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Uncovering the structural relationships among transaction costs in nearly zero energy building projects

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ABSTRACT

Transaction costs are widely recognized as a hidden constraint on scaling Nearly Zero Energy Buildings (NZEBs), yet existing studies largely treat them as isolated items and overlook how they interact across stages and stakeholders. This study adopts a structural perspective to examine transaction cost interactions in Chinese NZEB projects. Based on 36 transaction cost elements identified in prior empirical work, we conducted a two-round Delphi survey with 23 experienced practitioners to elicit perceived directional relationships and construct a consensus-based structural self-interaction matrix. An integrated ISM–MICMAC–SNA approach was then applied to identify the hierarchical structure, driving–dependence categories, and key nodes in the network of transaction cost elements, complemented by Louvain community detection. The analysis reveals a ten-level structure that can be grouped into three functional zones and yields four main findings. First, transaction costs in the bottom driving zone are mainly borne by developers, especially those related to consultant selection and contract negotiation. Second, transaction cost determinants show a hierarchical pattern, with asset specificity dominating the lower levels and uncertainty becoming more prominent in the upper levels. Third, construction-stage transaction costs are not structurally isolated. In the expert-consensus model, they are linked to perceived dependencies from the concept and design stages through consensus-based directional relationships. Fourth, the study identifies twelve key transaction cost elements and groups them into five categories: partner selection, contract negotiation, technical solution development, certification document preparation, and construction change and dispute management. These findings clarify perceived dependencies and reachability patterns among transaction cost elements and provide a basis for proposing prioritized mitigation strategies in NZEB delivery.

1. Introduction

As the global transition toward carbon neutrality and net-zero emissions accelerates, policymakers increasingly prioritize the building sector as a target for intervention. The building sector accounts for approximately 30% of global final energy consumption and contributes about 26% of energy-related carbon dioxide emissions [1,2]. In this context, Nearly Zero Energy Buildings (NZEBs), which aim to minimize operational energy use, have attracted sustained attention [3,4]. The core principle of NZEBs is to reduce operational energy demand through passive envelope design, integration of high-performance building systems, and the use of renewable energy. At the same time, NZEBs rely on on-site or nearby renewable energy supply to achieve near-zero operational energy consumption [5]. Therefore, both research and policy practice regard NZEBs as a key pathway to promote deep decarbonization and energy transition in the building sector. Due to their strong potential for energy savings and emissions reductions, NZEBs have been widely promoted in Europe, North America, Japan, and South Korea [6–8]. China has issued the Technical Standard for NZEBs and established a corresponding certification system. It has also incorporated NZEBs into its carbon peaking and carbon neutrality strategy as an important policy instrument [9,10]. However, despite strengthened policy support and improved financial incentives, the actual diffusion of NZEBs in China still faces multiple constraints. These constraints are not limited to technological and financial issues, but also stem from the complexity of coordinating multiple stakeholders, aligning interests, and making decisions within uncertain institutional environments [11–13]. Many stakeholders remain cautious about participation and investment [14].

Existing studies show that, besides incremental investment, NZEB

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projects often involve implicit transaction costs that are difficult to quantify, especially in projects with multiple actors and repeated coordination [12,13]. Scholars often regard these costs as a major constraint to the promotion and implementation of NZEBs [15,16]. Transaction costs mainly arise from complex institutional and market environments. In multi-organizational settings, they can increase further because of participatory decision-making, responses to new information, and scheduling and coordination across the system [17–19]. Asset specificity, uncertainty, and opportunistic behavior in multi-stakeholder collaboration drive transaction costs. Specifically, strict performance standards and multi-stage certification systems increase asset specificity in the design, construction, and operation stages. Frequent adjustments in regulations and technical pathways intensify project uncertainty. Multi-stakeholder collaboration and information asymmetry also increase the likelihood of opportunistic behavior [20]. Based on Transaction Cost Theory (TCT), existing studies identify several types of transaction costs, including information search, contract negotiation, monitoring, coordination, correction, and renegotiation. These costs constrain the development of NZEBs and other sustainable buildings [21]. Based on these insights, researchers propose various mitigation strategies to address transaction costs. These strategies offer important references for understanding and reducing transaction costs in building projects [22].

However, in NZEB projects, transaction costs are often interrelated across lifecycle stages and stakeholders rather than occurring in isolation. Williamson [23] argues that insufficient ex ante arrangements increase ex post governance efforts. The stages of NZEB projects are highly coupled, and multiple stakeholders must collaborate continuously. Therefore, information and contractual deficiencies in the early stages may be associated with additional transaction cost burdens in later stages. For example, insufficient information search or unclear requirement definition during the concept stage may lead to frequent contractor replacement and repeated negotiations in the construction stage. This process significantly increases coordination and monitoring costs for developers [24]. Incomplete contract arrangements with consulting firms in the concept stage may create unclear responsibility boundaries in the construction stage and increase dispute-resolution costs [25]. In addition, insufficient communication and lack of trust in early stages may evolve into excessive monitoring and redundant governance in later stages, further increasing the overall transaction burden [26].

