cold. Consequently, building heating is a significant energy demand of this city, and Hohhot is one of the pilot cities for energy-saving renovations of existing residential buildings. Urban areas in Hohhot consist of five districts. The two cases selected for this study are located in Saihan District and Xincheng District, respectively (see Table 5.1), which are the pilot districts for energy-saving renovation projects in Hohhot. They can be seen as examples of energy saving renovation of existing residential buildings. As for these two cases, the goals have been to 1) Describe the origin, official goals, and current situation of the project; 2) Investigate the actors, their objectives, and resources; 3) Build the relations of actors' interdependencies based on the resources they owned and their roles in arenas; 4) Understand in which arenas prevent further progress because required exchanges of resources have not occurred; and 5) Test how actors' interdependencies affected each other in the arenas and what effect this had on the implementation of the building energy-saving renovation projects.

The interviews were conducted in each of the two cases with representatives of involved actors. In total, 14 persons have been interviewed (see Table 5.4), six of whom have been interviewed more than once. The Chinese context of building energy-saving renovation projects, such as renovation area targets and financial plans at a national level, the involved actors, their objectives, and resources, are firstly understood through the official websites and relevant literature (in Section 5.3) in order to complement the interviews. In the following Section, descriptions of each of the cases are summarized.

TABLE 5.4 The profile of experts and interview method

Case	No.	Position	Organization
Case 1	1	Officer in Inner Mongolia autonomous region building energy efficiency evaluation Institution	Provincial government
	2	Officer in Hohhot Housing Security and Housing Authority	Municipal government
	3	Officer in Saihan District Construction Quality Supervision Institution	District government
	4	Project manager in Construction Engineering company of Inner Mongolia	Construction company
	5	Chief supervisor in Construction Supervision and Consulting company of Inner Mongolia	Supervision company
	6	Designer in Construction Design company of Inner Mongolia	Design company
Case 2	7	Officer in Inner Mongolia Autonomous Region construction of science and technology promotion and Development Centre	Provincial government
	8	Officer in Hohhot Housing Security and Housing Authority	Municipal government
	9	Officer in Hohhot Housing Security and Housing Authority	Municipal government
	10	Officer in Xincheng District community office	District government
	11	Chief supervisor in supervision company of Inner Mongolia	Supervision company
	12	Senior designer in Construction design company of Inner Mongolia	Design company
	13	Project manager in construction company of Inner Mongolia	Construction companies
	14	Resident living in the renovated building of case 2	/

5.5 Case analysis and results

5.5.1 Case 1

5.5.1.1 Actors and their roles

The local governments (including Inner Mongolia provincial government, Hohhot municipal government, and Saihan district government) played the leading role in Case 1. Encouraged by the goals set by the national government, the provincial government announced the goal of finishing renovations for about 50 million m^2 of

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building floor area during the 12^{th} FYP. In reality, the target for renovation work, which was to complete about 71.4 million m^2 of the building floor area by 2015, was significantly more ambitious than the central government's area targets.

- The national government, the Inner Mongolia provincial government, and the Hohhot municipal government provided financial contributions. Homeowners were not required to contribute.
- The Saihan district government supported case 1 (located in Saihan district) to be renovated and reported it to Hohhot municipal government to get approval for renovations.
- The Hohhot municipal government contracted the design company, the construction company, and the supervision company to provide design, construction, and supervision service.
- The design companies were responsible for providing the tasks of the site survey and renovation service.
- Construction companies were responsible for planning and dealing with the construction activities under the supervision of the supervision companies, Saihan district government, and Hohhot municipal government.
- The supervision companies were responsible for representing the local governments to supervise the renovation construction activities professionally.

5.5.1.2 Conflicts in arenas

In this paper, examples of '***arenas***' are target setting, project preparation, and project construction, where the main actors interact with each other regarding specific policies. In the target setting arena, the central government, Inner Mongolia provincial government, Hohhot municipal government, and Saihan district government were the primary implementers of energy renovation policies. To fulfil the central government's energy-saving renovation area targets, local governments strengthened the enforcement of central energy-saving directives. Moreover, provincial and municipal governments devised more concrete energy-saving policies for adapting to the characteristics of the specific provinces. For supporting the ambitious renovation area targets from the local governments, the funding system was crucial for the implementation of the building energy renovations.

These conflicts will affect the construction quality indirectly from the actors' interaction perspective. According to on-site investigations, some quality failures were found in case 1, such as: 'Detachment between the different EPS boards,' 'Misalignment of the waterproof roof layer,' 'Missing rivets.' These quality failures, such as missing rivets, may cause serious safety issues and poor energy performances. Missing rivets in practice leads to the potential hazards of thermal insulation materials falling off. Likewise, water leakage is possible to occur due to a non-specified waterproof layer.

1 Target setting

In the 12th Five-Year Plan (2011-2015), the Ministry of Finance (MOF) arranged funds to support the building energy-saving renovation projects in Northern China at a national level. The capital subsidy was granted according to climate zones: 55 RMB/m^2 (7.0 Euros/m^2) for Severe Cold Zone (where case 1 is located). In case 1, the Inner Mongolia provincial government and the Hohhot municipal government were also the financier of the building energy-saving renovation projects in the 12th Five-Year Plan. The energy efficiency rate is to achieve above 47% in this case.

Based on the interviews, the conflict in the target setting arena was that limited financial support from all investors causes that local governments and private companies have to work under high-cost pressure in building energy-saving renovation projects (interviewees 1 and 4). Meanwhile, more attention has been paid to renovation costs rather than the renovation quality. The following quote from interviewee 1 depicts the conflicts in the target setting:

“The renovation tasks need to be completed under intense funding pressure from the upper levels of governments, so we pay more attention on renovation costs.”

2 Project preparation

During the project preparation phase, construction companies were required to provide funds by themselves first, and the local governments would return the funding later (interviewee 4). The conflict was that the local governments promised to refund the construction companies after the completion of the renovation work, but had not actually done so until 2016 (interviewee 6). This governments’ behaviour has caused dissatisfaction among private companies. As interviewee 6 stated:

“The central and local financial supports were decisive factors that affect the implementation of building energy-saving renovation projects seriously. Furthermore, cost pressure in building energy-saving renovation projects was higher than other construction projects. However, an efficient financial support system has not been established yet. Hence, the speed of refunding to private companies from the governments is too slow.”

Meanwhile, in the project preparation phase, interviewees 4 and 5 pointed to another conflict in case 1. Due to the climatological conditions in case 1, the time of project preparation and construction in building energy-saving renovation projects should be shortened. However, the report and approval process has taken up too much time. The following quote from interviewee 4 explained this situation:

"According to the temperature characteristics of the Severe Cold Zone (where case 1 was located), the low temperature has a negative effect on the construction quality after the end of October. Therefore, the construction activities of renovation projects should be finished before November. The project approval took a long time, and we started the renovation works at the end of September 2015. That led to substantial pressure on the construction time."

