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What impedes stakeholders from implementing nearly zero-energy buildings in China? A multi-stage perspective based on transaction cost theory

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ABSTRACT

Nearly Zero Energy Buildings (NZEB) are widely seen as a key pathway to achieving energy efficiency and decarbonization in the building sector. Although subsidies in some regions of China cover most explicit costs, large-scale adoption remains limited. The main reason lies in the significant hidden costs borne by stakeholders due to multi-stage certification systems, emerging technologies, and complex policies. Despite their impact, these costs are underexplored in current research. To address this, this study applies transaction cost theory and interviews 23 NZEB experts to identify hidden costs, then develops mitigation strategies validated by 12 experts and a focus group, yielding a three-tier roadmap. It makes three contributions: 1) It introduces a replicable "stage–stakeholder–cost" framework to analyze hidden costs in NZEB practices; 2) It identifies 36 transaction cost items and maps cost flows across 11 stakeholder groups, providing a model for visualizing procedural frictions in complex building environments; 3) It targets major transaction cost bottlenecks and, drawing on international experience, proposes and validates strategies to reduce hidden costs, offering a roadmap for China and other emerging markets.

1. Introduction

Against the backdrop of an escalating global climate crisis, the construction industry's energy consumption and carbon emissions have drawn widespread attention [1]. Currently, the construction sector accounts for approximately 30% to 40% of global energy consumption [2]. It accounts for approximately 36% of global carbon dioxide emissions, making it a key focus of global energy conservation and emission reduction policies [3,4]. The significance of green, sustainable, low-carbon building technologies is constantly highlighted in this context. Notably, NZEB has demonstrated strong potential to enhance building energy efficiency and reduce carbon emissions. They have thus emerged as an effective pathway for advancing the sustainable transformation of the building sector [5]. Compared with conventional energy-efficient buildings, NZEB impose stricter requirements on building envelope performance, the efficiency of mechanical and electrical systems, and the integration of renewable energy systems. Moreover, they must undergo rigorous testing and certification processes to ensure near-zero energy consumption and realize the comprehensive energy transition [6–8]. In response, developed regions such as the United States, Australia, the United Kingdom, the European Union, South Korea, and Japan have incorporated NZEB into their regional energy and sustainable building policy frameworks, achieving significant energy-saving progress [9–13]. As a major energy consumer and carbon emitter, China has also recognized the crucial role of NZEB in achieving carbon peaking and carbon neutrality targets. To ensure the effective implementation of NZEB, China has issued a series of standards and incentive policies. These include the *Technical Standard for Nearly Zero Energy Buildings (GB/T 51,350–2019)* [2,14], and a multi-stage certification system that covers the design, construction, and operation stages [15–18].

However, despite the government's continuous efforts in terms of incentive policies, the development of NZEB in China has still fallen far short of expectations [19]. While some projects have achieved certain successes at the demonstration level, large-scale implementation has remained unsatisfactory [20,21]. Previous studies have highlighted high incremental costs as a key barrier to the adoption of NZEB. These costs often arise from investments in active and passive technologies, as well as renewable energy systems [5,15,22]. In practice, however, even in regions where government subsidies are sufficient to offset these incremental costs, stakeholders remain reluctant to implement NZEB,

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Abbreviations

NZEB	Nearly Zero Energy Buildings
TC	transaction costs
CS	concept stage
DS	design stage
CSS	construction stage
OS	operation stage
DEV	developer
CON	consultant
GOV	government
FIN	financial institution
DES	design company
CERT	certification body
GC	general contractor
SUP	supplier
SUPV	supervisor
PMC	property management company
OWN	owner
DBB	design-bid-build
IPD	integrated project delivery
HVAC	heating, ventilation, and air conditioning
BIM	building information modeling
EVM	earned value management
LEED	leadership in energy and environmental design
PHI	the passive house institute

resulting in the stagnant development of NZEB [15,23].

In fact, beyond the visible incremental costs, stakeholders must also invest extra time and effort, often considered as hidden costs, to address the specificities and uncertainties associated with NZEB implementation. For example, during the conceptual stage, developers usually spend considerable time collecting and interpreting various NZEB incentive policies [24]. During the design stage, to meet NZEB energy performance requirements, design companies often need to engage in extensive consultations and repeated adjustments with technical advisors to optimize integrated energy solutions [23,25]. During the construction stage, contractors and supervisors must perform multiple rounds of airtightness and thermal bridge tests, as well as on-site calibration, to ensure the building envelope meets NZEB performance standards [7,25,26]. Adding to the complexity, when policies, technologies and approval processes remain unclear, stakeholders, including developers, design companies, contractors, and property management companies, must undertake extensive additional efforts in information searching and coordination. These include collecting test data and communicating with certification bodies to meet the ongoing evaluation requirements for energy consumption and indoor environmental quality in the multi-stage certification process [27].

The additional efforts undertaken by stakeholders throughout the various stages of NZEB implementation can be regarded as hidden costs, namely transaction costs. These costs are easily overlooked by external observers [28]. However, for industry stakeholders, transaction costs represent a tangible burden that can influence their attitudes toward new technologies and even hinder technological advancement [29,30]. Existing studies on sustainable buildings have repeatedly mentioned that transaction costs in the process are key barriers to impede their development. These hidden costs include, but are not limited to, the time, effort, and resources stakeholders invest in information searching, contract negotiation, supervision, and dispute resolution [31–33]. Notably, in situations where policy environments, technological solutions, and approval processes are highly uncertain, these costs can accumulate [34,35], further hindering stakeholders. If these "invisible" burdens are not adequately identified and managed, sustainable technologies with market potential may stagnate due to their "high hidden costs." However, there remains a lack of systematic and in-depth empirical research on the distribution characteristics and causal mechanisms of transaction costs in NZEB implementation [6,23,36]. This research gap suggests that policymakers and industry regulators struggle to accurately recognize, understand, and manage these "hidden burdens." This makes it difficult for them to develop targeted incentives or effective management strategies, which ultimately impacts the overall progress of the building sector's energy transition.

To address this research gap, this study investigates the hidden costs that hinder stakeholders from implementing NZEB using a process-oriented perspective. Drawing on transaction cost theory, the study aims to understand the characteristics and underlying drivers of these hidden costs, as well as targeted mitigation strategies. Specifically, the study addresses three questions:

1) What does the actual implementation process of NZEB in China entail, and which stakeholders collaborate in it and undertake which tasks?
2) How do transaction costs occur within stakeholder collaboration during the NZEB implementation process, and what are their characteristics and causal mechanisms?
3) What are the strategies for addressing the transaction cost bottlenecks, and how are they prioritized in the Chinese context?

The main contributions of this paper are: 1) It develops a replicable three-dimensional analytical framework that links implementation stages, stakeholders, and transaction costs to systematically examine the generation and evolution of hidden costs throughout the NZEB lifecycle. This framework serves as a diagnostic tool for understanding procedural frictions in other low-carbon building projects; 2) Drawing on field interviews and coding analysis, the study identifies and maps 36 transaction cost items across the NZEB implementation process. It reveals their types, sources, determinants, and stakeholder-specific characteristics, and summarizes transaction costs bottlenecks, deepening the understanding of hidden costs in the low-carbon building transition process; 3) Based on the bottlenecks, the study integrates international experience with China's context to build a priority matrix of mitigation strategies. It outlines a tiered strategy implementation roadmap, providing empirical guidance for improving policy effectiveness and precision.

The rest of the paper is structured as follows: Section 2 reviews the development of NZEB and related transaction cost research, focusing on the challenges of NZEB's Chinese policy, technology, and certification, as well as relevant theoretical and mitigation approaches. Section 3 outlines the research methods, including expert interviews, data analysis to identify NZEB-related transaction costs, and the formulation and expert validation of mitigation strategies. Section 4 presents the main types, sources, determinants, and stakeholder-specific transaction costs characteristics. Section 5 presents mitigation strategies based on international experience and prioritizes them using a feasibility–appropriateness matrix. Section 6 provides an in-depth discussion of the transaction cost bottlenecks and outlines a layered mitigation strategies pathway. Finally, Section 7 summarizes the study and offers insights into potential future research directions.

2. Literature review

2.1. Policies, technologies, certifications, and implementation process of NZEB in the Chinese context

2.1.1. Incentive policies for NZEB in China

Under the guidance of China's carbon emission peak and neutrality strategies, local governments in China have actively introduced policies to support NZEB [19]. Since 2016, 15 types of NZEB-related incentive measures have been implemented nationwide [2]. Based on their form and intensity, these incentives can be categorized into direct economic, indirect economic, and procedural support [2]. However, studies have shown significant variations in the implementation of NZEB incentives across regions in China, with policy content subject to frequent adjustments [7]. For example, most provinces offer monetary subsidies ranging from 200 to 500 RMB per square meter, while some provide subsidies as high as 1000 RMB per square meter [15]. In addition, some local governments frequently modify subsidy standards or eligibility criteria and may revise policies multiple times within a short period [19]. The diversity and uncertainty of policy information present significant challenges for developers in accessing and interpreting these policies.

2.1.2. Key technologies of NZEB in China

The technical realization of NZEB is essential for significantly reducing building energy consumption and forms the foundation for its large-scale adoption. *The Technical Standard for Nearly Zero Energy Buildings (GB/T 51,350–2019)* outlines the core technologies of NZEB in China, including high-performance building envelopes, airtightness control, insulation systems, thermal bridge mitigation, and the integrated use of renewable energy systems [7,15].

However, these technologies pose various challenges to stakeholders during the design, construction, and operation stages. In the design stage, due to significant differences in climate conditions, building forms, and functional requirements across regions, design companies are required to develop tailored technical solutions to meet the specific needs of each area. For instance, while insulation improvement is essential for winter heating efficiency in cold northern regions, thermal bridge control plays a key role in balancing heating and cooling in hot summer–cold winter regions [37–39]. Moreover, the solar heat gain coefficient (SHGC) and window-to-wall ratio (WWR) of high-performance window systems must be precisely adjusted to achieve a balance between daylighting, shading, and energy efficiency based on local climate conditions [23,40]. NZEB design also involves multiple stages, such as energy modeling, equipment selection, and technical coordination, which increase design complexity and demand higher technical competence from designers [41,42].

In the construction stage, NZEB's stringent quality and technical standards place substantial demands on general contractors. They must ensure the building envelope achieves optimal airtightness, precisely install insulation materials, and effectively control thermal bridges [43]. Furthermore, general contractors are required to install high-performance windows and doors accurately, ensure seamless envelope integration, and coordinate the incorporation of renewable energy systems [26,44]. These multifaceted responsibilities necessitate advanced technical expertise and robust teamwork to meet the rigorous NZEB criteria [45,46].

During the operation stage, the system efficiency of NZEB is influenced by climate conditions, fluctuations in energy consumption, and changes in user demand [26]. Dynamic optimization can be achieved through intelligent building operation management systems (IBOMS) and energy monitoring platforms. However, complex data processing and system integration significantly complicate commissioning for property management companies [23].

2.1.3. NZEB multi-stage certification system

The multi-stage certification system of NZEB is a core mechanism for ensuring the effective implementation and enforcement of standards. China has established a lifecycle-based evaluation system based on the *Technical Standard for Nearly Zero Energy Buildings (GB/T 51,350–2019)* and the *Assessment Standard for Nearly Zero Energy Buildings(T/CABEE 003—2019)* [47,48] to ensure high performance throughout the design, construction, and operation stages. Thus, this system employs a multi-stage review process encompassing the design, construction, and operation stages, with specific evaluation criteria and required documentation detailed in Table 1.

China's NZEB certification system differs significantly from international certification systems and imposes additional burdens on project stakeholders. International systems, such as the European Union's Energy Performance Certificate (EPC) [49], Japan's Building Energy Efficiency Labeling System (BELS) [16], and Australia's Nationwide House

Table 1
Evaluation and documentation requirements for NZEB project stages in China.