Nevertheless, existing studies primarily focus on static identification of transaction costs [14,16,21,27]. Few studies examine how transaction cost elements are structurally related across stages and stakeholders. If governance strategies rank transaction costs only by their magnitude or distribution, researchers and practitioners may overlook the structural positions of specific transaction cost elements and their cross-stage dependency patterns. This approach makes it difficult to identify key elements in the hierarchy. Therefore, it is necessary to identify hierarchical relationships and key nodes through a structural analysis of transaction cost elements.

To address these limitations, this study adopts an integrated ISM–MICMAC–SNA approach to analyze the structural relationships among transaction cost elements in NZEB projects. Specifically, it examines how these elements are hierarchically ordered, connected across project stages, and positioned within the overall network. Because the analysis is based on Delphi-based expert judgments, binary SSIM coding, and consensus aggregation, the identified relationships are understood as perceived dependencies and reachability patterns within the expert-consensus model. Based on four analytical dimensions—project stage, stakeholder, transaction cost type, and determinant—this study derives four main findings. First, transaction costs in the bottom driving zone are mainly borne by the developer, particularly those related to consultant selection, contract formation, and early information search. Second, asset specificity dominates the lower levels, while uncertainty becomes more prominent in the upper levels. Third, transaction costs show stage-spanning dependencies among transaction cost elements, especially from the concept and design stages toward the construction and operation stages. Fourth, the study identifies twelve key transaction cost elements and groups them into five categories: partner selection, contract negotiation, technical solution development, certification document preparation, and construction change and dispute management. Through this analysis, the study provides a structural explanation of how transaction cost elements are organized in Chinese NZEB projects and offers a practical basis for prioritizing transaction cost mitigation measures.

2. Literature review

2.1. Transaction costs that hinder the implementation of NZEB projects in China

NZEB projects often require cross-disciplinary collaboration among architecture, MEP systems, envelope engineering, and energy simulation. Projects also need to meet evaluation and certification procedures as well as policy requirements [28]. As a result, project teams face a clear increase in workload related to information acquisition, communication and coordination, document preparation, and compliance review. This increase creates transaction frictions beyond those arising from direct construction inputs. Kiss [16] reports that the additional effort associated with such frictions can approach 20% of total costs in some projects. To identify and analyze these frictions during NZEB implementation, prior studies have applied Transaction Cost Theory [15].

Within the TCT framework, researchers often use asset specificity and uncertainty to explain differences in transaction costs [23]. In NZEB projects, several inputs show strong asset specificity, such as partnerships formed around specific performance targets, specialized expertise, technical solutions, material and equipment configurations, and commissioning and verification capabilities [15]. Such specific investments increase the complexity of contract design. They also make partner selection and replacement more difficult and complicate the allocation of risk and responsibility [29]. As a result, projects involve more negotiation and coordination, which increases related transaction costs. At the same time, updates in standards and policies create institutional uncertainty. Technical pathway selection and performance compliance also involve uncertainty. In multi-stakeholder collaboration, information asymmetry and misaligned incentives increase the workload of monitoring, verification, and coordination. They may also raise monitoring costs [27].

Compared with NZEB practices in the European Union [30], the United States [31], and South Korea [32], NZEB implementation in China needs to simultaneously address technical standards, stage-based evaluations, and procedural requirements related to multi-level policies and demonstration projects. At the national level, China has issued NZEB technical standards, such as GB/T 51350–2019, which specify technical requirements and evaluation methods [33]. As a result, project participants must continuously carry out tasks related to document preparation, evaluation, or review, and compliance confirmation. In both research and practice, these evaluation processes are organized by stage and usually include design evaluation, construction evaluation, and operation evaluation. Therefore, projects generate transaction activities such as document preparation, communication, and compliance review in different stages [9]. In addition, NZEB promotion often combines policy guidance, demonstration projects, and local supporting measures. Project teams also need to conduct policy information search, application procedures, and related communication. In this context, Wang et al. [14] empirically identify 36 transaction costs faced by different stakeholders in Chinese NZEB projects, including developers, consulting firms, general contractors, certification bodies, and property management companies. They classify these costs by transaction type, influencing determinant, and project stage. **Appendix A** further groups these transaction costs by project stage and provides a foundation for analyzing their potential interaction mechanisms.