3 Project construction

Interviewees 2 and 3 pointed to the conflicts in the project construction arena. The conflict included that local governments (municipal and district governments) had limitations to participate. Their roles were minimized to supervise private companies during project construction. The following quote is from interviewee 2:

"In the energy-saving renovation projects, as an investor, the local governments have transferred too much management rights to the supervision company, and they even do not participate in process management during project construction."

Interviewees 5 and 6 mentioned another conflict in the project construction arena. According to them, the construction companies involved procured and used 'unqualified' (or non-specified) construction material, like expanded polystyrene insulation (EPS) boards. The following quote from interviewee 5 explained the unqualified construction materials used:

"Fire resistance is an essential technical performance of expanded polystyrene insulation (EPS) boards, a type of thermal insulation materials used in roof and external wall renovation. In this case, we found out that the construction company procured and used the non-specified fire resistance of EPS boards to maximize the profit."

In three arenas of building energy-saving renovation projects, the conflicts are concluded (see Table 5.5).

TABLE 5.5 Conflicts in area target setting, project preparation, and project construction in case 1

Arenas in Case 1	Conflicts	Sources
Area target setting	High cost pressures	Interviewees 1 and 4
Project preparation	Low motivation of private companies	Interviewees 4 and 6
	Too long time used by approval processes	Interviewees 4 and 5
Project construction	Little participation of the local governments	Interviewees 2 and 3
	Unqualified material used by construction companies	Interviewees 5 and 6

5.5.2 Case 2

5.5.2.1 Actors and their roles

Below a sketch of the actors involved and their roles.

- The national government is responsible for setting mandatory renovation area targets for reducing the existing building energy consumption: 2.5 billion m^2 of building floor area in Northern China in the 13^{th} FYP.
- The Inner Mongolia provincial government supported the building energy-saving renovation projects to set renovation area targets at a provincial level.
- The residents need to pay for the new windows in energy building renovation projects.
- The Hohhot municipal government was responsible for the execution of the energy renovation project. The Hohhot municipal government found contractors to carry out the renovation after determining the buildings that would be renovated.
- The Xincheng district government represented the district where building energy-saving renovation projects were situated and was responsible for selecting buildings to undergo renovation.
- The Xincheng district government was responsible for judging the necessity of the existing buildings renovated and reported the list to municipal governments.
- Design companies provided a site survey and design documents to construction companies.
- Construction companies provided construction service and directed construction processes with preparing workers, materials, machines, and other necessities for construction.
- Supervision companies co-supervised construction quality with Hohhot municipal and Xincheng district government.

5.5.2.2 Conflicts in arenas

The conflicts have caused negative effects on energy performance. In case 2, the energy-saving rate was not achieved in the first on-site evaluation, and it improved to 43% after rework. Although it met the energy-saving requirements, this energy-saving rate is still low for the current energy-saving standard. Furthermore, because of conflicts among residents, residents' satisfaction is affected negatively.

1 Target setting

Compared with case 1, case 2 was renovated during a different period, so the renovation area targets in terms of floor area that should be renovated were different. In the target setting arena, in order to achieve the renovation area targets during the 13th Five-Year Plan, the provincial government renovated about 8.49 million m^2 of building floor area in the existing residential buildings within Inner Mongolia in 2016. Meanwhile, in 2016, the Hohhot municipal government (renovated 1.45 million m^2 of building floor area in Hohhot) and Xincheng district government (renovated 0.33 million m^2 of building floor area in Xincheng district) over-fulfilled the energy renovation area targets.

However, the local governments felt high-pressure. They transferred this high-pressure from top to down and other actors. Therefore, the high demand for renovation speeds and performance was still the main conflict between local government and private companies in the target setting arena. Additionally, the renovation project also required residents to pay for the new windows. Some uncooperative residents became an obstacle to the project (interviewees 10, 13, and 14). The following quote from interviewee 14 depicts the conflicts:

"I do not want to pay for the new windows, because this payment means so much money for me. Moreover, the old windows are still available. I, therefore, refuse to replace them."

2 Project preparation

In the arenas of project preparation, according to the interviewees, two conflicts emerged. First, the Xincheng district government selected the buildings to undergo renovation and submitted the list of selected buildings to the Hohhot municipal government for approval. The Hohhot government within the municipality determined which buildings would be renovated. The local governments (Hohhot municipal and Xincheng district governments) tried to simplify this preparation process as much as possible. A building renovation management office, operating under the Hohhot municipal government, was established to simplify and streamline the approval processes through leading and organizing the preparations of the building renovation projects. However, the conflict was that it still took too much time to select buildings, which resulted in the limited time for the subsequent bidding and tendering (interviewees 8 and 12).

Second, after making decisions about the list of buildings that would be renovated, Hohhot municipal government found the contractors through the tendering and bidding. Due to a low financial benefit of renovation projects, a number of private companies lacked the motivation to make a bid (interviewees 12 and 13). Therefore, the second conflict was that frustrations came up because private companies were reluctant to participate in the tender process. However, still, a few private companies decided to participate in the renovation projects. The following quote is a typical example that captures this frustration from interviewee 13:

"Actually, we do not prefer to choose to participate in the renovation projects, because the profit is very low."

3 Project construction

As for the project construction arena, the conflicts were similar to the one in case 1. The local governments had limited participation during the preparation processes (interviewees 9 and 11). Moreover, supervision companies did not check the selection and usage of construction materials strictly (interviewee 9). According to interviewee 9, the limited implementation of the key work checklists caused poor checking produces of supervisors in the on-site environment. Based on the interviewees, several conflicts were found in Case 2 (see Table 5.6).

TABLE 5.6 Conflicts in target setting, project preparation, and project construction in case 2

Arenas in Case 2	Conflicts	Sources
Target setting	Too much emphasis on the magnitude of the renovation targets	Interviewee 7
	Limited financial support from the government	interviewees 10 and 13
	Residents' non-cooperation of financial shares	interviewees 10 and 13
Project preparation	Complicated approval processes	Interviewees 8 and 12
	Low motivation of private companies to the participant	interviewees 12 and 13
Project construction	Limited involvement of the local governments in supervision tasks	Interviewees 9 and 11
	Inadequate checking procedures by supervisors	Interviewee 9

5.5.3 Comparative analysis of actor interdependency

The differences between the two cases are the actor interdependence maps during the target setting (see Fig.5.3). In the target setting arena, the main actors are the national government and local governments (provincial government, municipal government, and district government). The relationships of the main actors in this arena are drawn by arrows. In case 1, the central government, along with provincial and municipal governments, is one of the main investors for the renovation projects. The funding is transferred from the central government to the municipal government, which is different from case 2. Fig.5.3 shows the actor interdependency map of case 1 in the target setting arena. Unlike case 1, the residents also need to pay for the new windows, accounting for 5%-10% of the total investment per household in case 2. In Fig.5.3, funds from the residents flow to the renovation projects. Different actors' relationships in the funding structures have their obstacles to the renovation projects and even some quality failures.