Stages	Design Stage	Construction Stage	Operation Stage
Evaluation Focus	Compliance of design drawings with standards: Verify if the building designs meet the requirements of the *Technical Standard for Nearly Zero Energy Buildings (GB/T 51,350–2019).*	On-site testing: Evaluate the airtightness and thermal performance of building envelopes, as well as the installation quality of HVAC systems.	Indoor environmental quality: Assess temperature, humidity, PM2.5 levels, carbon dioxide concentration, lighting, and other standards.
	Calculation of energy efficiency indicators: Include parameters such as thermal transmittance of building envelopes, airtightness, and lighting design.	Inspection of key materials: Verify whether high-performance doors and windows, insulation materials, and ventilation systems meet design standards.	Monitoring actual energy consumption: Measure the overall energy consumption of the building and the efficiency of renewable energy systems.
	Design of renewable energy systems: Ensure the proper allocation of solar energy, geothermal heat pumps, and other systems.	Construction process records: Assess compliance with construction techniques and practices, including construction logs and quality control checkpoints.	Reliability of system operation: Ensure that equipment operates continuously and efficiently, with proper maintenance.
Required Materials	Construction drawings: Include detailed designs of building envelopes, HVAC systems, windows, and other elements.	Inspection reports: Provide testing data for building envelopes (e.g., exterior walls, window frames) and HVAC systems.	Energy monitoring data: Include electricity consumption, heating and cooling energy use, and the output of renewable energy systems.
	Energy consumption simulation model: Use nationally recognized energy simulation software.	Material compliance certificates: Provide documentation for airtightness materials, insulation systems, and ventilation systems.	Indoor environment test report: Include data on temperature, humidity, air quality, and lighting levels.
	Design descriptions and analysis reports: Provide reports on design compliance and energy efficiency indicators.	Construction records and visual documentation: Include photos of critical construction points and construction logs.	Equipment operation records: Provide maintenance and operation data, as well as re-inspection reports.

Adapted from [47,48].

Energy Rating Scheme (Nat HERS) [17], typically adopt a single-stage review model. These systems are characterized by streamlined procedures and centralized assessments, making them relatively easy to implement. In contrast, China's NZEB certification system spans the entire building lifecycle, encompassing the design, construction, and operation stages through a multi-stage, multi-node dynamic assessment process. While this system enhances standard enforcement and continuous regulatory oversight, it also significantly increases project complexity and uncertainty. To ensure compliance at each stage and ultimately obtain NZEB certification, stakeholders are required to invest substantial additional time and technical resources, thereby exacerbating the institutional burden throughout the implementation process.

2.2. The implementation process of NZEB in China

The implementation of NZEB in China includes four stages: concept, design, construction, and operation [7,50–52]. The successful implementation of NZEB highly relies on close collaboration and effective coordination among stakeholders at each stage [53,54].

Fig. 1 illustrates the implementation process of NZEB in China. In the concept stage, developers conduct feasibility studies through policy analysis, technical evaluation, and resource integration to ensure both the technical and economic viability of the project. In the design stage, design companies are responsible for energy-efficient design, energy simulation, and technical optimization to ensure that the building envelope and renewable energy systems meet certification standards. During the construction stage, contractors must adhere strictly to design specifications. Supervision agencies are required to monitor construction quality, and certification bodies must conduct on-site evaluations to ensure compliance with NZEB standards. During the operation stage, property management companies optimize system performance through regular equipment maintenance and energy monitoring. At the same time, certification bodies conduct regular performance inspections and utilize user feedback to drive continuous improvement.

Table 2 summarizes the definitions and core responsibilities of key stakeholders involved in NZEB projects in China. Compared to conventional buildings, NZEB involves more complex tasks at each stage, which not only increase the responsibilities of stakeholders but also introduce new roles, such as certification bodies and NZEB consultants, thereby complicating the collaboration network. This, in turn, raises the difficulty of coordination and increases communication costs.

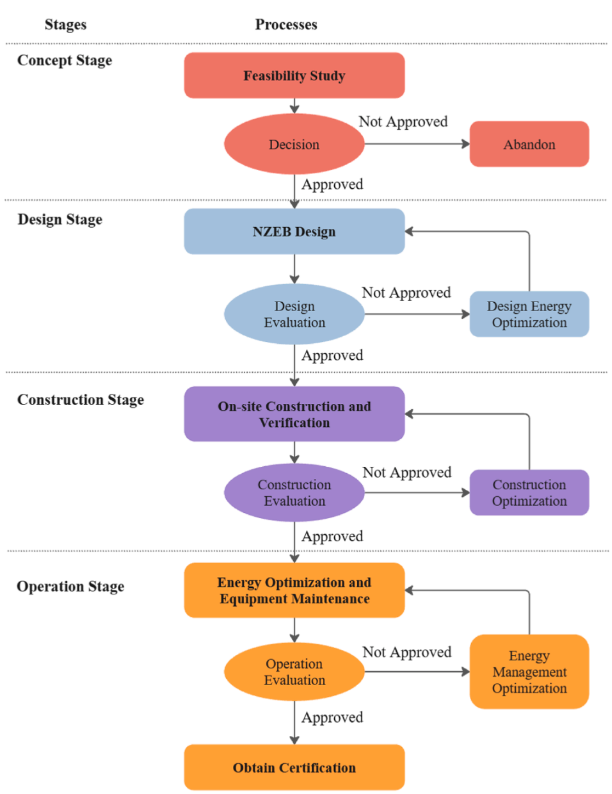

Fig. 1. Implementation process of NZEB in China [7,50–52].

Table 2
Key stakeholders and their roles in NZEB projects.

Stakeholder	Definition and Key Responsibilities
Developer	Initiates the project, is responsible for overall planning and progression, and coordinates with other stakeholders. Links policy incentives, organizes resources, and participates throughout the entire lifecycle, from concept to operation.
Design Company	Provides energy-efficient building designs, energy consumption simulations, and technical optimization solutions to ensure the design meets NZEB standards.
General Contractor	Completes construction according to design requirements, ensuring that construction techniques and quality comply with technical standards, including the implementation of high-performance building envelopes and renewable energy systems.
Supervisor	Monitors construction quality to ensure compliance with design standards and NZEB certification requirements and coordinates technical issues between developers and contractors.
Certification Body*	Conduct evaluation and certification across all project stages, from design to operation, ensuring compliance with the Technical Standard for NZEB and supervising continued performance during operations.
Property Management Company	Maintains building equipment during the operational stage, monitors energy consumption data, and optimizes systems to ensure long-term NZEB performance goals are met.
Government	Provides policy support, including incentives, regulatory requirements, and project approvals, while overseeing compliance and ensuring the achievement of policy objectives.
Supplier	Provides high-performance materials essential for construction, including insulation, efficient doors and windows, and key components for renewable energy systems, ensuring that material performance meets NZEB technical requirements.
Consultant*	Offers technical and informational consulting services to developers. This support enables them to manage technical achievements at every stage, ensuring the project passes the NZEB evaluation and certification.
Owner (End-User)	The end user of the NZEB project, whose usage behavior can also influence the building's energy consumption.

Adapted from [28,33,53].
* for additional stakeholders compared to traditional construction.

2.3. Transaction costs theory

The transaction cost theory was first proposed by Coase [55] and was further developed within the framework of new institutional economics [56,57]. The theory emphasizes that transaction costs are a core component in the organization and execution of economic activities, primarily arising from incomplete information, bounded rationality, and insufficient monitoring [58,59]. In other words, transaction costs are not directly related to the production of goods or services but represent unavoidable implicit expenditures during contract enforcement and market transactions, which may hinder the sustainable development of markets [60,61].

In the context of sustainable buildings, transaction costs refer to the additional expenses incurred from adopting new energy-saving technologies, policies, and processes [28]. These costs span the entire lifecycle of a building project, including planning, design, construction, operation, and subsequent maintenance [33]. According to existing studies, transaction costs in sustainable buildings can be categorized into four types [31–33]: 1) information search costs, including expenses related to obtaining certification standards, partners, case studies, technical specifications, policy regulations, and subsidy information; 2) due diligence costs, covering project feasibility assessment, evaluation of new technology solutions, decision-making processes, and compliance checks; 3) negotiation costs, including coordination and communication efforts, permit applications, contract negotiations, and dispute resolution; and 4) monitoring and compliance costs, involving quality control, random inspections, and regulatory compliance reviews.

Notably, these costs do not exist in isolation throughout the project process but are influenced by the interaction of multiple driving factors. According to Williamson's transaction cost theory, the main drivers include asset specificity, uncertainty, and transaction frequency [62]. Table 3 summarizes the types and determinants of transaction costs in NZEB implementation in China.

2.4. Mitigation strategies for transaction costs

To support the analytical framework developed in Section 2.3 and inform the design of feasible mitigation measures, this section presents a literature-based review of international strategies aimed at reducing transaction costs in sustainable building implementation. As identified in prior studies, Transaction costs are primarily driven by two categories of factors: asset specificity and uncertainty, each requiring tailored institutional and process-level interventions.

Under asset specificity, researchers have emphasized capacity-building approaches such as standardized professional training [78–80], centralized information management platforms [78,79], and contract standardization mechanisms including Integrated Project Delivery (IPD) or multi-party agreements [81–84]. Additionally, early-stage simulation and feasibility tools have been shown to enhance decision-making efficiency and reduce indirect transaction costs associated with design iterations [85,86]. In the domain of uncertainty, prominent strategies include relational governance models that align incentives and strengthen trust among stakeholders [87–89], digital review systems that automate compliance and design verification [81,90,91], and risk-driven contract structures that improve adaptability under policy volatility [92–94].

Table 4 summarizes these mitigation strategies by Transaction costs determinant, including representative tools and corresponding evidence from recent international construction studies. This synthesis forms the empirical and theoretical foundation for the strategic recommendations proposed in Chapter 5.

3. Research methods

This study investigates transaction costs associated with NZEB in China by developing a systematic analytical framework and a set of targeted mitigation strategies. The research is structured into four sequential stages, as illustrated in Fig. 2.

1) Developing an analytical framework for NZEB transaction costs in China

This study first reviews the technical pathways, policy frameworks, certification systems, and stakeholder networks involved in implementing NZEB in China. Based on transaction cost theory, it develops an analytical framework and corresponding mitigation strategies. This framework provides theoretical support and classification dimensions for the subsequent empirical research (see Section 2.1–2.3).

2) Identifying transaction costs in NZEB implementation in China

Using the above framework, 23 experts with practical experience in NZEB projects were invited to participate in semi-structured, in-depth interviews to collect primary data (see Section 3.1.2). The interview

Table 3
Determinants of transaction costs in NZEB implementation.

Determinant	Secondary Determinant	Reason	NZEB-Related Content	Involved Stages	Type	References
Asset Specificity	Expertise	Insufficient skills and training	Learning NZEB design processes and equipment maintenance techniques	DP, OP	Due diligence	[23,63]
		Need for high-level technical support	Proposing NZEB performance simulation optimization and construction techniques (e.g., high-performance windows, insulation, airtightness)	DP, CSP	Due diligence	[11,28,28]
	Specific Information	Lack of certification and partner information	Searching for partners with NZEB experience	CP, DP, CSP, OP	Information Search Costs	[64–66]
		Lack of information on NZEB materials and equipment	Searching for compliant NZEB materials and equipment	CSP	Information Search Costs	[11,67]
		Complex policy information	Searching for NZEB incentive policy information	CP	Information Search Costs	[7,18]
	Specific Contracts	Lack of standard contracts	Negotiating contracts for NZEB consulting, design, construction, materials, and operations management	CP, DP, CSP, OP	Negotiation costs	[5]
		Opportunistic behavior by collaborators	Monitoring the execution of NZEB consulting, design, construction, materials, and operations management contracts	CP, DP, CSP, OP	Monitoring and enforcement costs	[68]
	Professionals	Searching for professional partners	Finding NZEB-experienced consulting firms, designers, and other partners	CP, DP, CSP, OP	Information Search Costs	[69,70]
	Specific Project Requirements	Feasibility studies	Conducting feasibility studies for NZEB projects	CP	Due diligence	[5,71]
		Communication about land bidding requirements	Negotiating land requirements for NZEB projects	CP	Negotiation costs	[33]
		Financing communication	Negotiating green finance applications with financial institutions	CP	Negotiation costs	[5]
Uncertainty	Behavioral Uncertainty	Avoiding liability transfer	Reviewing design drawings before construction	DP, CSP	Negotiation costs	[72]
		Complex construction procedures and methods	Performance testing of NZEB materials and equipment	CSP	Monitoring and enforcement costs	[65]
		Dispute resolution	Resolving disputes during construction	CSP	Negotiation costs	[28]
	Technological Uncertainty	Additional testing/ inspection of materials and equipment	Quality inspection during construction processes	CSP	Monitoring and enforcement costs	[73–75]
		Communication for new technology integration	Communicating complex NZEB processes	DP, CSP, OP	Negotiation costs	[76]
		Complex approval processes	Communicating for NZEB evaluation and certification	DP, CSP, OP	Negotiation costs	[77]

Concept Stage: CP, Design Stage: DP, Construction Stage: CSP, Operation Stage: OP.