2.2. Interaction of transaction costs and the static limitations of existing studies

As discussed above, existing studies identify transaction costs in the building sector from the perspectives of transaction cost types, determinants, and project stages. They often use quantity or frequency to determine which types, stages, or stakeholders are more prominent. Deng and Wu [34] find that developers typically bear higher transaction costs. This pattern reflects their central role in forming contractual relationships and organizing resources and coordination across parties. In terms of stage distribution, studies often identify more transaction costs in the construction stage. This result relates to high technical complexity, strict process control requirements, and heavy coordination workload [21]. Research on green building certification and incentive policies also shows that certification processes increase additional work, such as document preparation, verification, and consultant-related efforts [27]. At the same time, the additional work borne by different stakeholders does not always match the benefits they receive. This phenomenon indicates that transaction costs involve issues of burden sharing and allocation among stakeholders [35].

However, these studies mainly answer questions such as “which transaction costs exist,” “which stages involve more,” and “which stakeholders bear more.” They rarely analyze relationships among transaction cost elements. Williamson [23] distinguishes ex ante costs (e.g., contract drafting and negotiation) from ex post costs (e.g., monitoring and enforcement, adjustment, and dispute handling). He also emphasizes their linkage: insufficient ex ante arrangements increase ex post governance efforts. This linkage becomes more salient when asset specificity is high and uncertainty is strong. Therefore, transaction costs are more likely to occur through mutual influence rather than as independent items.

This also implies that, if mitigation strategies focus only on the stages, stakeholders, or types with the largest counts, researchers and practitioners may obtain only a local priority order. This approach also makes it difficult to distinguish between lower-level transaction cost elements and upper-level dependent elements, thereby weakening the overall effectiveness of transaction cost mitigation. Therefore, it is necessary to examine how transaction cost elements are hierarchically related and where key nodes are located within the system.

Based on this rationale, this study proposes the following research questions:

RQ1: In NZEB projects, what hierarchical structure characterizes the consensus-based directional relationships among transaction cost elements? What are their driving–dependence features?

RQ2: Within the structural relationships among transaction cost elements, which elements occupy key structural positions?

2.3. Analytical approach for identifying structural relationships among transaction cost elements: ISM–MICMAC–SNA

It is important to understand the structural relationships among transaction cost elements in NZEB projects. Listing these elements alone is not sufficient for systematic mitigation. Research also needs to identify hierarchical dependence among elements and locate core elements that play key roles in the system [36]. Therefore, this study introduces an integrated approach to analyze relationships among transaction cost elements.

Among methods for identifying structural relationships, Interpretive Structural Modeling (ISM) and its combination with MICMAC analysis are widely used to examine interactions among elements in complex systems [37,38]. Warfield [39] proposed ISM to reveal direct and indirect relationships among variables and their dependence pathways through a multi-level structural model. ISM relies on expert judgment and relational matrix analysis. It decomposes complex systems into hierarchical subsystems, improves structural clarity, and supports element prioritization and level sequencing. Because this method effectively captures multi-factor system structures, researchers have applied ISM in various contexts, such as low-carbon transition in the construction industry [40], heritage building maintenance management [37], and residential project risk mitigation [41].

Building on ISM, MICMAC analysis quantifies driving power and dependence to classify the elements identified by ISM. It groups them into driver elements, dependent elements, linkage elements, and autonomous elements [42]. By integrating these attributes into the hierarchical structure, researchers can further identify structural clusters and subsystem groupings within the system [43].

However, ISM–MICMAC provides limited support for identifying key nodes. Social Network Analysis (SNA) can address this limitation. As an important method for analyzing relational structures in complex systems, SNA has been widely applied in innovation networks [44], supply chain collaboration, and project risk management [45]. It helps identify key elements in the system.

SNA represents transaction cost elements as network nodes based on a relational matrix. It characterizes their structural positions using centrality measures and community detection [46]. Nodes with higher in-status centrality receive incoming links from other nodes and thus lie closer to positions of dependency convergence [47]. Nodes with higher betweenness centrality are more frequently located on network paths, thereby indicating bridging positions [48]. In addition, community detection identifies densely connected groups of nodes in the network and reveals clustering patterns and subsystem divisions among transaction cost elements [49].

Therefore, this study combines ISM–MICMAC and SNA to develop a multi-level structural analytical framework for interactions among transaction cost elements. This study systematically identifies structural features of transaction cost elements in NZEB projects from two dimensions: hierarchical dependence structure and network key elements.

2.4. A four-dimensional transaction cost analytical framework

To analyze the results of structural identification, this study develops a four-dimensional transaction cost analytical framework based on the preceding literature review and theoretical analysis. This framework integrates the project process perspective, the stakeholder perspective, and the Transaction Cost Theory (TCT) perspective. The framework includes four dimensions.

(1) **Stage**: the lifecycle stage in which transaction costs occur, such as the concept stage and the design stage.

(2) **Stakeholder**: the actor that bears transaction costs, such as developers, consulting firms, and contractors.

(3) **Transaction cost type**: the specific form of transaction costs, such as information search costs, due diligence costs, negotiation costs, and monitoring costs.

(4) **Transaction cost determinant**: the main source of transaction costs, such as asset specificity and uncertainty.