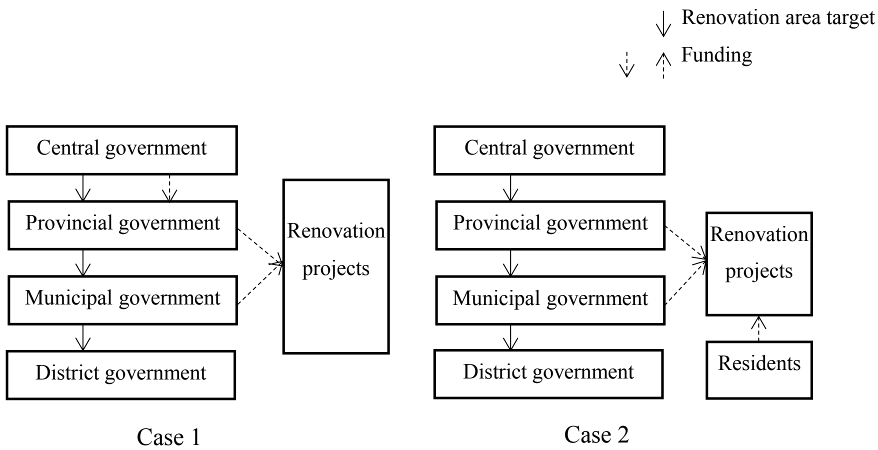

FIG. 5.3 Actor interdependency map in target setting arena

In the project preparation and construction arena, the actor interdependency maps are similar between case 1 and case 2. For the project preparation period (shown in Fig.5.4), the main actors include local governments (provincial, municipal, and district governments) and private companies (design companies, supervision companies, and construction companies). In this arena, the resources, including information and legal approval, are exchanged between different actors. The building information is transferred from bottom to up, while the legal approval is in a top-down manner.

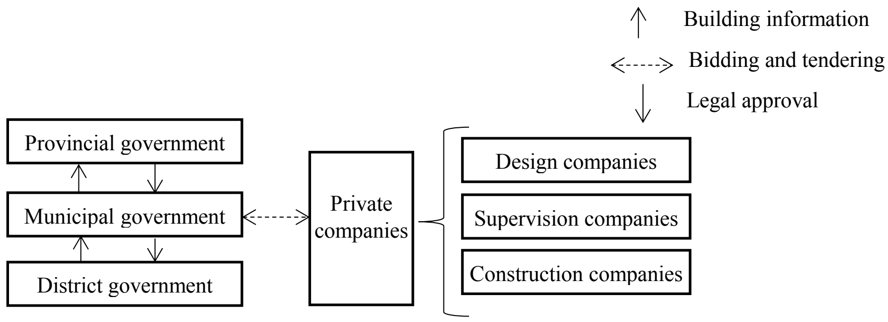

FIG. 5.4 Actor interdependency map in the project preparation arena

In the project construction arena (shown in Fig.5.5), the main actors include municipal governments, district governments, supervision companies, design companies, as well as construction companies. In Fig.5.5, construction information is reported to municipal and district governments by supervision companies. Meanwhile, the supervision company also obtained the construction information throughout site supervision and documents from both the construction company and the design company.

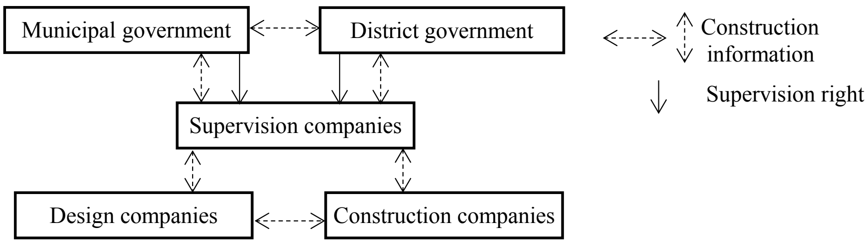

FIG. 5.5 Actor interdependency map in the project construction arena

In the two cases, government-led is the standard mode. After determining which buildings will be renovated, the municipal government finds the private companies to construct and supervise the renovation. Construction and supervision rights are transferred from the government to the construction companies and supervision companies through the bidding and tendering contract. Conversely, municipal and district governments only play the role of manager based on the contract to ensure the realization of project performance and public interest.

5.6 Discussion

Based on the interviews in two renovation cases, we relate the actor interdependencies to understand their conflicts better. The quality failures can be explained by conflicts among the actors in different arenas. In the following Section, conflicts and their explorations in the target setting, project preparation, and project construction are discussed through actor interdependencies in the two cases.

5.6.1 Inefficient cooperation of public-private partnerships

In the Chinese context, the renovation programme is conducted through government subsidies and government investments, which is the government-led mode. In case 1, the central government is one of the significant financial contributors. Local governments provide additional subsidies. The original objective of the government's investment is to reduce the pressure on private companies to promote the implementation of building energy-saving renovation projects. However, the central government's financial allocation has resulted in slow progress and inefficient cooperation to refund the private companies, according to case 1.

From the conflicts in both cases, too long a time used by the renovation approval processes could cause various problems in renovation contracts signed by the public authorities and private companies. As shown in Fig. 5.3, the complicated approval structure required that the district government reports the existing buildings, which are planned to renovate, to the municipal government, and then this list will be reported to the provincial government to make decisions. In this approval structure, it took too much time to choose renovated buildings because of the complicated report flow (interviewee 8). Then, the municipal government needed to contract tasks with private companies. This complicated approval processes needed too much time. In order to complete the renovation project on time, the time of bidding and tendering had to be shortened. Therefore, it was troublesome to check the details of the renovation contracts for private companies. Due to the poor public-private relationships, there is the ambiguity of items and unclear definitions from the contract documentation for renovation working content.

The result obtained from the case study is overall comparable to those of traditional studies (Liu, Liu, et al. 2020; Liu, Li, et al. 2020), which provide positive evidence on the government's involvement. The public-private collaboration shown in the previous studies is significant in energy projects (Dempsey, Burton, and Duncan 2016; Foo et al. 2015; Lu, Sun, and de Jong 2020).

Although public-private partnerships play an important role in providing funding for projects, the complex procedure can also demotivate private actors' involvement to some extent. In many countries, the efforts to simplify the cooperative procedures have had a prominent place on the national political agenda (Meijer and Visscher 2017a).