Table 4
Summary of transaction cost mitigation strategies based on international practice.

Determinant	Subcategory	Strategy & Tool Example	Effect (Mechanism)	Countries and regions involved	Source
Asset Specificity	Expertise	Standardized training (e.g., PHI, BUILD UP Skills)	Reduces technical asymmetry and initial learning cost, improves efficiency and credibility	Germany, European Union	[78–80]
	Specific Information	Centralized NZEB/BIM databases (SPHERE, Passive House DB)	Reduces information incompleteness and search costs	Germany, European Union	[78,79]
	Specific Contracts	Standardized/IPD contracts	Reduces repeated negotiation costs, prevents opportunism, and improves contract execution	Australia; Finland; Malaysia; Norway; Sri Lanka; UK; USA	[81–84]
	Professionals	Platform-based expert recruitment (PROF/TRAC)	Precisely match expertise needs, reduce search and screening costs	European Union	[78,80]
	Specific Project Requirements	Feasibility tools, performance simulation	Improve early decision efficiency, reduce indirect transaction costs caused by redesign	Australia; Serbia	[85,86]
Uncertainty	Behavioral Uncertainty	Relational governance, IPD contracts, multi-party profit sharing	Enhance trust relationships and shared responsibility, reduce monitoring and dispute resolution costs	Australia; Finland; Malaysia; Norway; Sri Lanka; UK; USA	[87–89]
	Technological Uncertainty	Digital review systems (LEED Online, INNOVance, BIM–Green Building Index)	Real-time review feedback avoids inefficient coordination and rework	Italy; Malaysia; USA	[81,90,91]
	Policy/External Uncertainty	Risk-driven governance models	Flexibly respond to external institutional changes, reduce renegotiation and compliance costs	China; Iran; Pakistan	[92–94]

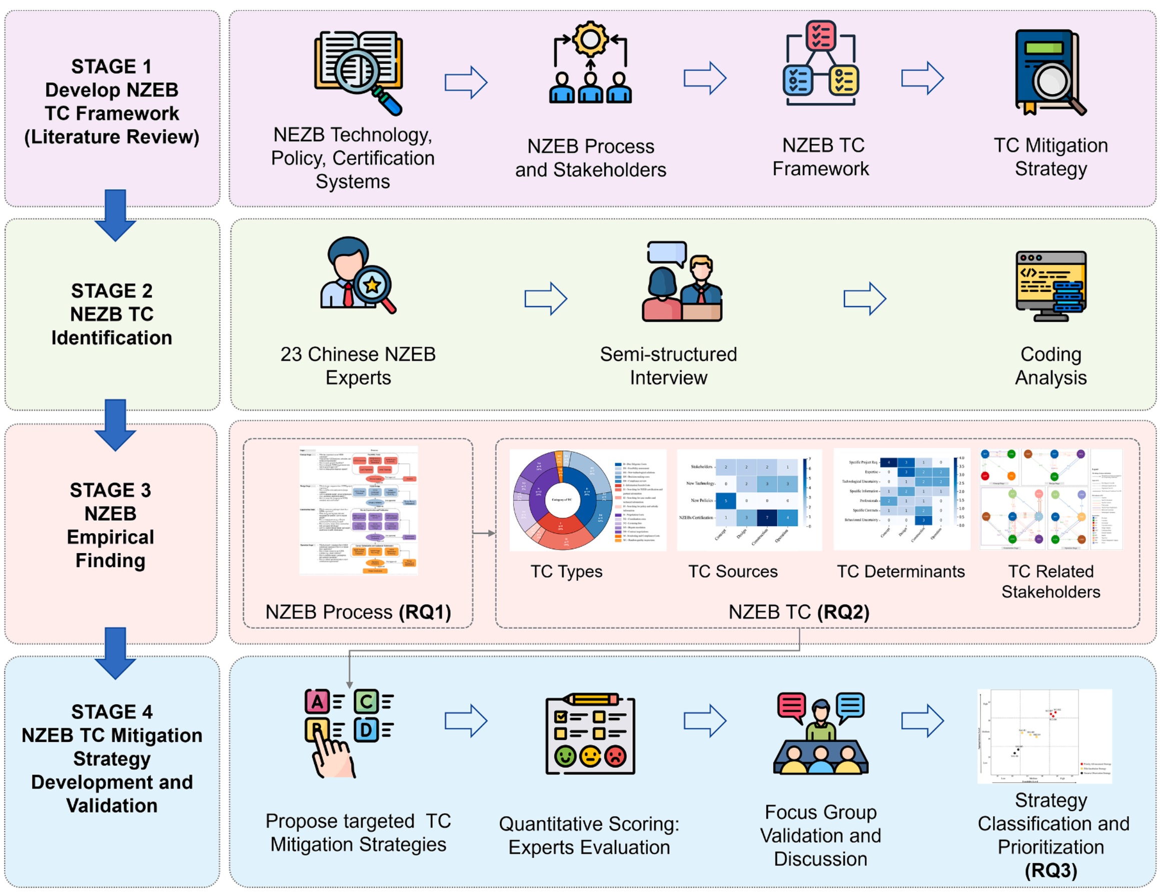

Fig. 2. Research framework.

transcripts were then coded using Atlas.ti to systematically identify the major types and components of transaction costs involved in the implementation of NZEB in China (see Section 3.1.3).

3) Empirical findings on transaction costs

Based on the coding analysis, the findings are presented in four dimensions: key transaction cost types, specific sources, determining factors, and associated stakeholders, synthesizing transaction cost bottlenecks that constrain the implementation of NZEB in China (see Section 4).

4) Strategy formulation and validation

In response to the four identified bottlenecks, the study builds on transaction cost mitigation strategies and international practices (see Section 2.4) to propose a set of targeted strategies. These strategies were then validated and refined through expert scoring and a focus group discussion (see Section 3.2). Based on the quantitative scores and expert input, the strategies were subsequently categorized and prioritized according to their applicability and feasibility (see Section 5).

3.1. NZEB transaction costs identification

This study aims to examine the distribution, sources, and determinants of transaction costs among stakeholders across different stages of NZEB implementation in China. This study adopts a qualitative, interpretivist paradigm [95] and employs an inductive approach to analyze data from government documents, industry reports, and semi-structured interviews. This approach is suitable for contexts where stakeholder perspectives are critical but existing understanding remains limited [96]. We systematically code and conduct thematic analysis of the data to identify major transaction costs in the concept, design, construction, and operation stages, including their types, involved stakeholders, sources, and determining factors.

3.1.1. Sampling strategy

We used a non-probability snowball sampling method to recruit experts with experience in NZEB. Since NZEB is still in the early stages of promotion in China and practitioners are relatively dispersed, we first contacted professionals who had presented at the “China Passive House Designers Conference” and asked them to recommend other experts. Our goal was to ensure technical expertise while capturing a diverse sample of interviewees. We invited professionals from various sectors, including developers, consultants, design companies, general contractors, supervisors, suppliers, property management companies, government, and financial institutions. We prioritized experts with at least five years of experience in NZEB and a deep understanding of project management or technical solutions.

Given the significant climatic variation across China, we did not use the project location as a primary criterion for sampling. Instead, we focused on experts who had participated in or overseen NZEB projects across various climate zones and building types. We aimed to include experts with experience in cold regions, hot summer–cold winter zones, and temperate areas, covering both residential and public buildings. To ensure data relevance, we applied two selection criteria for interviewees: (1) they represented all major stakeholder groups involved in NZEB implementation; (2) they reflected diversity in organizational level and functional roles, ranging from frontline practitioners to senior decision-makers (e.g., technicians and managers). In addition, all participants had experience with multiple projects, each exceeding 10,000 square meters in floor area.

Initially, we approached 35 candidates, and 23 experts agreed to participate, meeting our criteria, as shown in Table 5. About 70% of them had served or were serving on expert panels at the national, provincial, or municipal level, with an average of over ten years of industry experience. As interviews progressed, information began to repeat, indicating that theoretical saturation had been reached.

3.1.2. Data collection

Before the formal interviews, we conducted two pilot interviews to test the interview protocol. These pilots helped refine question clarity and identify potential issues related to interview length and audio recording. To simplify participants’ understanding of the abstract concept of “transaction costs,” we followed previously established interview methods for transaction cost studies and rephrased technical terms into more accessible language [33]. For example, we avoided using the term “transaction costs” directly and instead asked, “What additional costs or burdens did these activities create?” and “What were the main difficulties you encountered?” This approach encouraged participants to reflect on their own project experiences and describe the transaction costs associated with information searching, communication, negotiation, and supervision.

The formal interviews consisted of three parts: 1) Implementation process and stakeholder collaboration. We inquired about the project’s background, key activities, and decision points at each stage (concept, design, construction, and operation), as well as interactions among stakeholders; 2) Distribution of transaction costs. This section examined the additional time, effort, and resources invested by stakeholders, as well as their subjective experiences; and 3) Types, sources, and determinants of transaction costs. Participants described the specific activities that created these “additional burdens” and explained their underlying causes (e.g., asset specificity, behavioral uncertainty). Each interview lasted between 45 and 60 min. Between January and February 2025, we conducted 23 formal interviews. The interview protocol was reviewed and approved by the Human Research Ethics Committee (HERC) of the authors’ institution. All interviews were audio-recorded and transcribed with the participants’ consent.

3.1.3. Data analysis

After each interview, we transcribed the recordings and anonymized the content to ensure confidentiality. We imported the transcripts into Atlas. ti for coding and thematic analysis, following the three-stage method proposed by Williams and Moser [97].

In the first stage, open coding, we reviewed the transcripts and tagged statements related to “additional learning,” “collaboration

Table 5
Respondents information.

Stakeholder	No.	Type of Organization	Position	Degree	Working Year
Government	GOV1	Municipal Commission of Urban-Rural Development	Deputy Director	Bachelor	30
	GOV2	Municipal Commission of Urban-Rural Development	Director	Master	12
Consultant	CON1	NZEB Consulting Company	Director	Master	10
	CON2	NZEB Consulting Company	Manager	PhD	8
	CON3	NZEB Consulting Company	Chairman	PhD	28
Developer	DEV1	Real Estate Company	Deputy General Manager	Bachelor	18
	DEV2	Real Estate Company	Design Manager	Bachelor	16
	DEV3	Real Estate Company	Development Manager	Master	6
General Contractor	GC1	Construction Engineering Company	Deputy General Manager	Bachelor	21
	GC2	Construction Engineering Company	Project Manager	Master	14
	GC3	Construction Engineering Company	Crew Leader	Bachelor	29
Supplier	SUP1	High-performance Window Company	Sales Director	Bachelor	15
	SUP2	External Insulation Materials Company	Manager	Bachelor	9
	SUP3	Heat Recovery Ventilation System Company	Technical Director	Master	13
Property Management Company	PMC 1	Property Management Company	Manager	Bachelor	17
	PMC2	Property Management Company	Maintenance Technician	Bachelor	26
Design Company	DES1	Architectural Design Firm	Deputy Chief Architect	Bachelor	18
	DES2	Architectural Design Firm	Architect	Master	6
	DES3	Architectural Design Firm	Chief Architect	Master	11
Certification Body	CERT1	Certification Body	Manager	PhD	6
	CERT2	Certification Body	Technical Director	Bachelor	21
Financial Institution	FIN1	Regional Bank Branch	Deputy Branch Manager	Master	8
	FIN2	Regional Bank Headquarters	Director	Bachelor	10

difficulties," and "information search or negotiation coordination." We also captured content that aligned with or intersected the four analytical dimensions from the literature: type, source, determinant, and stakeholder role. We kept this stage open to identify new themes or phenomena beyond the existing literature. In the second stage, axial coding, we organized, merged, and compared initial codes, gradually mapping them to a predefined transaction cost framework that included 1) stakeholders; 2) types of transaction costs; 3) sources of transaction costs; and 4) determinants of transaction costs. In the third stage, selective coding, we integrated the transaction cost data and clustered, compared, or merged different types and sources of costs to develop core themes that directly addressed the research questions. This stage also involved comparing perspectives across stakeholder groups to identify the drivers of key transaction costs and to uncover feasible strategies for addressing them.