Table 1 systematically summarizes the categories and explanations of these four dimensions and provides theoretical support for subsequent research design and empirical analysis.

3. Methodology

As shown in Fig. 1, the methodology includes two components: (1) identifying perceived relationships among transaction cost elements, and (2) applying ISM–MICMAC–SNA.

First, this study builds on the identified transaction cost elements in NZEB projects and uses the Delphi method to conduct a two-round survey with 23 experts who have extensive NZEB practical experience. Based on the survey results, this study identifies perceived directional relationships among transaction cost elements and constructs a

Table 1
A Four-Dimensional Transaction Cost Analytical Framework in the NZEB Context.

Dimension	Category	Description under the NZEB Context	Source
Stages	Concept stage	Consultant selection and contracting; identification of policy and compliance requirements; feasibility assessment and decision-making; land bidding and financing communication	[14]
	Design stage	Design partner selection and contracting; design-related technical training; performance simulation and optimization; preparation and communication of design evaluation documentation	[50]
	Construction stage	Partner and supply-chain configuration; construction instructions and process optimization; change and dispute resolution; construction monitoring, inspection and certification documentation	[14]
	Operation stage	Property management selection; training in NZEB operation and maintenance; energy consumption optimization; operational evaluation documentation and certification communication	[51]
Transaction cost determinants	A1 Expertise (asset specificity)	NZEB implementation requires specialized knowledge and skills, including performance simulation, integration of high-performance envelopes and renewable energy systems, commissioning, and equipment maintenance. This requires dedicated time and learning efforts.	[52,53]
	A2 Specific information (asset specificity)	NZEB-related information is fragmented and specialized, including certification requirements, compliant materials and equipment, partner experience, and policy incentives. This increases information access and verification costs	[52,54,55]
	A3 Specific contracts (asset specificity)	NZEB contracts lack standardization and remain incomplete, with unclear boundaries and deliverables across consultancy, design, construction, supply, and operation and maintenance. This increases negotiation and enforcement risks	[56,57]
	A4 Professional personnel (asset specificity)	Experienced NZEB teams and professionals are often difficult to replace. This creates dependency and increases coordination and replacement costs	[57,58]
	A5 Specific project requirements (asset specificity)	NZEB projects involve specific requirements, such as feasibility studies, land-bidding conditions and green finance applications. These generate additional due diligence and negotiation costs	[14,59]
	U1 Behavioral uncertainty (uncertainty)	Ambiguous contract boundaries and responsibilities may trigger opportunistic behavior, such as liability shifting. This increases coordination and dispute-related negotiation costs	[52,53,60]
	U2 Technological uncertainty (uncertainty)	NZEB involves complex technologies and approval processes, including additional testing and inspection, integration of new technologies, and certification communication. These increase verification burdens and change-related risks	[61,62]
Transaction cost types	I Information search costs (I1–I4)	Efforts required to collect and verify NZEB-related information, including specifications and certification requirements (I1), partner information (I2), case studies and technical information (I3), and policy and subsidy information (I4)	[52,54,63–65]
	D Due diligence costs (D1–D4)	Costs associated with feasibility assessment and preparation of compliance evidence, including feasibility assessment (D1), new technical solutions (D2), decision-making (D3), and compliance review (D4)	[21,52,66]
	N Negotiation costs (N1–N4)	Additional burdens from inter-organizational communication and agreement-making, including coordination (N1), licensing fees (N2), dispute resolution (N3), and contract negotiation (N4)	[24,52,67]
	M Monitoring costs (M1)	Costs related to implementation, monitoring, and performance verification, including random quality inspection and verification activities required by NZEB evaluation and certification	[21,54,66]
Stakeholders	Stakeholders	Government; Developer; Consultant; Design company; General contractor; Supervisor; Supplier; Certification body; Property management company; Owner or end-user.	[14,68]