5.6.2 Unsatisfactory impacts of the residents' and local government's involvement

Case 2 of building energy renovation belongs to local governments' and residents' investment projects. Yet, in building energy-saving renovation projects, the residents who live in the old apartments are predominately from a low socioeconomic background. Even if residents pay a small share of the new windows, it is still a significant sum for the poor. This results in a situation that the homeowners will choose to opt-out. Lo (2015) also stated that the financial support in the energy-saving renovation projects is insufficient to provide owners to renovate their home.

Based on the previous studies on building energy renovations (Liu et al. 2015), the residents' participants can facilitate the implementation of energy-saving renovation projects to some extent. However, in the Chinese context, the residents' financial involvement will have a negative impact on the implementation of building energy-saving renovation projects. That is because the living condition of most residents is still low in this area, and their concern for the basic living condition is much stronger than environmental protection. Hence, if the building energy renovations cannot significantly improve the living comfort, the extra cost will not be paid by the residents.

In terms of the implementation plan, local governments have to realise the renovation area targets under intense pressure. Fig. 5.3 presents that renovation area targets are transferred from higher-level government to lower-level government. Indeed, the renovating magnitude is regarded as the top-down mandatory renovation area targets, which are set according to the national energy policies. These top-down renovation area targets of the renovation projects are then allocated to lower levels of governments. In this way, the goals of renovating building areas are announced in the Five-Year-Plan by the provincial governments. Accordingly, the municipal government established the objective of renovating building areas in specific periods and released the implementation plan. Moreover, to have a good performance, the provincial and municipal governments' renovation area targets are significantly more ambitious than the goals of the central government. This results in the municipal governments' renovation work and tasks being executed under the intense construction time and cost pressures.

Consequently, municipal governments lack interest in achieving energy saving and climate change. In turn, they pay more attention to the construction schedule. In particular, based on Lo's study (2014b), the local governments have changed the energy-saving objectives and diverted attention from the environmental performance.

5.6.3 Conflicting perceptions among actors

The perceptions of private companies and public parties are inconsistent with the mission of renovating the existing residential buildings. In building energy renovation, governments need to realize renovation area targets and social satisfaction rather than high-quality performance (Shilei and Yong 2009). In these two cases, governments lack the motivation to focus on construction quality, and they even ignore process quality management.

The significant interests of private companies are about maximizing companies' profit. Multi-layer energy-renovation plans make that the amount of building energy renovation at local levels was larger than planned at the high level. Thus, the actual cost of the building energy-saving renovation projects was over the original budget. Governments try to reduce costs, so the cost pressure in building energy-saving renovation projects was higher than other construction projects. This is why the little benefit is obtained by private companies in energy-saving renovation projects.

Consequently, the private companies lack the motivation to improve construction quality. Furthermore, construction companies use inferior materials and even cut corners to maximize their profit. Janipha and Ismail (2013) illustrate that construction companies were likely to give the lowest specification of certain construction materials and products in order to obtain their profit.

Similarly, the conflicting perceptions have caused the failures to check construction procedures. In the building energy-saving renovation projects, supervision rights are delegated to the supervision company, so local governments' roles are minimized (see Fig. 5.5). In other words, the structure between the local government and the supervision company is a principal-agent relationship, where the local government plays the principal, and the supervision company is the agent. The features of this structure also do not differ much from previous studies (Amecke et al. 2013). It leads to a moral hazard of the supervision companies based on the information asymmetry in the principal-agent relationship. In detail, as shown by Akerlof (1970) and Chi (1994), information asymmetry will give rise to the problem of moral hazard possibly causing resource exchanges in the market to break down. In line with previous findings (Yuan et al. 2017), the market mechanism promoting building energy-saving renovation projects is still out of place.

For building energy-saving renovation projects in China's context, the information asymmetry between the local government and the supervision companies is much more probable to cause moral hazard than other construction projects. Consequently, supervision companies, in short, have the chance to skip some supervision steps or 'stand in line' with the construction companies they are supposed to supervise. This is consistent with previous studies with the argument that the conflicting perceptions of private companies and public parties are the primary cause of the quality failures in construction projects (Wu et al. 2012).

5.7 Conclusions

China's achievement in improving building energy efficiency, in terms of significant progress, can largely be attributed to the government's planning and policies of energy strategies, together with strong and consistent support from central and local governments. Indeed, building energy renovation plays an important role in the overall framework of energy conservation policies and programmes. However, the implementation of these policies in China has presented a huge challenge in renovating the existing buildings in order to control energy use, because, in practice, many quality failures were found to be repeated in the building energy-saving renovation projects. Thus, it is necessary to research the causes of these particular quality failures, in order to facilitate the successful accomplishment of the building energy-saving renovation projects in future.

In most of the earlier research studies, the causes of quality failures have been attributed to factors such as: worker's default; the changes in the design documents; poor/incompetent supervision; and incomplete drawings. However, the authors argue here that the implementation processes of the renovation programmes have not been studied sufficiently, resulting in a limited understanding of how the key actors and their interaction, in reality, affects and causes quality failures during the renovation policy implementation process.

The novelty of this research lies in the fact that a policy network theory is applied to analyse the causes of quality failures in building energy-saving renovation projects. This enables useful suggestions to be provided based on the influences of the actors and their interaction. Two cases serve as appropriate for understanding the relationships of the actors during renovation processes. In conclusion, the analysis here shows that although the local government had made significant contributions to the energy-saving renovation projects, the public-private collaboration is a ***vital*** part of construction preparation and construction processes. Yet, in terms of the financial collaboration of public and private parties, a better solution is likely to emerge if specific management offices are established to press for government-side funding flows, in turn, improving the speed of the refund from the government.

In addition, this research finds that there are a number of outstanding challenges in the way forward in the promotion of building energy renovations. These challenges may cause some quality failures from the external environment, including very tight renovation area time-schedule targets, insufficient local organization structures, limited financial support systems, and other external causes. They are created due to the actors' relationships and have a commanding influence in changing the behaviour of the main stakeholders, resulting in quality failures during renovation processes. Therefore, there is a need for upgrading the actors' interactions of building energy renovations to mitigate and solve the problems from the external causes. Moreover, a broader sustainability scope is to be developed in the building energy renovation policies and regulations.

In sum, this research attempts to study the cause of quality failures in building sectors, and we focus more on the perspective of the conflicts between actors regarding perceptions, goals, and strategies. Only when actors are able to bring their perceptions together, and so formulate common goals and interests, will policy games lead to satisfactory outcomes. However, the cases in this research study have not shown this trend. We accept that one way out of conflicts and deadlocks may involve actors abandoning their original position and pursuing new goals, which will benefit both parties. Alternatively, as the authors of this paper suggest, future research should explore both the conflict management strategies and their resolution, in order to avoid the causes of quality failures in building energy-saving renovation projects.