Throughout the coding process, we used color labels and annotations to differentiate between roles, including developers, consultants, and government officials. We repeatedly reviewed codes after each interview to ensure accuracy and confirmed theoretical saturation when no new information emerged. We resolved discrepancies in code interpretation through internal discussions or double-coding checks to reduce bias and ensure consistency. This process enabled us to develop a classification framework for NZEB-related transaction costs, which supports the interpretation of findings and the formulation of policy recommendations.

3.2. Development and validation of mitigation strategies

To convert the NZEB transaction cost bottlenecks identified in Section 4 into actionable solutions, this section follows four sequential steps:

(1) Strategy formulation

Building on transaction cost mitigation strategies identified in the literature, as well as international NZEB and sustainable building practices, we formulated a set of targeted strategies to address transaction cost bottlenecks. We focused on completeness and cross-contextual applicability, ensuring that each measure works both in theory and in practice.

(2) Rationale for validation

To assess the potential for large-scale adoption, we selected appropriateness and feasibility as the primary evaluation criteria [98,99]. These indices have proven effective in distinguishing between high- and low-adoption strategies. According to the latest ERIC/SISTER report, strategies that score high on both indices deserve to be prioritized. At the same time, those with low feasibility often fail to scale, even if theoretically important [100].

(3) Expert Scoring and Focus Group Discussion

On June 12, 2025, we selected 12 participants from the 23 experts interviewed in the first round, ensuring representation across 9 stakeholders: government (GOV1, GOV2), designer (DES1), construction (GC1), consultant (CON3, CON2), suppliers (SUP3, SUP1), certification body (CERT2), Property Management Company (PMC2), developer (DEV1), and Financial Institution (FIN2).

The expert team applied the four IAM and FIM scales [99], along with a five-point Likert scale (1 = strongly disagree; 5 = strongly agree), to assess each strategy's appropriateness and feasibility in mitigating transaction-cost bottlenecks. Previous studies have confirmed the reliability and validity of these scales across multiple domains [101–104]. This assessment aimed to examine the implementation potential of each strategy in the Chinese context. To ensure scoring consistency, all experts attended a calibration meeting led by the research team before formal scoring. We demonstrated examples and held group discussions to standardize criteria and resolve ambiguities [105].

After scoring, the research team calculated each strategy's mean and standard deviation on both Appropriateness and Feasibility and tested internal consistency using Cronbach's α (all scales $\alpha \geq 0.75$).

After completing the scoring, we held a focus group to classify strategies into "Priority Advancement Strategies," "Pilot Incubation Strategies," and "Reserve Observation Strategies," and analyzed the main factors driving score differences among categories and proposed optimized implementation paths and supporting measures.

4. NZEB implementation process and transaction costs

4.1. Multi-stage implementation process of NZEB in China

Fig. 3 illustrates the four key stages—concept, design, construction, and operation—identified in the practical implementation of NZEB projects in China. Based on empirical evidence, this figure outlines the stakeholder collaboration and tasks undertaken during the implementation process of NZEB in China.

Concept Stage: At this stage, developers must decide whether to adopt NZEB. A limited understanding of incentive policies, technical options, and payback periods, combined with regional variations in policy and technology, complicates the decision-making process. To address this, developers often hire consultants with local expertise to support information gathering, policy analysis, and the evaluation of technical and financial feasibility, which informs decisions and financing.

"…Local consulting teams usually maintain close ties with municipal governments, which helps developers access policy incentives more easily." (Developer, DEV3, January 10, 2025).

Design Stage: Due to NZEB's high-performance standards, developers must seek experienced design companies that meet certification requirements through accurate energy modeling. However, regional variations in NZEB technical standards increase the complexity of the design process. Firstly, consultants must help developers select suitable companies and guide them through energy simulations, focusing on airtightness and thermal bridge design. Then, developers, consultants, and design companies must work closely to prepare the required documentation for the design certification process. At the same time, consultants must also handle compliance checks, process supervision, and communication with certification bodies to ensure that the final design meets the required standards.

"…Energy requirements vary across climate zones, and so do the technical solutions. We constantly need to optimize the design to meet the specific standards" (Design Company, DES2, January 15, 2025).

Construction Stage: Building NZEB requires high-performance materials and construction techniques that are significantly more complex than those used in conventional projects. Furthermore, the continuous supervision and strict inspection requirements of certification bodies further challenge the construction process. To address this, developers often rely on consultants and supervisors to select qualified contractors and suppliers, as confirmed by on-site evaluations. To meet NZEB certification requirements, contractors must document key components of the building envelope and collaborate with consultants and supervisors to prepare the necessary materials. If problems arise during certification, the certification body provides feedback and coordinates adjustments to ensure final compliance.

"…We lack expertise in NZEB, and since we do not have a direct contract with the consultants, we rely on the developer to coordinate their involvement in the construction process" (General Contractor, GC1, January 17, 2025).

Operation Stage: NZEB relies heavily on system coordination and the integrity of the building envelope, while user behavior also significantly affects energy performance. Developers usually hire property management companies with experience in high-performance building operations to achieve long-term energy-saving goals and ensure efficient system performance. In addition to regularly training users to operate energy control systems correctly and develop energy-saving habits, these companies also need to collaborate with equipment suppliers to learn maintenance and repair procedures, enabling them to respond

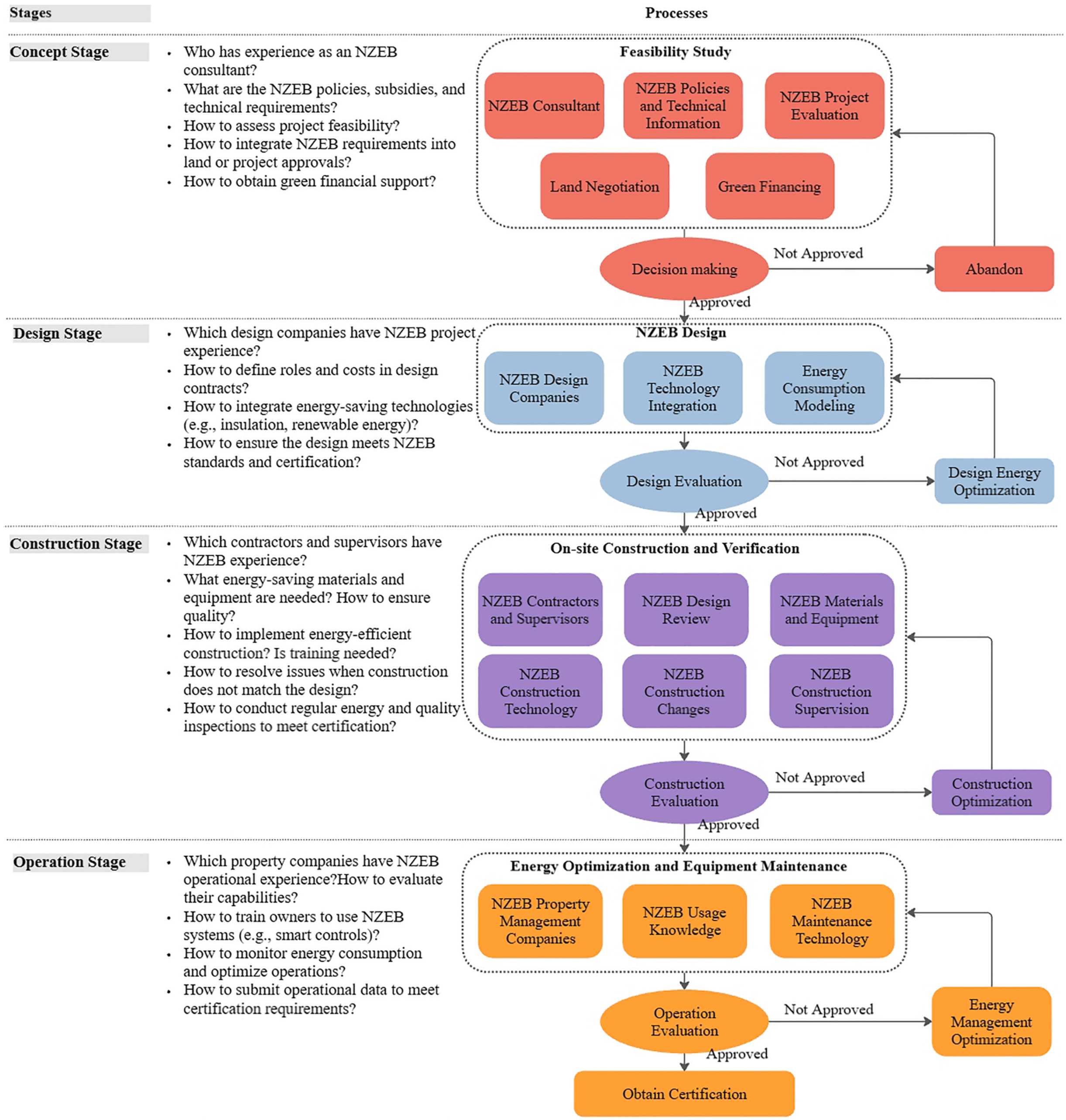

Fig. 3. The NZEB implementation process in China found in practice.

promptly to potential failures. During the operational certification process, developers and property managers submit performance data and maintenance records to the certification body, then adjust operational strategies based on evaluations to maintain compliance and retain certification.

"…We place energy-saving reminders near equipment switches and promote awareness to influence user behavior" (Property Management Company, PMC2, February 3, 2025).

4.2. *Transaction costs in NZEB implementation in China*

Based on the systematic coding of interview data, this study identifies 36 transaction costs arising from stakeholder collaboration at different stages of NZEB implementation in China. Table 6 presents the detailed distribution of these 36 transaction costs across the four stages of NZEB. It explains the types, sources, and determinants of these transaction costs, as well as the stakeholders involved at each stage.

4.2.1. *Types of transaction costs in NZEB implementation*

Fig. 4 presents the frequency and proportion of four major categories and twelve subcategories of transaction costs identified during the implementation of NZEB. Among the major categories, due diligence costs (D) appeared most frequently, with 14 times (39% of the total), followed by negotiation costs (N), with 12 times (33%). At the subcategory level, the cost of new technical solutions (D2) and searching for NZEB certification and partner information (I1) appeared 7 times, ranking highest. The cost of new technical solutions (D2) primarily includes technical learning efforts and the negotiation or communication costs incurred due to plan modifications during the design, construction, and operation stages. In addition, the cost of searching for NZEB certification and partner information (I1) refers to transaction costs incurred when collecting detailed data on certification requirements and

Table 6
Verified transaction costs in the implementation process of NZEB in China.