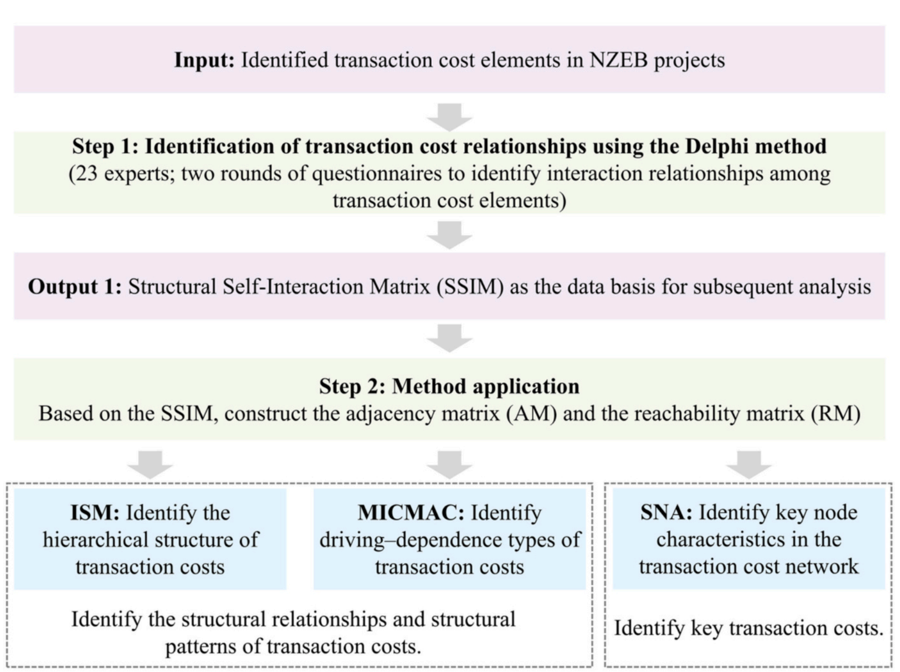

Fig. 1. Research framework for identifying perceived relationships and structural characteristics of transaction cost elements in NZEB projects.

Structural Self-Interaction Matrix (SSIM) as the data basis for subsequent analysis.

Next, this study uses SSIM to construct adjacency and reachability matrices. It then applies ISM, MICMAC, and SNA to identify the hierarchical structure, driving–dependence categories, and key-node characteristics of transaction cost elements. Sections 3.1 and 3.2 describe the detailed steps.

3.1. Delphi survey

Perceived relationships among transaction cost elements in Chinese NZEB projects are subjective and context-dependent, and objective data cannot directly quantify them. Therefore, this study adopts the Delphi method to collect expert judgments and build consensus. The Delphi method integrates expert knowledge through multiple rounds of anonymous consultation and controlled feedback. It addresses complex and uncertain problems and has been widely applied in construction management and decision-making research [40]. An important advantage of this method is that it allows each expert to provide opinions under relatively equal conditions. This design reduces bias caused by authority influence, opinion competition, and group pressure [69]. During multiple rounds, experts revise their views based on feedback and adjust their judgments through mutual learning. Delphi studies usually require at least two rounds to complete [70]. This study conducts two rounds of Delphi surveys to identify perceived directional relationships among the 36 transaction cost elements in NZEB projects.

3.1.1. Expert selection

The NZEB industry in China remains at an early development stage [33]. Professionals with systematic implementation experience are therefore limited in number and geographically dispersed. Therefore, conventional random sampling is unlikely to effectively identify the target experts. This study uses snowball sampling and leverages industry networks to progressively identify core practitioners, thereby ensuring professional relevance and stakeholder coverage [71]. The research team first contacted industry experts who delivered keynote speeches at the China Passive House Designer Conference and asked them to recommend other candidates who met the study requirements. This process expanded the expert pool step by step and ensured that selected participants had clear professional qualifications and practical experience.

This study selected experts based on two criteria. First, this study emphasizes stakeholder representativeness. Selected experts came from key participants in NZEB implementation, including developers, consultants, government agencies, financial institutions, design companies, certification bodies, general contractors, suppliers, supervisors, and property management companies. All experts had directly participated in or managed the implementation of NZEB projects. Second, this study focuses on professional competence and project experience. Selected experts took core responsibilities in NZEB projects across different climate zones, including cold regions, hot-summer and cold-winter regions, and temperate regions [9]. This study also covered both frontline technical roles and senior management roles. To ensure the practical depth of expert judgments, this study applied a common inclusion criterion: each expert had participated in or supervised NZEB projects with a gross floor area above 10,000 m^2 and had at least five years of relevant implementation experience.

During recruitment, the research team contacted 35 candidates. Twenty-three met the criteria and completed two rounds of Delphi surveys. Overall, the sample has strong professional credentials. The experts had more than ten years of work experience on average, and some served on national or regional review committees, reflecting strong industry authority and practical experience. Hsu and Sandford [72] note that most Delphi studies use panels of 10–50 experts. This study uses a panel of 23 experts, which aligns with this recommendation. To reduce the risk of a single-perspective expert panel, this study intentionally included experts from different stakeholder groups, including government agencies, developers, consultants, design companies, contractors, suppliers, certification bodies, financial institutions, and property management companies. Table 2 provides basic information about the expert panel.

3.1.2. Two-round Delphi procedure and consensus rules

The Delphi survey was used to identify structural relationships among the 36 transaction costs. Experts were asked to assess each pair of cost elements and determine whether an influence relationship existed and, if so, in which direction. A two-round Delphi procedure was adopted to allow experts to reconsider uncertain judgments after receiving controlled group feedback.

In the first round, experts evaluated each pairwise relationship in the transaction cost relational matrix and selected one of four SSIM symbols. If transaction cost p influences q but q does not influence p, the relationship was marked as V. If q influences p but p does not influence q, the relationship was marked as A. If the two influence each other, the relationship was marked as X. If no relationship exists, the relationship was marked as O. These rules follow the Structural Self-Interaction Matrix (SSIM) procedure in ISM and have been applied in low-carbon

Table 2
Profile of Delphi Experts.