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6 Conclusions

6.1 Introduction

The energy-saving renovation projects of existing residential buildings play a critical role worldwide, which is expected to achieve significant energy savings in the building sector (Zhao et al. 2019). The building sector currently consumes almost 30% of the world's overall energy, and the need to renovate them is imperative. Energy savings through renovating the existing building stock is one of the most attractive options for reducing energy consumption, and improving environmental sustainability. In response to the international efforts in improving energy & environmental sustainability, the Chinese government has started proactively to promote the implementation of building energy renovation projects to address the rapidly growing energy needs. Since 2007, building energy renovations have entered a large-scale implementation stage in Northern China (Liu et al. 2018).

The design of upgrades to thermal insulation to walls, floors and roofs of residential buildings is based on well-understood and tested technologies. However, various quality failures, arising from applying those technologies, such as insulation against heat loss, in practice, do not meet the technical requirements. Sadly, these failures frequently occur in energy renovation projects (Chen and Wang 2016; Aïssani et al. 2016; Nardi et al. 2019). In the Chinese context, such quality failures can strongly affect the thermal and energy performance of the existing buildings (Gang et al. 2016). Consequently, the presence of quality failures increases overdue schedules and unexpected costs in energy-saving renovation projects of the existing residential buildings (Liu 2015b; Love, Teo, and Morrison 2018; Schultz et al. 2015). Accordingly, quality failures have resulted both in energy losses and the dissatisfaction of residents living in these homes after project completion (Lo 2015).

It follows that it is essential to consider the quality failures associated with building energy renovation projects, and, in particular, there is a huge need for further understanding of how quality failures occur during the renovation process. In the available literature reviewed, several studies have provided evidence that there is a variety of causes that induce quality failures in project practices and the implementation of policies. Yet, prior to this study, there wa still a difficult step not yet made: a) to analyse both types of causes of quality failures; and b) to provide some suggestions for reducing these causes. In this direction, the present research aimed to: 1) identify the quality failures and their sources, impacts, and frequency; 2) establish the framework of causes of quality failures; 3) analyse the characters and relationships of the causes; 4) provide useful implications and valuable recommendations for the different construction participants in building energy renovation projects.

Chapter 6 is structured as follows. In the next section, we answer the research questions set in the Introduction of this thesis. Section 6.2 sums up the conclusions of this research. Section 6.3 reflects on the limitation of this research. Section 6.4 presents recommendations for further research based on this PhD research experience.

6.2 Analysis of causes of quality failures in building energy renovation projects

This research aims to answer the main question “What are the main causes of quality failures for the energy-saving renovation projects of existing residential buildings in Northern China? “ This main question is elaborated in previous chapters, and accordingly, it is answered step by step through four questions. The answers are summarized in Table 6.1.

6.2.1 What are the quality failures and their characteristics in energy-saving renovation projects in Northern China?

The purpose of this section is to identify the quality failures occurring in building energy renovation projects and evaluate the characteristics of these quality failures. This research defines quality as the fulfilment of the technical requirements issued by regulatory agencies in building energy-saving renovation projects. The characteristics of quality failures evaluated include likelihood, impacts, sources, and causes. In practice, on such renovation projects, there is a requirement to record and document the nature of any quality failures that are discovered. Thus, from five cases of building energy renovations, quality failures are identified and classified into three technical categories: door and window, roof, and the external wall.

Most quality failures appear in the process of installing new doors and windows for the doors and windows renovations. Therefore, installing new doors and windows is a key construction step to control quality. During roof renovation processes, the main sources where most quality failures are identified are “waterproof roof” and “install 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.”

This thesis focuses on the impacts of quality failures. For example, rework of the installation of windows and doors will hinder the completion of the renovation projects on time. If the fire resistance of expanded polystyrene insulation (EPS) boards cannot meet the technical requirement, 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 and concrete cracks. Water leakage may be the result of the misalignment of the roof waterproof layer during the usage phase. Due to water leakage, residents’ complaints negatively affect the evaluations of the success of building energy renovations. Concrete cracks are common in renovation projects, and consequently, the high rework cost will influence the overall cost increase in these projects.

These quality failures can cause unexpected losses. Quality failures cause direct costs ranging from 5% to 20% of the contract value increase. Moreover, residents’ dissatisfaction caused by quality failures is acting as the dominant barrier for the successful implementation of future building energy renovation projects. Due to quality failures, it is hard to achieve the goals of energy efficiency rates, and such failure leads to conflicts with the aims of improving building energy performance. Yet, the main stakeholders who participate in the whole project cycle could do better, by a focus on reducing quality failures to achieve successful projects.

6.2.2 What causes quality failures in building energy renovation projects?

This section seeks to establish a framework of the causes of quality failures. The natures of these causes, including the impacts, frequency, origin, and scale, are analysed and evaluated. Therefore, we first reviewed the body of literature that identified the causes of quality failures in construction projects. Then, these causes from international practice were tested and confirmed, or otherwise, by the experts working in the building energy renovation projects in China. The experts were asked if the causes were possible to appear during construction processes that they had observed or were familiar with. The questionnaire survey was to prioritize the final causes, to be further analysed regarding the impacts and frequency of the causes. Finally, we carried out a focus group study to evaluate the efforts required to tackle these causes.

It is clear that the impact and frequency of the causes are a vital prerequisite in order to prevent and eliminate quality failures. In normal practice in China, prior to any design work of building energy renovation projects, a site survey is necessary to know the structure, appearances, existing installation, and other characteristics . The interviews with experts revealed that “Incomplete construction site survey” had the greatest impact on construction quality. In energy-saving renovation projects, all renovated buildings were built before 2007. Thus, it is hard to find information details of old building documents, and so the most common cause was recorded as “Incomplete building information in projects.”

The level of tackling a cause of quality failures referred to their origin and scale. In order to complete energy-saving targets, both the factors of construction time and cost pressure in building energy renovation projects are higher than those in other construction projects. In this paper, the emergence of the causes is internal or external to the project based on the origin of the causes. The internal causes originated inside the project, and the external causes are those that originated outside the project. Both “working under high-cost pressure” “working under high-time pressure” are external influences, because these two causes originate outside the project. Most of the external causes (see table 3.7), like “adverse natural conditions” and “fraud of construction companies,” are at the macro-scale with a high level of challenge to tackle. Based on the evidence in this section, these external causes are more likely to be influenced at the policy level.

6.2.3 What are the relationships among the causes of quality failures in building energy renovation projects?

The above Questions 1 and 2 established the foundation for identifying the quality failures and their causes and provided a basic understanding of the causes. In order to reduce the causes, Questions 3 and 4 explored ways to avoid or reduce these causes at both project and policy levels, and so give some suggestions to the different stakeholder participants in the building energy renovation projects.