Stage	Specific transactions under each determinant	TC type	TC determinant	TC source
Concept Stage	TC1 Searching for experienced consultants	I2 Searching for partner information	Professionals	NZEB Consultation
	TC2 Signing consultancy contracts	N4 Contract negotiation	Specific Contracts	NZEB Consultation
	TC3 Policy search	I4 Searching for policy and subsidy info	Specific Information	NZEB Policies and Technical Info
	TC4 Feasibility Assessment	D1 Feasibility assessment	Specific Project Requirements	NZEB Solution Evaluation
	TC5 Decision-making costs	D3 Decision-making costs	Specific Project Requirements	NZEB Solution Evaluation
	TC6 Compliance review	D4 Compliance review	Specific Project Requirements	NZEB Solution Evaluation
	TC7 Land bidding	N2 Licensing fees	Specific Project Requirements	Land Negotiation
	TC8 Financing	N4 Contract negotiation	Specific Project Requirements	Green Financing
Design Stage	TC9 Searching for experienced design companies	I2 Searching for partner information	Professionals	Experienced Design Company
	TC10 Drafting design contracts	N4 Contract negotiation	Specific Contracts	Experienced Design Company
	TC11 Design-technology training for energy-oriented design	D2 New technical solutions	Expertise	NZEB Technical Integration
	TC12 Performance simulation	D2 New technical solutions	Expertise	Energy Simulation
	TC13 Information on design evaluation requirements	I1 Searching for specifications and certification requirements	Specific Information	Design Evaluation
	TC14 Preparation and confirmation of design evaluation documents	D4 Compliance review	Specific Project Requirements	Design Evaluation
	TC15 Communication of design evaluation information	N1 Coordination costs	Technological Uncertainty	Design Evaluation
Construction Stage	TC16 Searching for experienced partners	I2 Searching for partner information	Professionals	Experienced NZEB Contractors and Supervisors
	TC17 Partner contract negotiation	N4 Contract negotiation	Specific Contracts	Experienced NZEB Contractors and Supervisors
	TC18 Construction instructions	N3 Dispute resolution	Behavioral Uncertainty	Drawing Reviews
	TC19 Material and equipment selection	I3 Searching for case studies and technical information	Specific Information	NZEB Materials and Equipment
	TC20 Material and equipment contract negotiation	N4 Contract negotiation	Specific Contracts	NZEB Materials and Equipment
	TC21 Demonstrating construction processes	D2 New technical solutions	Expertise	NZEB Construction Techniques
	TC22 Construction process optimization	D2 New technical solutions	Expertise	NZEB Construction Techniques
	TC23 Change and dispute resolution	N3 Dispute resolution	Behavioral Uncertainty	NZEB Construction Changes
	TC24 Construction monitoring	M1 Random quality inspection	Behavioral Uncertainty	NZEB Construction Monitoring
	TC25 Collecting inspection results during construction	D4 Compliance review	Technological Uncertainty	NZEB Construction Monitoring
	TC26 Information on construction evaluation requirements	I1 Searching for specifications and certification requirements	Specific Information	NZEB Construction Evaluation
	TC27 Preparation and confirmation of construction evaluation documents	D4 Compliance review	Specific Project Requirements	NZEB Construction Evaluation
	TC28 Construction evaluation review	N1 Coordination costs	Technological Uncertainty	NZEB Construction Evaluation
Operation Stage	TC29 Searching for experienced property management companies	I2 Searching for partner information	Professionals	NZEB Property Management Company
	TC30 Training on NZEB building usage	D2 New technical solutions	Expertise	NZEB Usage Knowledge
	TC31 Training on NZEB building maintenance	D2 New technical solutions	Expertise	NZEB Maintenance Techniques
	TC32 Energy consumption optimization	D2 New technical solutions	Expertise	NZEB Maintenance Techniques
	TC33 Information on operational evaluation requirements	I1 Searching for specifications and certification requirements	Specific Information	Operation Evaluation
	TC34 Preparation and confirmation of operational evaluation documents	D4 Compliance review	Specific Project Requirements	Operation Evaluation
	TC35 Operational evaluation review	N1 Coordination costs	Technological Uncertainty	Operation Evaluation
	TC36 Certification communication	N1 Coordination costs	Technological Uncertainty	Certification

Source: Based on in-depth interviews with 23 NZEB stakeholders.

potential collaborators, such as technical capacity, project experience, and product output. These costs tend to be high, as the information is scattered across multiple sources and rarely supported by a centralized platform or standardized format.

"…Energy modeling requires repeated adjustments for different climate zones, which makes this technical task highly resource-intensive in the early project stage." (Consultant, CON2, January 17, 2025).

"…Every NZEB material and equipment supplier presents impressive marketing. However, we lack access to reliable information about their capabilities, forcing us to spend much time and money on-site visits." (Developer, DEV1, January 2, 2025).

4.2.2. *Sources of transaction costs in NZEB implementation*

Fig. 5 summarizes the number of transaction costs from four sources across the four stages of NZEB implementation. The number of transaction costs varies significantly across sources, with NZEB certification accounting for the most, totaling 15 items. These include 3 in the concept stage, 7 in the design stage, and 4 in the construction and operation stages. Certification-related costs span the design, construction, and operation stages, reflecting the comprehensive impact of NZEB certification throughout the project lifecycle. These transaction costs primarily arise from communication between designers and consultants regarding performance simulation, identifying certification requirements, preparing documentation, interacting with certification

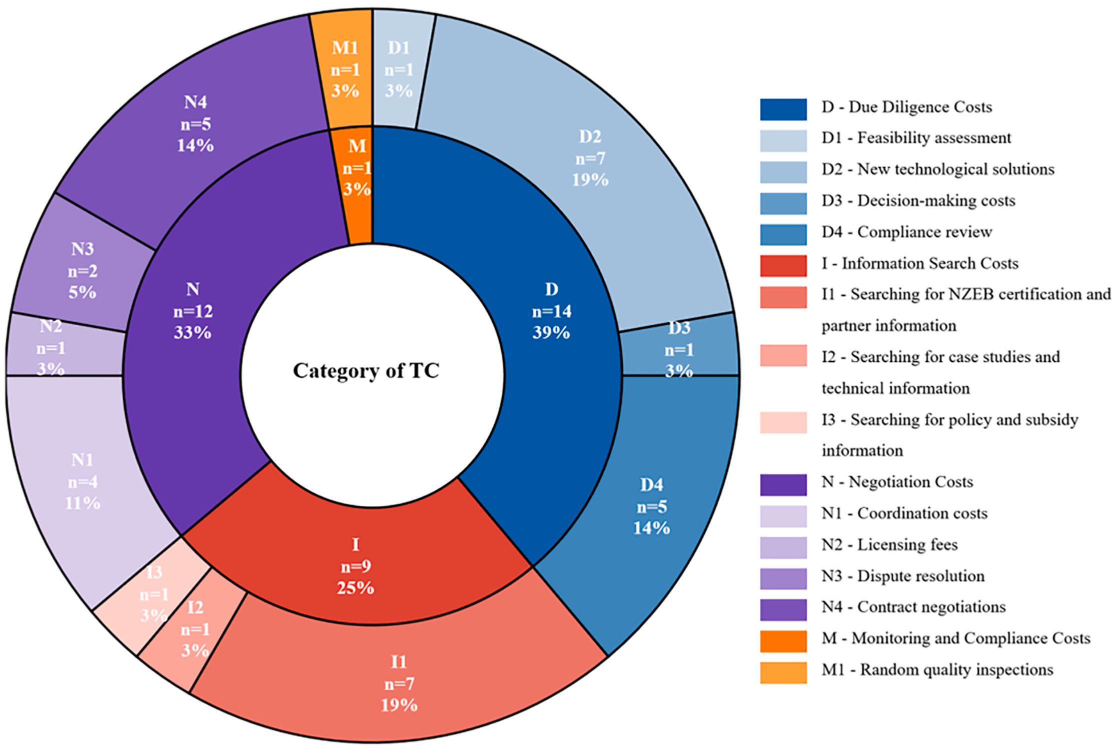

Fig. 4. Distribution of transaction cost types in NZEB implementation.

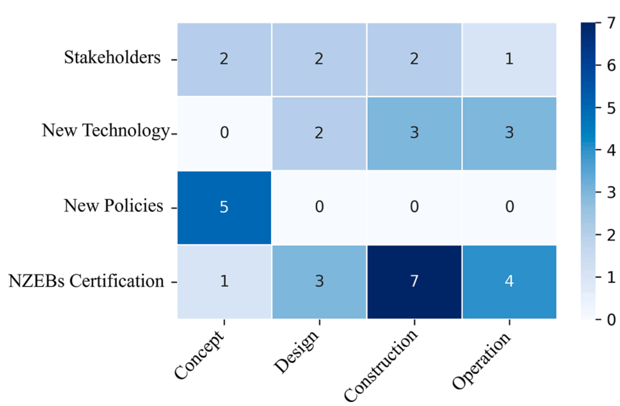

Fig. 5. Distribution of transaction cost sources in NZEB implementation.

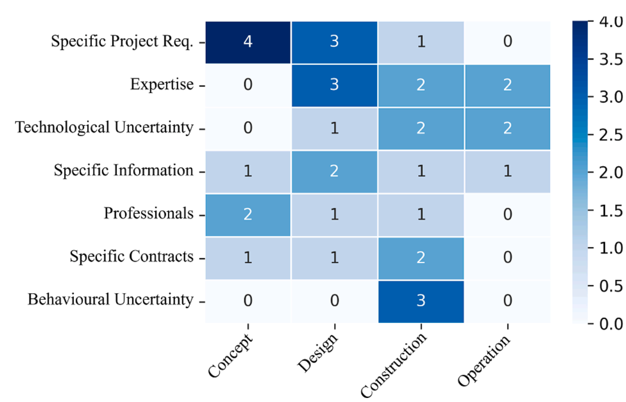

Fig. 6. Distribution of transaction cost determinants in NZEB implementation.

bodies, and the repeated review of submission materials by consultants. Due to non-standardized documentation, lack of technical guidance and binary "pass/fail" certification feedback mechanism, frequently resulting in repeated rework and further increasing the transaction burden on stakeholders.

"…NZEB certification in China affects every project stage. We spend a huge amount of time and energy gathering stage-specific requirements and repeatedly coordinating the certification process to ensure final approval." (Developer, DEV2, January 4, 2025).

4.2.3. Determinants of transaction costs in NZEB implementation

Fig. 6 summarizes the number of transaction costs associated with seven determinants across the four stages of NZEB implementation. Specific project requirements and expertise emerged as the main determinants associated with 8 and 7 transaction costs, respectively. Transaction costs triggered by specific project requirements mainly occur in the early stages—concept and design—such as feasibility assessments (TC4), land bidding (TC7), and Preparation and confirmation of design evaluation documents (TC14). Transaction costs driven by expertise are evident across the design, construction, and operation stages, indicating that NZEB requires high technical competence from stakeholders throughout the implementation process, resulting in high learning costs.

4.3. Stakeholder collaboration in NZEB projects based on transaction costs

Transaction costs show stakeholder interactions across different stages of NZEB implementation. Based on the results provided in the appendix (Table A1), we developed an interaction diagram of stakeholder relationships based on transaction costs, as shown in Fig. 7. Each stakeholder is represented as a node, with different types of transaction cost determinants distinguished by color and labels on the connecting lines. Arrows point from the stakeholders bearing the transaction costs to the stakeholders associated with those costs.