NO.	Organization	Role in Organization	Working Year	Degree
1	Municipal Commission of Urban-Rural Development (Government)	Deputy Director	30	Bachelor
2	Municipal Commission of Urban-Rural Development (Government)	Director	12	Master
3	NZEB Consulting Company	Director	10	Master
4	NZEB Consulting Company	Manager	8	PhD
5	NZEB Consulting Company	Chairman	28	PhD
6	Real Estate Company (Developer)	Deputy General Manager	18	Bachelor
7	Real Estate Company (Developer)	Design Manager	16	Bachelor
8	Real Estate Company (Developer)	Development Manager	6	Master
9	Construction Engineering Company (General Contractor)	Deputy General Manager	21	Bachelor
10	Construction Engineering Company (General Contractor)	Project Manager	14	Master
11	Construction Engineering Company (General Contractor)	Crew Leader	29	Bachelor
12	High-performance Window Company (Supplier)	Sales Director	15	Bachelor
13	External Insulation Materials Company (Supplier)	Manager	9	Bachelor
14	Heat Recovery Ventilation System Company (Supplier)	Technical Director	13	Master
15	Property Management Company	Manager	17	Bachelor
16	Property Management Company	Maintenance Technician	26	Bachelor
17	Architectural Design Firm (Design Company)	Deputy Chief Architect	18	Bachelor
18	Architectural Design Firm (Design Company)	Architect	6	Master
19	Architectural Design Firm (Design Company)	Chief Architect	11	Master
20	Certification Body	Manager	6	PhD
21	Certification Body	Technical Director	21	Bachelor
22	Regional Bank Branch (Financial Institution)	Deputy Branch Manager	8	Master
23	Regional Bank Headquarters (Financial Institution)	Director	10	Bachelor

building research [73].

For consensus assessment, this study used the percentage agreement on the dominant SSIM judgment. Percentage agreement is commonly used in Delphi studies to define consensus [74]. A 70% agreement threshold was predefined as the main analytical criterion for retaining a directional relationship [75]. Because the Delphi panel consisted of 23 experts, this threshold was implemented using a strict integer rule: at least 17 of 23 experts had to select the same dominant SSIM judgment. This corresponds to 73.9% agreement. The threshold was therefore higher than a simple majority and was used to retain only relationships with sufficient group support.

After the first round, the research team aggregated expert judgments and calculated the agreement rate for the 630 unique pairwise relationships formed by the 36 transaction costs.

In the second round, all pairwise relationships were returned to experts for confirmation. Relationships that did not reach the predefined consensus threshold in the first round were highlighted for focused re-evaluation. For these relationships, experts received controlled group feedback, including the agreement rate and the distribution of group judgments across V, A, X, and O. Experts were allowed to either retain or revise their original judgments for any pairwise relationship. This design enabled the study to examine both the convergence of initially non-consensual judgments and the stability of judgments that had already reached consensus in the first round. The feedback was provided in statistical form only, without identifying individual experts, to reduce authority influence and conformity pressure.

After the second round, the final SSIM was constructed according to the predefined consensus rule. Relationships that reached the agreement threshold were included in the final SSIM, whereas relationships that still failed to reach consensus were excluded from the final structural matrix. Importantly, consensus refers to agreement on one of the four SSIM categories, including O. Therefore, consensual O judgments indicate agreement on no relationship and were not retained as structural links in the final matrix. Only consensual V, A, or X judgments were retained as structural relationships for the subsequent ISM analysis.

To assess the consensus quality and robustness of the Delphi process, this study further conducted checks on response concentration, round-to-round stability, inter-rater reliability, and threshold sensitivity. First, response concentration was measured using the dominant response proportion, namely the proportion of experts selecting the most frequently chosen SSIM category for each pairwise relationship. Because V/A/X/O judgments are nominal categories rather than ordinal scores, conventional variance statistics were not directly applicable. Therefore, this study used the distribution of V/A/X/O judgments and changes in the dominant response proportion to reflect patterns of disagreement among experts [76]. Second, round-to-round stability was assessed by examining whether the dominant SSIM category for each pairwise relationship remained unchanged across the two Delphi rounds [77]. Third, because SSIM judgments are categorical responses, Fleiss' kappa was used to assess inter-rater reliability [78]. Finally, a threshold sensitivity analysis was conducted using 60%, 70%, and 80% thresholds to examine whether the retained relationships were sensitive to the selected consensus threshold [79].