The causes do not occur as isolated influences, but rather appear with complex correlations in hindering good quality performance. Causal factors working together have a greater influence. Yet, in practice, neglecting the relationships among the causes has resulted in the ongoing failures to improve the quality of construction projects. Thus, an underlying cause with high driving-power is defined as the ***primary cause*** and placed on the linkage-cause cluster or independent-cause cluster. Causes, such as “lack of experienced project managers”; “unauthorized changes in design documents”; “incomplete building information in projects”; and “poor on-site coordination” are examples of such independent (or indirect) causes with high driving-power but low dependence-power. Efforts to solve/reduce these four causes would mean that their elimination allows the solving of several other most frequent causes in building energy renovations. On the other hand, causes including “use of poor materials,” “inadequate equipment performance,” and “inaccurate design work” are known as the most direct causes. They are frequently impacted by other causes and also easier to be reduced than other causes.

The findings in this research provide valuable solutions to reduce the causes from a management perspective, according to pathways of the interactions among different causes of quality failures. The solutions were categorised in terms of people, material and equipment, design, and organization, based on the quality management processes.

6.2.4 How do the actors and their interactions affect and cause quality failures during the renovation implementation process?

The energy-saving initiatives are supposed to be implemented in existing buildings of Northern China. Thus, we examined, in practice, how to implement an energy renovation programme to renovate existing residential buildings. In particular, too little attention has been paid towards the implementation processes of the renovation, resulting in limited information on how the actors and their interactions affect and cause quality failures during the renovation implementation process.

In the target-setting arena, the main actors are the national government and local governments (provincial government, municipal government, and district government). For some renovation projects, the central government, provincial and municipal governments are the main investors. The funding is transferred from the central government to the municipal government, which is different from other energy-saving renovation cases. Unlike energy-saving renovation projects above, the residents *also* need to pay for the new windows in parts of energy-saving renovation projects of the existing buildings. Thus, as well as funds from government bodies, funds from the residents flow to the renovation projects. Different actors' relationships in the funding structures have their obstacles to the renovation projects and even lead to some quality failures.

For the ***project preparation arena***, the main actors include local governments (provincial, municipal, and district governments) and private companies (design companies, supervision companies, and construction companies). In this arena, the resources, including information and legal approval, are exchanged between different actors. The building information is transferred from bottom to upper levels, while the legal approval is in a top-down manner.

In the ***project construction arena***, the main actors include municipal governments, district governments, supervision companies, design companies, as well as construction companies. Supervision companies report construction information to municipal and district governments. Meanwhile, the supervision company also obtains the construction information throughout site supervision and documents from both the construction company and the design company.

In these energy-saving renovation projects, government-led is a standard mode applied. After determining which buildings will be renovated, the municipal government finds the private companies, through tendering, to construct and supervise the renovations based on their past performances in the construction industry. The construction and supervision rights are transferred from the government to the construction companies and supervision companies through the agent contract. Conversely, municipal and district governments only play the manager's role based on the agent contract to ensure the realization of project performance and public interest. As a consequence, the local governments are responsible for on-site inspection. Construction flow supervision does not provide complete checking procedures. Table 6.1 summarizes the findings of the four chapters of the thesis.

TABLE 6.1 Summary of the answers to the research questions

Chapter	Questions	Sub-questions	Check List of Responses to the Questions
Chapter 2	What are the quality failures and their characters in building energy renovation projects in Northern China?	What are the quality failures appearing during the construction period?	• Incorrect installation of the steel nails; • Uncleaned wall; • Cracks of roof concrete, etc.
		What are the sources of quality failures?	• Install new doors and windows; • Install thermal insulation materials; • Waterproof roof, etc.
		What are the impacts of quality failures?	• Rework; • Potential fire safety hazards; • Serious safety issues, etc.
		What is the occurrence frequency of quality failures?	• Incorrect size of the new window frame and door frame; • Misalignment of the waterproof roof layer.
Chapter 3	What causes quality failures in building energy renovation projects in Northern China?	What are the relationships between quality failures and their causes in building energy renovation projects?	The causes appear at the root level: • Lack of experienced project managers; • Unauthorized changes in design documents; • Incomplete building information in projects, etc.
		What are the impact and frequency of each cause?	The cause of the greatest impacts on construction quality is the "Incomplete construction site survey."
			"Incomplete building information in projects" is the most frequent.
		What is the origin of each cause?	A framework of the causes was presented according to their origin.
		What is the scale of each cause?	The micro-meso-macro scale model is used to classify the causes based on their scale.
Chapter 4	What are the relationships among the causes of quality failures in building energy renovation projects?	How do the causes of quality failures affect construction quality?	The structural relationships of the causes affecting construction quality are obtained.
		What are the driving-power and dependence-power of the causes?	Using ISM and MICMAC techniques, driving and dependence power of the causes are analysed.
Chapter 5	How do the actors and their interactions affect and cause quality failures during the renovation implementation process?	Who are the actors during the renovation implementation process?	• Central and local levels of governments; • Construction companies, • Supervision companies, • Design companies, etc.
		What are the interactions of the actors?	Actor interdependency maps in: • target setting arena; • project preparation arena; • project construction arena.
		How do the actors affect construction quality?	Based on the case study, the conflicts of different actors are used to analyse stakeholders' impact on quality failures.

6.3 Reflections on the Research Outcomes and Recommendations

Avoiding the causes of quality failures needs not only to identify the causes but also to assess the relationship of these causes in the energy-saving renovation projects. High-time and high-cost pressure are regarded as the dominant cause of quality failures, especially in building energy-saving renovations. High-cost pressure is related to the lack of funding in the Chinese context. The building energy-saving renovation programme belongs to government investment projects, and it is conducted through government subsidies and investments. For most building energy-saving renovation projects, financial support is central funding (from the central government) combined with local funding from local governments (provincial and municipal governments). Nevertheless, these funds are not enough to support construction companies to educate project managers.

Another dominant cause is high-time pressure during the renovation implementation processes in China. The ambitious targets for the renovation area are closely related to the high-time pressure. The Chinese national government sets the top-down targets for the renovation area. For example, the renovation area targets are 150 million m^2 (building floor area) of the residential buildings during the 11th Five-Year Plan (2006-2010). During the 12th Five-Year Plan (2011-2015), the area target was that 400 million m^2 of building floor area in existing residential buildings must be renovated. The central government intends to renovate 1.2 billion m^2 of building floor area of the residential buildings during 2016-2020. To have a good performance, the provincial and municipal governments' renovation area targets (local renovation area targets) are significantly more ambitious than the goals of the central government. Therefore, in order to achieve the local renovation targets, local governments' and other stakeholders' renovation work are under intense construction time pressure. Thus, they may neglect construction quality and pay more attention to the construction schedule in building energy-saving renovation projects.

High-time and high-cost pressure trigger the other four causes from an internal origin of renovation projects. They are the "Lack of experienced and knowledgeable project managers," "Unauthorized changes in design documents," "Inefficient information transfer," and "Poor on-site coordination", all of which are significant because they have strong impacts on construction quality and other causes. These four are all explained below.