Fig. 8 builds on the results presented in Fig. 7 and displays a chord

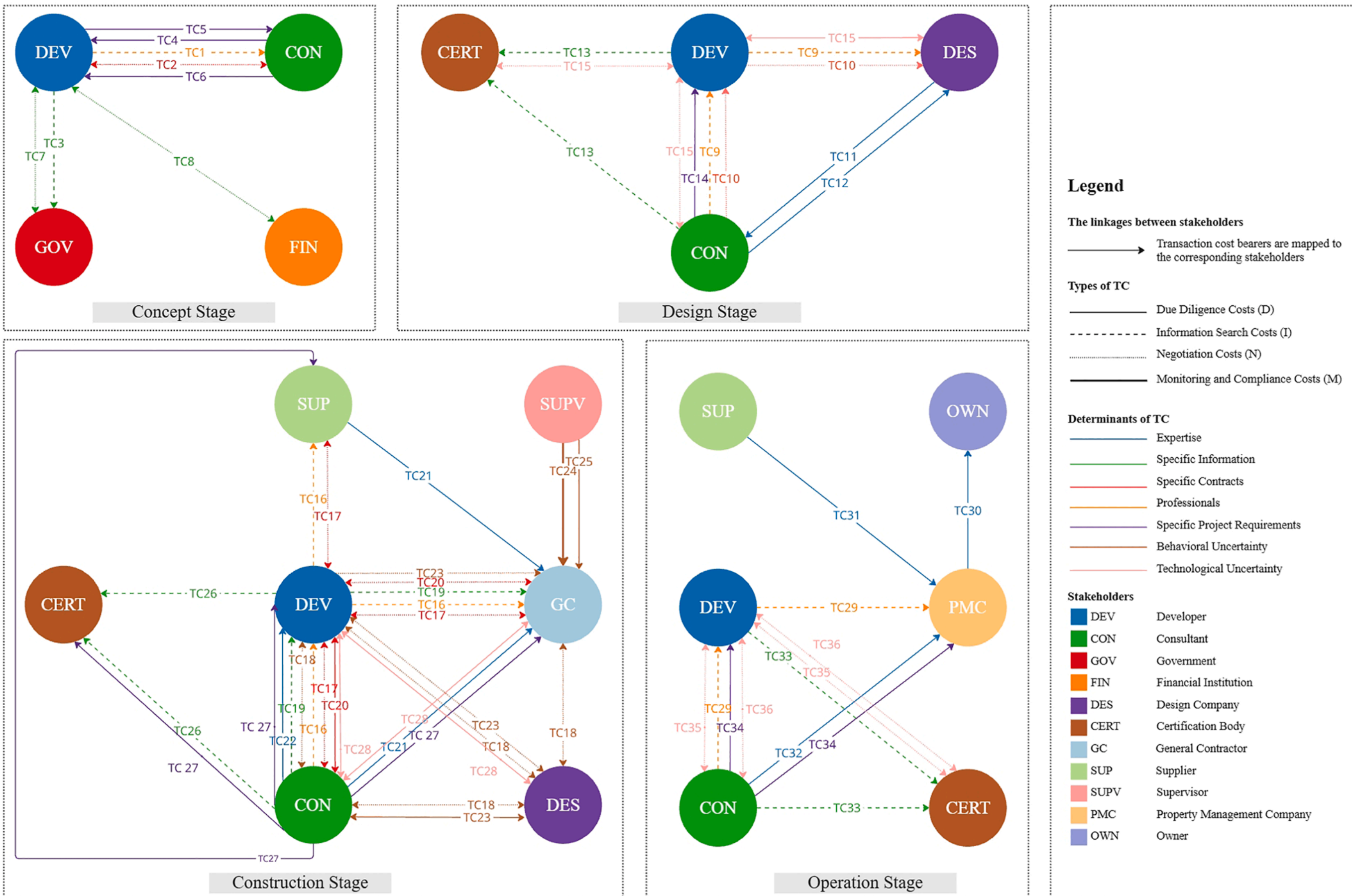

Fig. 7. Interactive stakeholder relationships based on transaction costs.

diagram illustrating the distribution of transaction costs among stakeholders involved in NZEB implementation. Each stakeholder group occupies a sector on the circle, with colors representing different actor types (e.g., blue for developers, red for government agencies, and orange for financial institutions). Chords connecting the sectors represent transaction costs arising between stakeholders during NZEB implementation. The width of each chord indicates the number of transaction costs. The diagram shows that developers are the stakeholders involved in the most transaction costs. In particular, transaction costs between developers and consultants total 18, significantly higher than those between other stakeholder pairs. Due to information asymmetry, developers are compelled to engage in repeated consultant selection and contract negotiations. In addition, under the design-bid-build (DBB) model, where consultants are contracted solely by developers and lack formal authority over other stakeholders, weak contractual constraints force developers to assume responsibility for extensive coordination with consultants, design companies, and contractors. This fragmented structure also contributes to cross-stage collaboration failure, as the contractual and operational disconnect between the design and construction stages often leads to misalignment and increased coordination efforts throughout the project lifecycle.

"…Due to the contract model of construction projects in China, consultants and design companies do not have direct contracts with contractors. As a result, any advice we give must go through the developer to be accepted by the design firm or contractor." (Consultant, CON1, January 17, 2025).

"…During the selection of passive doors for a project in Shandong, the consultant strongly recommended a brand they had long collaborated with, citing its compliance with NZEB energy performance standards and cost-effectiveness. However, we felt that the process lacked transparency, so we spent considerable time conducting an on-site inspection of the manufacturer. What we ultimately found was that its production capacity was insufficient to meet the project's requirements. In the end, we selected an additional supplier to supplement the shortfall." (Developer, DEV2, January 4, 2025).

5. Mitigation strategies for transaction cost bottlenecks

Based on the coding result of transaction cost types, sources, determinants, and associated stakeholders, combined with their frequency distribution, this study identified bottlenecks, including: information asymmetry risk (B1), dispersed information sources (B2), weak consultant contractual constraints (B3), repeated rework (B4), lack of technical guidance and binary "pass/fail" certification feedback mechanism (B5), non-standardised documentation (B6), high learning costs (B7) and cross-stage collaboration failure (B8). For each specific bottleneck, we matched empirically validated interventions from international NZEB and sustainable building programs to ensure both practical operability and cross-context transferability, and then validated them by expert scoring and focus group discussions.

5.1. Empirical evaluation

Table 7 summarizes descriptive statistics for eight strategy–bottleneck pairs across two key indices: appropriateness and feasibility. All items demonstrated high internal consistency, with Cronbach's α ranging from 0.78 to 0.89 for appropriateness and from 0.76 to 0.91 for feasibility, indicating strong scale reliability. In terms of mean scores, the "Authoritative NZEB Data Platform" (SC1) ranked highest in both appropriateness ($M = 16.33$, SD = 1.87) and feasibility ($M = 17.42$, SD

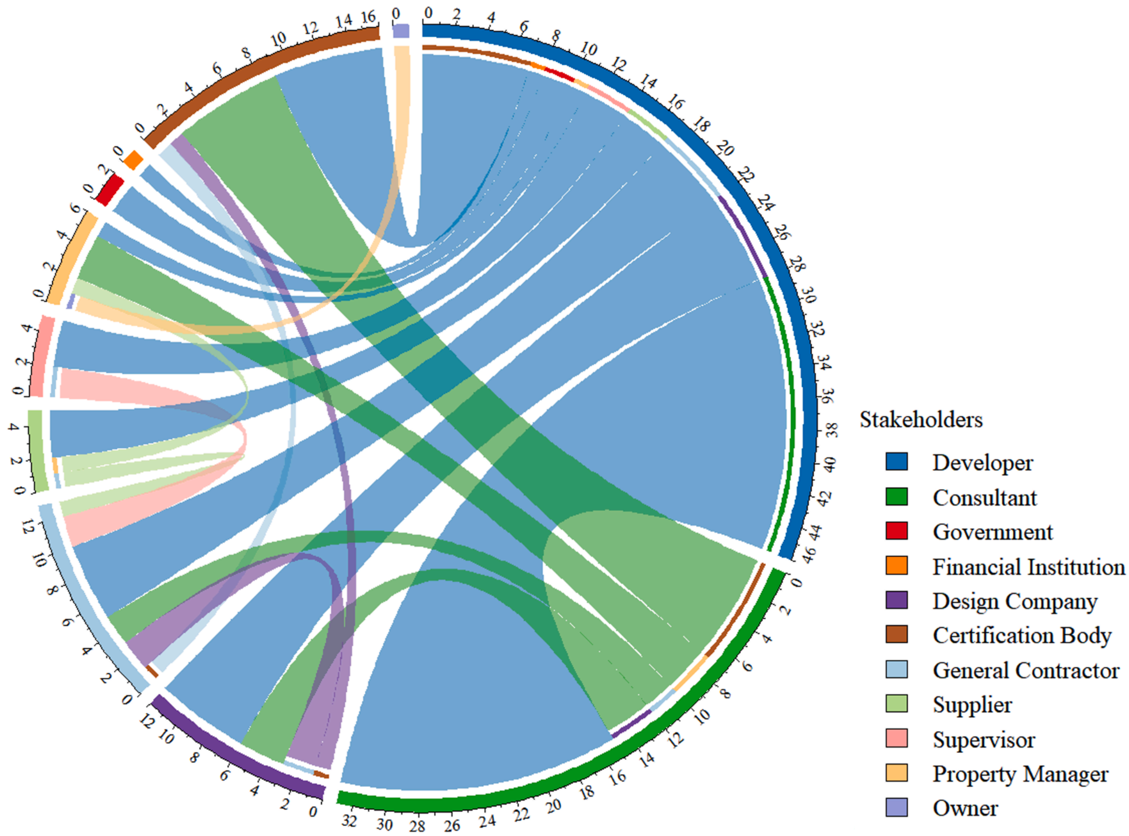

Fig. 8. Chord diagram of transaction cost–based relationships among NZEB stakeholders.

= 2.21), suggesting it is broadly perceived as both actionable and worthwhile—a clear implementation priority. In contrast, the IPD approach for addressing information asymmetry (SA1, C1a) received the lowest scores on both dimensions (appropriateness $M = 14.25$; feasibility $M = 12.58$), indicating that this strategy requires further refinement for effective application in the Chinese context. Using the empirical thresholds of μ ± 1σ (appropriateness: 14.58 / 16.13; feasibility: 13.05/ 16.97) [106], strategies were classified into three tiers: low, medium, and high.

5.2. Focus group validation

After completing the dual-dimensional evaluation of eight strategy–bottleneck combinations (see Table 8) and categorizing them into low, medium, and high tiers based on $\mu \pm \sigma$ thresholds. This allowed us to integrate the quantitative findings with qualitative insights drawn from a focus group ($n = 12$ experts from government, development, and research sectors). We first cross-classified strategies based on their appropriateness and feasibility scores, generating three levels of implementation priority: Priority Advancement, Pilot Incubation, and Reserve Observation. Then, drawing on expert commentary regarding legal and fiscal support, technology readiness, and organizational capacity thresholds, we annotated each strategy's implementation path, enabling conditions, and potential risks. This matrix preserves the objectivity and comparability of quantitative scoring while embedding contextualized operational insight. It enables policymakers and project owners to make evidence-based decisions when resources are limited, helping them rapidly identify which NZEB transaction cost mitigation strategies are ready for immediate deployment, suitable for small-scale piloting, or require long-term observation.

We conducted a two-dimensional evaluation of eight strategy–bottleneck combinations (see Table 8) and classified them into low, medium, and high tiers based on the $\mu \pm \sigma$ threshold. We then integrated the quantitative results with qualitative insights from a focus group ($n = 12$) comprising experts from government, development, and research sectors. First, we cross-classified each strategy based on suitability and feasibility scores to define three levels of implementation priority: immediate deployment, pilot incubation, and deferred observation. Next, based on expert commentary on legal and financial support, technological maturity, and organizational capacity thresholds, we identified implementation pathways, enabling conditions, and potential risks for each strategy. This matrix preserves the objectivity and comparability of the quantitative scores. Additionally, it incorporates context-specific operational insights. These features help policymakers and project leads, especially under resource constraints, quickly identify which NZEB transaction cost mitigation strategies are ready for immediate deployment, suitable for small-scale pilots, or require long-term observation.

6. Discussion

6.1. Transaction cost bottlenecks in China's NZEB

6.1.1. Developer–consultant collaboration: rising costs from information asymmetry and institutional constraints

As shown in Section 4.3, the findings indicate that developers, as project initiators, bear the highest level of transaction costs (Fig. 8). This finding is consistent with research on prefabricated buildings [33], which shows that developers invest substantial resources in contract drafting, monitoring partner performance, and selecting qualified collaborators. Developers heavily depend on consultants, yet they must also be cautious of them. This guard has resulted in significant transaction costs in managing information and coordinating efforts. This result is surprising as it contrasts with previous findings suggesting that developers hire consultants to solve technical issues and reduce transaction costs [107,108].

Table 7
Descriptive statistics of appropriateness and feasibility ratings for internationally derived NZEB transaction cost mitigation strategies.