The results indicate that the Delphi iteration improved the concentration, stability, and reliability of expert judgments. The average dominant response proportion increased from 65.1% in the first round to 82.7% in the second round, suggesting that expert judgments became more concentrated after controlled feedback. The dominant SSIM category remained unchanged for 468 of the 630 pairwise relationships, accounting for 74.3%, indicating that the overall judgment structure was relatively stable across the two rounds. Fleiss' kappa increased from 0.486 in the first round to 0.724 in the second round, moving from moderate agreement to substantial agreement. This indicates that the Delphi feedback promoted convergence toward more stable dominant judgments after correcting for chance agreement [80].

The consensus transition results also support the convergence effect of the Delphi iteration. Under the 70% consensus criterion, 332 pairwise judgments shifted from non-consensus in the first round to consensus in the second round, indicating that controlled feedback mainly promoted convergence among expert judgments. The threshold sensitivity analysis showed that, as the threshold became more conservative, the number of retained non-O structural relationships decreased from 131 under the 60% threshold to 76 under the 80% threshold. Under the main 70% threshold, 107 non-O structural relationships were retained, producing an intermediate structure between the more inclusive and more conservative alternatives. Therefore, the 70% threshold provided a relatively balanced solution by avoiding both the inclusion of weakly supported relationships and the excessive exclusion of potentially meaningful relationships.

Based on these results, this study did not conduct a third Delphi round. All survey procedures received approval from the Human Ethics Review Committee (HERC). The final Delphi results provided the data basis for the subsequent ISM–MICMAC–SNA analysis.

3.2. ISM–MICMAC–SNA approach application

Before presenting the detailed analytical steps, it is necessary to clarify the nature of the relationships modeled in this study. The Delphi-based SSIM records expert judgments about perceived directional relationships among transaction cost elements. These judgments are subjective, binary, and consensus based. Therefore, the identified relationships represent perceived dependencies and consensus-based directional relationships rather than empirically validated causal effects.

In this study, "transaction costs" refers to the general cost burdens arising from information search, negotiation, coordination, monitoring, and compliance-related activities. "Transaction cost elements" refers specifically to the 36 coded analytical units used in the ISM–MICMAC–SNA model. Therefore, when discussing hierarchical levels, MICMAC classifications, SNA centrality, and key nodes, this study uses "transaction cost elements" to emphasize that the analysis concerns modeled elements rather than directly measured cost magnitudes.

In this study, ISM is used to reveal structural ordering and reachability logic, MICMAC is used to classify driving and dependence features, and SNA is used to identify the structural importance of nodes. These methods do not provide causal identification, effect magnitude, or temporal dynamics. Therefore, the terms "influence," "driving," and "pathway" are used in a structural sense, referring to structural influence and perceived dependency in the expert-consensus model.

The detailed ISM–MICMAC–SNA analysis procedure is as follows:

Step 1: Identifying the set of transaction cost elements (TCs). Assuming that there are n ($n \geq 2$) elements in the system, which can be described as formula (1):

$$S = \{TC_1, TC_2, \ldots, TC_n\} \tag{1}$$

Step 2: Variable identification and Structural Self-Interaction Matrix (SSIM) construction:

The Delphi survey was used to elicit expert judgments on the perceived directional relationships among transaction cost elements in NZEB projects. Experts assessed the perceived directional relationship between each pair of transaction cost elements, resulting in the construction of a Structural Self-Interaction Matrix (SSIM). In the SSIM, the symbols "V," "A," "X," and "O" indicated the presence and direction of a perceived relationship [73].

Step 3: Adjacency matrix generation:

Based on predefined transformation rules, this study converts the Structural Self-Interaction Matrix (SSIM) into a binary adjacency matrix (AM) to represent direct directed relationships among transaction cost elements.

If the SSIM entry is V, then $(TC_i, TC_j) = 1$ and $(TC_j, TC_i) = 0$;
If A, then $(TC_i, TC_j) = 0$ and $(TC_j, TC_i) = 1$;
If X, then $(TC_i, TC_j) = 1$ and $(TC_j, TC_i) = 1$;
If O, then $(TC_i, TC_j) = 0$ and $(TC_j, TC_i) = 0$.

This binary matrix represents the existence and direction of direct consensus-based relationships and serves as the foundational input for both ISM and SNA. However, because all identified relationships are coded equally as 1, this matrix does not capture differences in relationship strength, frequency, or criticality.

Step 4: Transitive closure and reachability matrix formation:

To capture both direct and indirect structural influence pathways, the adjacency matrix was combined with the identity matrix (IM) and iteratively raised to successive powers under Boolean algebra until convergence, in accordance with the transitive closure principle [40], formally expressed as formula (2):

$$RM = (AM + IM)^{n+1} = (AM + IM)^{n} \neq (AM + IM)^{n-1}$$

$$\neq \cdots (AM + IM)^{2} \neq (AM + IM) \tag{2}$$

where IM is the identity matrix. Boolean operations follow:

Addition: $0 + 0 = 0, 0 + 1 = 1, 1 + 1 = 1$;

Multiplication: $1 \times 0 = 0, 1 \times 1 = 1$.