6.3.1 Lack of experienced and knowledgeable project managers

The project managers' lack of experience and knowledge during project management processes in energy-saving renovations results in quality failures. Various construction works are heavily dependent on project managers. In practice, the project managers should be responsible for emphasizing the quality control points for workers and managing the on-site construction. In the current situation, the project managers are not able to properly manage and organize building energy-saving renovations. On the one hand, some project managers are beginners to work on building renovation projects, so they cannot provide the key points to control quality for workers. For example, cracks of thermal insulation are due to the fact that project managers do not emphasize to the workers the critical points of cleaning the walls. On the other hand, the research shows that some project managers do not have adequate knowledge of the waterproofing techniques and other technical requirements. During waterproofing the roof, project managers lack knowledge that waterproof material is sensitive to low temperature. The misalignment of roof waterproof layer is the result.

For a lack of experience in renovation work, the advice for supervision companies and local governments is to organize meetings for the project managers to share their experiences. The key points of quality management are discussed in the meeting to enrich project managers' experiences. The finding suggests to policy makers that funding from the governments should be increased to build the education system for project managers to improve their knowledge level. In building energy-saving renovation projects, more financial supporters, such as a heating service company should be involved to provide enough funding for the education system. This recommendation is in line with many international studies emphasizing that gaps in the project managers' management and construction knowledge can be improved by building a training system (Aljassmi and Han 2012).

6.3.2 Unauthorized changes in project specifications

Construction companies may change the project specifications without authorization by designers and local governments. During the survey and design period, the designers provide a set of project specifications, technical drawings, and other relevant documents, which guide construction processes and materials used. "Unauthorized changes in project specifications" has more capability to influence other causes. Missing rivets occurs in installing mechanical fixings of the renovation of the external wall. The problem of missing rivets is a potential hazard of thermal insulation materials falling off. Construction companies change the number and the distribution of rivets, unauthorized, by cutting corners to reduce construction cost. According to the nature of the construction companies, the primary interest of construction companies is to reduce their costs and increase company income. For supervisors and designers, they do not have a strict inspection of installing mechanical fixings to ensure that the project specifications are correctly conducted by construction companies.

Designers carry out the project specifications but they are not required to manage the implementation of these project specifications. Therefore, designers rarely join the on-site supervision team. It is recommended that local governments establish an on-site supervision team including supervisors, designers, and officers in local government during the construction processes. In the team, supervisors are encouraged to timely share on-site information with designers. Designers can respond about whether construction companies renovate the buildings according to the project specification. The practical task to supervise the implementation of technical specifications would be allocated by the designers. Policies and regulations should be designed by the local government to increase punishment so that construction companies do not have the motivation to change the project specification. Once it is discovered that the project specifications are changed by construction companies unauthorized, the construction companies need to pay huge compensation to the local government. The heavy punishment can result in two or three times the rework cost.

6.3.3 Incomplete construction site survey

The errors in the on-site investigation and design work caused by the incomplete construction site survey led to incorrect construction implementation in building energy-saving renovation projects. During installing new doors and windows, a mismatch between the size of the new window or door and the original opening is recorded as ‘Incorrect size of the new window frame and door frame’. Designers or workers make errors in measuring and recording the size of the doors and windows during the survey and design stage. The workers ignore to check the actual size of doors and windows on the construction site. The final result is that new windows or doors could not be installed. Rework of installation windows and doors will hinder the completion of the renovation projects on time.

The site survey is essential for the construction processes, especially in energy-saving renovation projects. A construction site survey could impact the design work of the projects directly, but it is always paid too little attention to the designers and workers. The local government needs to emphasize the survey processes and to supervise designers and workers to obtain actual data in an on-site survey. If it is necessary, every household living in renovation buildings should be investigated by designers and workers. The checklist can be used to avoid the designer and workers' missing any household survey. As stated by Janipha and Ismail (2013), the information in the site investigation is important to ensure the right decisions are made, and appropriate supervision can be taken in the future.

6.3.4 Poor on-site coordination

The on-site coordination of the construction team is inefficient for the construction processes in energy-saving renovation projects. Based on the result of this research, "Poor on-site coordination" is more significant to affect others. It needs to be given priority for attention and avoidance. The standard practice in on-site coordination in the Chinese situation is that when key work is to be completed by the construction workers, project managers would inform the site supervisors. The site supervisors need to check the quality of construction work. However, project managers do not inform the site supervisor to check. The site supervisors do not check for themselves but proceed to call for an inspection by other site staff. Consequently, the inaccurate or outdated information is transferred among these stakeholders. Cracks of roof concrete are common in roof renovation. The high rework cost of concrete cracks will influence the construction cost increase. After painting the protection layer, project managers fail to inform the site supervisor and to provide the proportion information of mixing concrete materials. The site supervisors do not check in time to give their feedback on the protection layer. Obviously, the on-site participants cannot obtain the latest and correct information from the others due to the poor coordination, resulting in quality failures.

An efficient information-sharing system, such as the Building Information Model (BIM), could be applied in building energy renovation projects to improve communications between on-site participants. Doloi et al. (2012) and Doumbouya et al. (2016) proposed effective cooperation between the stakeholders of the projects has a relationship with the sharing of project information. Meijer and Visscher (2017b) also advise governments to develop some online tools further to guide and organize the on-site participants through the construction process.

6.4 Added value of the research

6.4.1 Scientific contribution

Many previous studies have already investigated the causes of quality failures in general construction projects. However, far less attention has been paid to the causes of quality failures in building energy-saving renovations. Moreover, the situations in the Chinese context are considered by few researchers. This thesis offers a methodical study for reducing the causes of quality failures in energy-saving renovation projects in China. This new knowledge and understanding of quality failures can lead to an improvement in outcomes.

There are a number of existing studies that outline the quality failures in construction projects and suggest possible strategies. However, the existing research studies lack identification and analysis of the characteristics of the quality failures in building energy-saving renovations. In this thesis, the identification of the quality failures and their characteristics are firstly jointly researched in energy-saving renovations in the Chinese context. The likelihood, impacts, sources, and causes of quality failures are obtained to fill the research gap. This thesis adopts the fuzzy-set evaluation to study the frequency of occurrence of various quality failures in the building energy renovation projects. The majority of previous researches used the evaluation methods based on exact numerical values that are used to represent respondents' judgments. The benefit of the fuzzy-set evaluation is that the experts can express their opinions on words rather than crisp values. Fuzzy-set evaluation is quite useful to avoid the uncertainty of people's subjective decisions. Therefore, the fuzzy-set theory is utilized to deal with an ambiguous occurrence frequency of quality failures from subjective decisions by respondents. The analysis of the fuzzy-set evaluation method shows the most common quality failures that occurred in the construction processes of the projects.