Strategy ID	Strategy	Bottleneck ID	Bottleneck Description	n	Mean (Appropriateness)	SD (Appropriateness)	α (Appropriateness)	n	Mean (Feasibility)	SD (Feasibility)	α (Feasibility)
SA1	IPD	B1	Information asymmetry risk	12	14.25	2.11	0.82	12	12.58	2.62	0.85
SA2	Profit-sharing incentive mechanism	B3	Weak consultant contractual constraints	12	14.33	2.19	0.83	12	12.83	2.73	0.84
SB1	Optimised recommendation feedback mechanism	B5	Lack of technical guidance & binary "pass/fail" certification feedback mechanism	12	15.17	1.93	0.78	12	14.42	2.12	0.91
SB2	Digital online certification platform	B4	Repeated rework	12	15.08	2.21	0.85	12	15.08	2.31	0.88
SC1	Authoritative NZEB database	B2	Dispersed information sources	12	16.33	1.87	0.79	12	17.42	2.21	0.81
SC2	Standardised templates + auto-validation	B6	Non-standardised documentation	12	16.17	1.96	0.89	12	17.33	2.47	0.87
SC3	Continuing-education training module (SC3)	B7	High learning costs	12	16.25	1.82	0.87	12	17.25	2.07	0.76
SA1	IPD(SA1)	B8	Cross-stage collaboration failure	12	15.25	1.91	0.86	12	13.17	2.59	0.85

First, the limited understanding of NZEB-related technologies, combined with complex policies and processes, constrains developers' decision-making under conditions of bounded rationality. Although developers hold a leading role in the project, they often face an information disadvantage when negotiating and collaborating with consultants. Consultants who possess specialized expertise enjoy significant informational advantages, which may lead to opportunistic behavior. In other words, during early-stage contract negotiations, consultants may prioritize suppliers or technical solutions that align with their interests rather than those that are most suitable for the developer [81]. To mitigate the risks associated with such information asymmetry, developers often hire third-party agencies to conduct independent assessments and verification, which significantly increases the costs of information search and monitoring.

Second, most NZEB projects in China employ the DBB contract model [109], which further intensifies transaction costs between developers and consultants. Under this model, consultants typically sign contracts only with developers and lack direct legal ties with other project participants, such as general contractors or suppliers. However, consultants still need to provide technical support and advice to those parties during project implementation. Without formal contractual authority, these stakeholders are often unwilling to follow the consultant's guidance, which disrupts information flow and execution. In response, developers must step in as coordinators between consultants and other stakeholders, frequently engaging in communication and mediation to ensure the project remains on track. This increases the developer's managerial workload and significantly raises coordination and monitoring costs during the implementation process.

6.1.2. NZEB certification system: essential yet a trial-and-error trap for stakeholders

Unlike the single-stage certification systems in the EU, Japan, and Australia, China's NZEB follows a multi-stage certification process designed to ensure compliance with technical standards and energy efficiency goals under the widely used DBB model [7,110]. However, as shown in Section 4.2.2, the study reveals that this critical component of NZEB implementation often traps stakeholders in trial-and-error cycles, resulting in substantial transaction costs and, in some cases, frustration or resistance among stakeholders.

First, the certification system lacks targeted guidance, forcing stakeholders to engage in a trial-and-error process during the design stage. Currently, China's NZEB certification primarily relies on final energy consumption outcomes but offers little systematic guidance tailored to different climate zones or building types [15]. As a result, design companies and consultants receive no clear direction. They can only rely on their own experience, repeatedly testing combinations of materials and systems to find a viable path toward meeting energy standards.

Second, the rigidity of the certification feedback mechanism increases stakeholders' trial-and-error costs. The current system relies on a binary "pass/fail" evaluation without offering targeted recommendations for improvement. This means that when a proposal fails to meet certification, applicants receive no concrete guidance for revisions and must instead rely on guesswork and repeated iterations to resubmit. This lack of informative feedback forces design and consulting teams into inefficient and repetitive trial-and-error cycles, thereby further increasing transaction costs. Moreover, the multi-stage certification process requires stakeholders to submit extensive documentation across the design, construction, and operation stages. Without clear guidance, this process often leads to redundant efforts. As Ohene et al. [5] have pointed out, complex certification procedures can reduce efficiency and discourage stakeholder engagement in the implementation of NZEB. While China's multi-stage certification system plays a key role in maintaining NZEB quality, its implementation is often hindered by a cumbersome process, limited guidance, and an inefficient feedback loop. These issues expose stakeholders to high trial-and-error costs and

Table 8
Empirical classification of internationally derived NZEB transaction cost mitigation strategies under the Chinese context.

Strategy ID	Strategy	Bottleneck ID	Bottleneck Description	Appropriateness	Feasibility	Priority Level	Expert Comments
SA1	IPD	B1	Information asymmetry risk	Low	Low	Reserve Observation	Given that China's Construction Law still mainly follows the DBB model and lacks insurance provisions and liability rules that support risk-sharing under IPD, experts believe that IPD cannot effectively reduce information asymmetry under the current system, and its mitigating effect remains limited. Therefore, they recommend postponing large-scale implementation. After the Regulation on Construction Project Insurance and related joint insurance mechanisms are implemented, pilot tests can be carried out on a small scale within EPC general contracting projects led by major central state-owned enterprises.
SA2	Profit-sharing incentive mechanism	B3	Weak consultant contractual constraints	Low	Low	Reserve Observation	Since profit-sharing calculations heavily depend on the transparency of consultants' data, China has not yet established standardized cost disclosure rules or contract templates. Experts believe this mechanism easily triggers opportunistic behavior and amplifies disputes, making it nearly impossible to address the issue of weak contractual constraints. Therefore, they recommend postponing large-scale adoption.
SB1	Optimised recommendation feedback mechanism	B5	Lack of technical guidance & binary "pass/fail" certification feedback mechanism	Medium	Medium	Pilot Incubation	Relying on hundreds of completed NZEB demonstration projects across different climate zones, it is possible to categorize energy-saving technology systems for different building types. Experts believe that developing an intelligent feedback recommendation engine based on the China Association of Building Energy Efficiency's certification database can partially address the lack of technical guidance during certification. Therefore, they recommend launching pilot programs in economically developed regions such as the Beijing-Tianjin-Hebei area and the Yangtze River Delta, where NZEB adoption is widespread.
SB2	Digital online certification platform	B4	Repeated rework	Medium	Medium	Pilot Incubation	The BIM review system in Shanghai has demonstrated that automated model checks can significantly reduce repeated revisions. However, discrepancies in data formats caused by multi-stage certification remain. Experts believe that a digital online certification platform can partially mitigate this bottleneck, provided that data standards are simultaneously improved. Therefore, they suggest conducting pilot implementations in economically advanced regions with widespread NZEB adoption and integrating with SC2.
SC1	Authoritative NZEB database	B2	Dispersed information sources	High	High	Priority Advancement	The China Green Building Materials Certification Platform and the NZEB project database maintained by the China Association of Building Energy Efficiency already provide a solid data and institutional foundation. Experts unanimously agree that establishing a unified and authoritative database would significantly consolidate fragmented information and directly ease current bottlenecks. They recommend prioritizing this strategy and accelerating the development of a "project-material-expert" data platform.

(continued on next page)

Table 8 (*continued*)

Strategy ID	Strategy	Bottleneck ID	Bottleneck Description	Appropriateness	Feasibility	Priority Level	Expert Comments
SC2	Standardised templates + auto-validation	B6	Non-standardised documentation	High	High	Priority Advancement	Experience from Shanghai's BIM review system shows that standardized templates combined with rule-based engines can reduce transaction costs caused by format inconsistencies. Experts find this approach highly effective in addressing issues with non-standard documentation and recommend immediate implementation.
SC3	Continuing-education training module	B7	High learning costs	High	High	Priority Advancement	Provincial housing authorities have initiated NZEB training programs, and online MOOCs and short videos can significantly lower the learning barrier for frontline workers. Experts conclude that this module effectively mitigates the high cost of learning. They suggest leveraging SC1 to build a national NZEB continuing education platform, integrating it into the credit systems for licensed architects and construction managers, and developing site-based demonstration courses to achieve scale efficiency.
SA1	IPD	B8	Cross-stage collaboration failure	Low	Low	Reserve Observation	IPD will restructure the current "multi-contract, multi-winner" profit distribution model, triggering stakeholder resistance and lacking provisions for cross-phase responsibility continuity. Experts believe it offers limited short-term relief for coordination failure. Therefore, they recommend postponing widespread implementation.

contribute to widespread frustration during the implementation process.

6.1.3. *Information constraints: lack of authority and certification templates*

As shown in Section 4.2.1, the cost of searching for NZEB assessment and partner information ranks among the highest categories of transaction costs, highlighting the difficulties stakeholders face in accessing certification information and identifying reliable partners. This finding aligns with Ohene's research on barriers to net-zero carbon buildings, which identifies limited access to information as a major reason for resistance among stakeholders [5]. This study further reveals that the absence of authoritative sources and standardized certification templates is a key driver of high information search costs.

First, NZEB projects require strict technical and material standards, prompting stakeholders to gather large volumes of information when selecting partners and products to ensure technical adequacy and material performance [28,107]. However, due to the lack of authoritative platforms, data on NZEB technologies, products, and case studies remain highly fragmented [5]. Besides, some suppliers may even exaggerate the performance or conceal the limitations of their products for marketing purposes. This information asymmetry forces developers to invest heavily in market research, site visits, and expert consultations to mitigate risk, thereby significantly increasing information searching costs. Additionally, China's multi-stage NZEB certification process requires extensive documentation but lacks transparent and standardized technical templates [7,48]. In this case, to avoid certification failures caused by incomplete or improperly formatted documents, stakeholders must invest significant time and resources in repeated communication with certification bodies to ensure compliance with submission requirements.

6.1.4. *Technical resistance: high learning costs and cross-stage coordination failures*

Based on the analysis in Section 4.2.3, this study finds that the advanced technologies required for NZEB create significant resistance among stakeholders, consistent with prior research [5,111]. However, unlike earlier studies that attribute this resistance to general technical barriers [5], this study examines its underlying causes from a transaction cost perspective, identifying high individual-level learning costs and failures in cross-stage technical coordination as the primary drivers.

Individual-level learning costs stem from the advanced technical requirements imposed by NZEB. As Ascione et al. [107,112] note, NZEB projects involve multiple interdisciplinary technologies, such as energy modeling, high-performance envelope construction, specialized window installation, and operational management, that demand integrated expertise. However, Chinese universities have not yet established systematic training programs tailored to NZEB, leaving many technical managers without the necessary skills to operate in this domain. Additionally, professionals in the field often lack access to structured, ongoing training. As a result, "learning by doing" has become the norm in practice, placing a heavy burden of learning on both individuals and organizations [14]. Furthermore, the absence of standardized training platforms, combined with weak internal incentives for in-depth skill development, further exacerbates the difficulty of knowledge acquisition, thereby increasing learning-related transaction costs.

At the same time, NZEB implementation remains constrained by China's traditional DBB model [109], which separates the objectives and interests of the design and construction stages, thereby increasing disputes and communication costs [109]. Under the DBB model, design companies primarily focus on passing energy simulation assessments rather than ensuring constructability, material compatibility, or engineering feasibility [5,28]. This misalignment leads to frequent design modifications during construction, triggering stakeholder disputes, coordination challenges, and additional technical adjustment costs. Additionally, because both contractors and designers are contractually bound only to the developer, the developer must assume additional coordination responsibilities to ensure the implementation of technical solutions. This requires developers to invest substantial resources in mediating across stakeholders, which further increases transaction costs.

6.2. Mitigation pathways for transaction cost bottlenecks in China's NZEB

Based on the Appropriateness–Feasibility matrix and insights from focus group discussions, we categorized the seven internationally informed strategies into three implementation tiers, as shown in Fig. 9.

6.2.1. Priority advancement strategies

SC1 (Authoritative NZEB database), SC2 (Standardised templates + auto-validation), and SC3 (Continuing-education training module) each achieved scores exceeding 16.13 for appropriateness and 16.97 for feasibility. SC1 can build on existing infrastructure, including the NZEB project database from the China Association of Building Energy Efficiency [15] and the National Green Building Materials Certification Information Platform [113], enabling rapid deployment and reducing upstream information search and validation costs [114]. SC2 is supported by the successful deployment of Shanghai's BIM-assisted review system, which standardised IFC templates and automated rule checks to streamline certification. This provides practical evidence for SC2's nationwide replication. Inspired by the EU's PROF/TRAC framework [79], SC3, linked to SC1, can be integrated into China's existing licensing and continuing education systems for engineers and site workers, thereby lowering the barrier to technical adoption and addressing skill disparities in the current construction sector. As underlying data systems and institutional pathways are already in place, these three strategies can be scaled nationally with minimal legislative intervention.

6.2.2. Pilot incubation strategies

SB1 (Optimised recommendation feedback mechanism) and SB2 (Digital online certification platform) received moderate scores in both appropriateness and technical feasibility. This suggests that, while international certification models provide valuable references, these strategies cannot be directly applied to the Chinese NZEB context and require localized adaptation to align with existing institutional and operational conditions.

For example, the feedback mechanism used in international systems, such as LEED, is based on a point-based scoring structure, where building performance is evaluated across multiple criteria, and missing scores can be compensated for through targeted improvements. In contrast, China's NZEB standards center on quantitative energy performance indicators that span the design, construction, and operation stages. Variations in climate zones and building typologies further complicate efforts to establish a unified optimization mechanism [115]. As a result, LEED point-based mechanisms are not directly transferable. A more feasible approach may be to develop a scalable, localized feedback system, for example, a hybrid mechanism that combines AI-generated preliminary recommendations with expert review and interpretation based on regional experience [116]. In addition, China's NZEB certification requires energy modeling during design, on-site testing during construction, and operational monitoring post-occupancy, creating a need for multi-source, cross-stage data integration [117]. This multi-stage structure demands that certification platforms support synchronous data generation, integration, and verification. To implement SB2's end-to-end digital certification, it is essential to develop localized platform systems that accommodate regional diversity and stage-specific requirements.

6.2.3. Reserve observation strategies

IPD-based integrated project delivery (SA1) and profit-sharing incentive mechanisms (SA2) received the lowest scores, reflecting structural shortcomings in both incentive alignment and institutional readiness. Although international experience from countries such as Finland and the United States suggests that these mechanisms significantly improve multi-stakeholder collaboration and incentive structures [81,82], their implementation in China faces major practical challenges. First, contractors in China operating under the DBB model have long relied on change orders to generate additional profits [118]. This

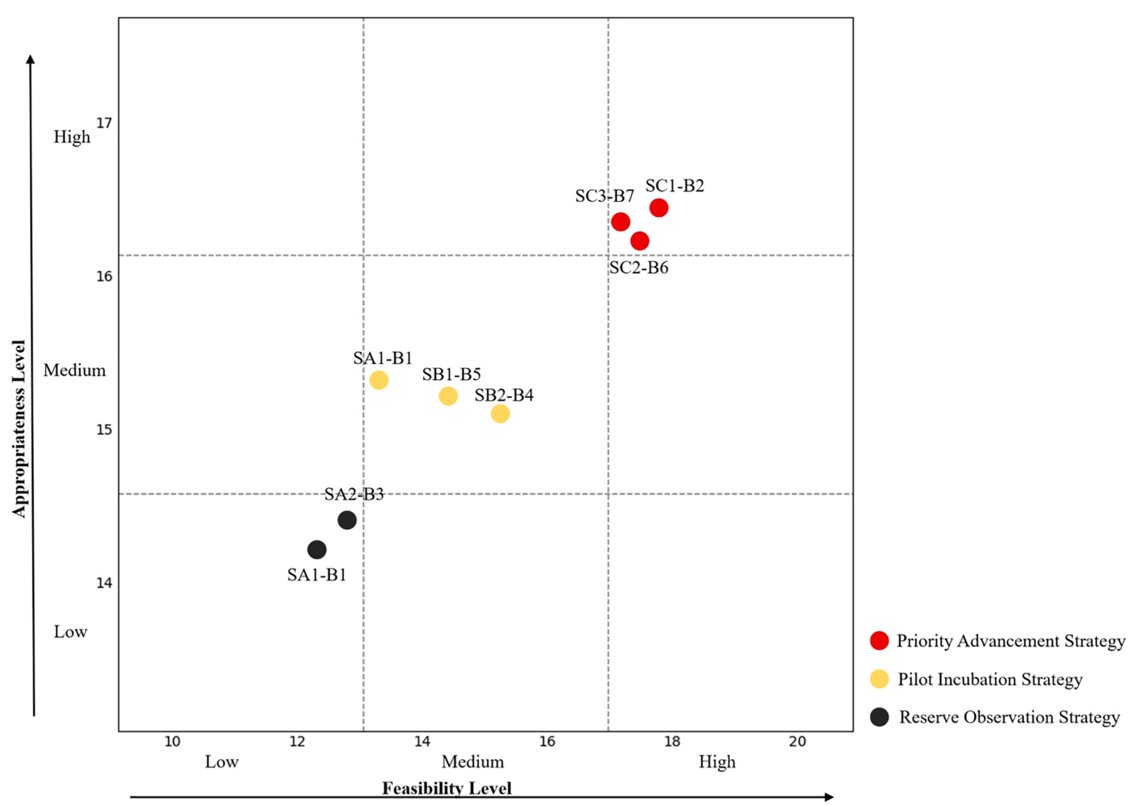

Fig. 9. 3 × 3 threshold grid mapping NZEB cost-mitigation strategies by feasibility and appropriateness.

entrenched path dependency directly conflicts with the logic of IPD's profit-sharing structure, weakening its incentive effectiveness and triggering systemic resistance during implementation. In addition, China's current bidding laws further constrain the flexibility needed to select IPD contractual partners [119,120]. Second, even if SA2 is introduced, developers still rely on consultants to provide detailed technical data for calculating the shared profit margin. If information disclosure is insufficient, consultants may exploit this asymmetry to influence the profit distribution, further undermining collaboration and trust [118]. Given these constraints, we recommend deferring implementation until robust systems for information disclosure, cost accounting, and multi-party oversight are in place, and until collaborative tools like BIM are widely adopted and integrated into a closed-loop regulatory framework.

7. Conclusions

This study aims to uncover the hidden transaction costs associated with developing NZEB in China's construction sector. Unlike previous studies that focus primarily on visible capital expenditures, this study highlights the procedural invisible burdens that can impede the adoption of sustainable technologies. Based on in-depth interviews with 23 industry experts, we systematically identify and analyze 36 transaction costs observed during the implementation of NZEB in China across multiple dimensions, including type, source, determinant, and stakeholder involvement. The findings highlight several key friction points, including information asymmetry and institutional constraints between developers and consultants, repeated trial-and-error due to multi-stage certification, barriers to information access resulting from the lack of authoritative sources and standardized templates, and rising technical adjustment costs driven by limited learning and poor coordination across project stages. Drawing on international experience, this study proposes seven strategies and prioritizes them to help mitigate transaction costs, offering a practical roadmap for scaling up NZEB development in China.

This study contributes by shifting the focus from static capital costs to dynamic, stakeholder-related hidden costs in the implementation of NZEB. It builds a structured transaction cost framework that helps identify and anticipate potential "hidden cost hotspots" within NZEB projects. The results suggest that fragmented policies, complex multi-stage certification processes, and the absence of systematic technical guidance — these "invisible burdens" — can be just as detrimental as conventional capital costs. This finding addresses a critical gap in the current literature regarding the limited understanding of hidden costs in NZEB implementation. In addition, drawing on identified transaction cost bottlenecks, this study integrates international practices with expert evaluation to develop a strategy prioritization and implementation matrix tailored to the Chinese context. This matrix provides a practical decision-making tool for policymakers and industry stakeholders in formulating targeted interventions.

Despite its contributions, this study has certain limitations and opens opportunities for future research. First, the analytical framework is derived from interviews with experts in China's NZEB sector, and its applicability to other countries, regions, or building types remains to be tested. Second, while snowball sampling effectively captures expert insights, it may introduce sampling bias due to potential overlaps in respondent backgrounds, perspectives, or social networks. Finally, although the study develops a framework for identifying transaction costs in NZEB projects, it does not explore the interrelations among different types of transaction costs. Future research could examine the interactions among multiple transaction costs to identify key leverage points for reducing stakeholder burdens more effectively during the implementation of NZEB.

CRediT authorship contribution statement

Hanbing Wang: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Queena K. Qian:** Writing – review & editing, Supervision. **Henk Visscher:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1
Verified Transaction costs in the Implementation Process of NZEB in China.

Stage	Specific transactions under each determinant	Type	DEV	CON	GOV	FIN	DES	CERT	GC	SUP	SUPV	PMC	OWN
Concept Stage	TC1 Searching for experienced consultants	I2 Searching for partner information	△	X									
	TC2 Signing consultancy contracts	N4 Contract negotiation	△	△									
	TC3 Policy search	I4 Searching for policy and subsidy info	△		X								
	TC4 Feasibility Assessment	D1 Feasibility assessment	X	△									
	TC5 Decision-making costs	D3 Decision-making costs	△	X									
	TC6 Compliance review	D4 Compliance review	X	△									
	TC7 Land bidding	N2 Licensing fees	△		△								
	TC8 Financing	N4 Contract negotiation	△			△							
Design Stage	TC9 Searching for experienced design companies	I2 Searching for partner information	△	△			X						
	TC10 Drafting design contracts	N4 Contract negotiation	△	△			X						
	TC11 Design-technology training for energy-oriented design	D2 New technical solutions					△						
	TC12 Performance simulation	D2 New technical solutions		△			X						
	TC13 Information on design evaluation requirements	I1 Searching for specifications and certification requirements	△	△				X					

(continued on next page)

Table A1 (*continued*)

Stage	Specific transactions under each determinant	Type	DEV	CON	GOV	FIN	DES	CERT	GC	SUP	SUPV	PMC	OWN
	TC14 Preparation and confirmation of design evaluation documents	D4 Compliance review	X	△			X						
	TC15 Communication of design evaluation information	N1 Coordination costs	△	△			△	△					
Construction Stage	TC16 Searching for experienced partners	I2 Searching for partner information	△	△					X		X		
	TC17 Partner contract negotiation	N4 Contract negotiation	△	△					△		△		
	TC18 Construction instructions	N3 Dispute resolution	△	△			△		△				
	TC19 Material and equipment selection	I3 Searching for case studies and technical information	△	△						X			
	TC20 Material and equipment contract negotiation	N4 Contract negotiation	△	△						△			
	TC21 Demonstrating construction processes	D2 New technical solutions		△					X	△			
	TC22 Construction process optimization	D2 New technical solutions	X	△									
	TC23 Change and dispute resolution	N3 Dispute resolution	△				△		△				
	TC24 Construction monitoring	M1 Random quality inspection	△	△					X		△		
	TC25 Collecting inspection results during construction	D4 Compliance review							X		△		
	TC26 Information on construction evaluation requirements	I1 Searching for specifications and certification requirements	△	△				X					
	TC27 Preparation and confirmation of construction evaluation documents	D4 Compliance review	X	△					X	X			
	TC28 Construction evaluation review	N1 Coordination costs	△	△				△	△				
Operation Stage	TC29 Searching for experienced property management companies	I2 Searching for partner information	△	△								X	
	TC30 Training on NZEB building usage	D2 New technical solutions										△	X
	TC31 Training on NZEB building maintenance	D2 New technical solutions								△		X	
	TC32 Energy consumption optimization	D2 New technical solutions		△								X	
	TC33 Information on operational evaluation requirements	I1 Searching for specifications and certification requirements	△	△				X					
	TC34 Preparation and confirmation of operational evaluation documents	D4 Compliance review	X	△								X	
	TC35 Operational evaluation review	N1 Coordination costs	△	△				△					
	TC36 Certification communication	N1 Coordination costs	△	△				△					

Conventions.
△Stakeholders Bearing TC.
X Stakeholders Related to TC.
DEV: Developer, CON: Consultant, GOV: Government, FIN: Financial Institution, DES: Design Company, CERT: Certification Body, GC: General Contractor, SUP: Supplier, SUPV: Supervisor, PMC: Property Management Company, OWN: Owner.

Data availability

Data will be made available on request.

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