An analysis into the network of causes of quality failures is carried out in this thesis. This part departs from previous studies, because previous studies did not focus on the causal relationships among the causes of quality failures. This research investigates and maps the causes of quality failures in the field of energy-saving renovation projects for the first time in the Chinese context. This thesis contributes to the scientific field by applying the policy network theory to energy-saving renovation projects and can enrich the existing theoretical framework. Until this study, the implementation of the renovation policy using policy network theory has been barely even considered in the Chinese context. Based on the framework of policy network theory, this thesis has found how the actors and their interactions affect construction quality from a policy implementation perspective.

6.4.2 Societal contribution

Construction management measures and policy environments affect construction quality. This thesis provides information to help both construction practitioners and policy-makers to adopt effective policies and measures. This is of importance for ensuring that quality failures are reduced in numbers and severity and to promote the construction quality of building energy renovation projects. Construction practitioners and policy-makers can benefit from focusing on critical causes of quality failures and then developing effective actions. Moreover, the project coordinators have failed to manage the quality of construction projects due to the neglect of the causal relationships among these causes of quality failures. The findings of this research provide information for understanding the pathways of the interactions among different causes of quality failures. Furthermore, considering the roles of various causes, some solutions for the reduction of quality failures have emerged and are provided from both quality management and a renovation policy perspective.

Construction is a dangerous business. In China, there were increasing safety incidents due to quality failures on construction projects over recent decades. Indeed, safety accidents due to poor quality are significantly worse in the Chinese context. Most building quality incidents occur during the construction phase. Based on the findings of this thesis, the impacts of the uncleaned wall and missing rivets are such that thermal insulation material cracking or chipping off can be serious safety issues for the on-site workers and residents living in renovated buildings. There are management strategies that can jointly improve construction quality and safety performance of renovation projects.

Poor quality performance negatively affects energy consumption and the indoor environment. The reduction of quality failures will not only improve the indoor environment of the existing residential buildings, but it will also help reverse the rising energy consumption of the building sector. Thus, the renovation building market is facilitated to move toward sustainability through the findings and solutions of this thesis. Due to quality failures, residents' complaints negatively affect the evaluations of the success of building energy renovations. Thus, applying good practice highlighted here, the residents can benefit from the satisfactory quality performance of energy-saving renovation projects. This would help to improve resident satisfaction levels in building energy-saving renovation projects.

6.5 Limitations

This study presents certain limitations that suggest further research would yield fruitful results. Quality failures may result in serious consequences. An adequate database regarding quality failures in renovation (or construction) projects is lacking in China. It is, therefore, difficult to find sufficient information and a quantitative description of quality failures. As the effect of quality failures is a comprehensive result of the various causes, it is difficult to quantify the effectiveness of a specific cause in a certain period. More achievements would be made if the detailed data of quality failures for energy efficiency could be provided and regarded as quantitative evidence.

Second, a building regulation system contains many public requirements and defines the rights, tasks, and responsibilities of the main actors in the process (Visscher, Meijer, and Branco 2012). Yet, technical requirements are only a part of a building regulation system. In this research, quality is defined as the (minimum) quality level need as set / stated in the technical requirements, which is a narrow definition. The integral building regulation system can be researched to improve both the quality of construction work product and the process quality.

Additionally, the scope of this research is the building energy renovation projects of Northern China. Cases were only chosen in the Chinese context. The features of renovation practices and technical measures in the northern regions do not represent the overall situation in China and even less worldwide. The technology guidelines and renovation standards are different compared with the diverse climates in other regions.

A fourth limitation is that only seven cases are used to represent the features of energy-saving renovation projects of residential buildings. Besides, a part of the thesis has been researched via reasonably limited fieldwork. In future research, additional cases can be collected, and further research could be considered solely onto the Chinese situation.

Finally, this research only covers the quality failures during the construction period in the energy renovation projects of the existing residential buildings. Many other aspects can also be studied, such as the energy renovation projects of the public buildings and quality failures occurring during the residents' usage period.

6.6 Recommendations for future research

Two areas of future research are proposed in the Chinese situation. The first is to interpret the impact of quality failures in energy-saving renovations and provide a quantitative description of energy losses after they occur. This thesis only focuses on the causes of quality failures and studies the reduction of quality failures based on the characters of their causes. The solutions to the causes are described to prevent quality failures before they occur. However, the negative impacts of the quality failures after they occur may cause poor thermal performance and energy inefficiency. Future work can study the impact of the quality failures on energy performances, such as thermal performance, energy efficiency, and living comfort.

The second area is to explore the quality failures appearing during the usage periods caused by the influences of residents' behaviour. This thesis indicates that quality failures occur only in the construction stage. However, quality failures may be caused by the design, construction, and the usage stage of building projects. There is a clear need for further work to identify quality failures during the usage processes for building energy renovation projects. The residents are the main stakeholders to affect renovation quality, and thus more attention should be paid to the relationships between their behaviour and quality failures. This may help project managers to correct key control points considering residents' influences.

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Curriculum Vitae

Yuting Qi was born in March 1991 in Inner Mongolia, China. She obtained her bachelor's degree in engineering management from Chongqing Jiaotong University in 2014. She then won the scholarship to support her master at the same university. During the master period, she studied the quality management and cost risk in construction projects. This built a foundation for her Ph.D research topic. In 2016, she received a scholarship from China Scholarship Council to support her Ph.D. research at the Department of Management in the Built Environment (OTB department 2015-2019), Faculty of Architecture and the Built Environment, Delft University of Technology in the Netherlands. She has been carrying out her research work in the field of quality management in energy-saving renovation projects of existing residential buildings.

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Quality failures in Energy-saving renovation projects in Northern China

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The energy-saving renovation of an existing building is a critical strategy in achieving a long-term energy goal in the Chinese context. However, in China, building energy renovation projects are subjected to quality failures resulting in energy wastage, a decrease in the energy efficiency of the project, an increase in project cost, and thus negatively affecting the overall performance of the renovation projects. In order to avoid them happening in the future, it is essential to find and analyse the causes of quality failures in energy-saving renovation projects. Therefore, using a four-step process, this research aims to deepen the understanding of the causes of quality failures in energy-saving renovation projects of the existing residential buildings. The first and second steps are to identify and analyse the quality failures and their causes. The deeper insights from a quality management perspective are explored in the third step. The fourth step is to investigate how the actors and their interactions affect and cause quality failures during the renovation policy implementation process. This research mainly concludes the causes of quality failures in the building energy renovation projects. It is important to state that most of the quality failures can be avoided at the management level. Some external causes originated at a policy level and outside the project. The findings of this research would be valuable for policy-makers and project coordinators both for predicting and avoiding quality failures and for developing proper action and policy interventions to ensure successful building energy renovations in the future.

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