This iteration accumulates all paths until equals, yielding the final reachability matrix. Then, it conducts level partition analysis by evaluating each element's reachability set R(TCi), antecedent set A(TCi), and their intersection C(TCi) to construct the hierarchical structure of transaction cost elements and identify their perceived dependency patterns.

Step 5: ISM hierarchical modeling:

For each TC, the reachability set R(TCi), antecedent set A(TCi), and their intersection C(TCi) were determined from the RM. Transaction cost elements for which R(TCi) = C(TCi) were assigned to the bottom level of the hierarchy. These variables were then removed, and the process was repeated to identify subsequent levels. This stepwise level partitioning produces a multi-level ISM model that visualizes the structural ordering and perceived dependency logic of transaction cost elements.

Step 6: MICMAC driver–dependence classification:

Using the RM, the driving power of each transaction cost element (the total number of elements it can reach) and its dependence (the total number of elements that can reach it) were calculated. Transaction cost elements were then plotted on a two-dimensional driving power–dependence grid and classified into four MICMAC categories:

(1) autonomous elements, with low driving power and low dependence; (2) dependent elements, with low driving power and high dependence; (3) linkage elements, with high driving power and high dependence; and (4) driver elements, with high driving power and low dependence.

This classification provides insight into the systemic position of each transaction cost element within the modeled network.

Step 7: SNA network-structure analysis:

The RM was further analyzed using SNA to identify key nodes in the network of transaction cost elements. This study calculates status-out centrality, status-in centrality, and betweenness centrality. It also applies Louvain community detection to identify cohesive subnetworks and to support the interpretation of each node's structural position. Based on these indicators, this study distinguishes transaction cost elements occupying antecedent, bridging, and dependent structural positions. It further integrates network visualization and path tracing to identify nodes located along structural pathways connected to high in-status nodes.

Step 8: Role-specific integration for key node identification:

Building on the established functions of ISM, MICMAC, and SNA, this study did not treat their outputs as interchangeable indicators. ISM is used to reveal hierarchical relationships among elements through reachability and level partitioning [81]. MICMAC classifies elements according to driving power and dependence power [82]. SNA identifies network positional importance through centrality measures, such as out-status, in-status, and betweenness centrality [83]. Based on these methodological roles, this study adopted a role-specific logic for identifying key transaction cost nodes.

Table 3
Role-specific criteria for identifying key transaction cost nodes.

Key node type	Main identification criterion	Role of ISM	Role of MICMAC	Role of SNA
Structurally antecedent key nodes	Consistency among ISM, MICMAC, and SNA	Lower ISM levels (bottom driving zone)	High driving power and low dependence power	High out-status centrality
Structurally dependent key nodes	Consistency among ISM, MICMAC, and SNA	Upper ISM levels (upper dependent zone)	High dependence power and low driving power	High in-status centrality
Bridging key nodes	Mainly based on SNA betweenness	–	–	High betweenness centrality
Path-relevant key nodes	Mainly based on path tracing	–	–	Repeated appearance in directed pathways leading to high in-status nodes

The criteria in Table 3 are based on the complementary roles of ISM, MICMAC, and SNA. ISM mainly indicates the hierarchical position of a node, showing whether a transaction cost is closer to the upstream side, the transmission process, or a downstream dependent position in the structure. MICMAC further explains the driving–dependence role of a node, indicating whether it has broad structural reachability or is more strongly influenced by other elements. SNA complements these analyses by identifying the network positional importance of nodes, including outward influence, inward convergence, and pathway-bridging roles. Therefore, structurally antecedent key nodes require consistency among lower ISM levels, high MICMAC driving power, low dependence power, and high SNA out-status centrality, because this combination indicates an upstream position, broad structural reachability, and outward network influence. By contrast, structurally dependent or convergence key nodes require consistency among upper ISM levels, high MICMAC dependence power, low driving power, and high SNA in-status centrality, because this combination indicates a downstream dependent position, strong dependence, and inward convergence. Bridging key nodes are identified mainly through SNA betweenness centrality because bridging is essentially a pathway-position issue rather than a hierarchical-position or driving–dependence classification issue. Path-relevant key nodes are identified through path tracing, because their importance lies in repeated appearance in directed pathways leading to high in-status nodes.

4. Results

4.1. Hierarchical patterns based on ISM and MICMAC

4.1.1. ISM hierarchical results

First, this study builds the Structural Self-Interaction Matrix (SSIM) based on the Delphi results (see **Appendix B**), converts it into the adjacency matrix (see **Appendix C**), and then derives the reachability matrix (see **Appendix D**) to determine hierarchical levels (see **Appendix E**). Next, this study constructs a 10-level structural model (see Fig. 2).

4.1.2. MICMAC clustering results

This study further applies MICMAC analysis to calculate the driving power and dependence of each transaction cost element. Driving power indicates the number of elements that a given element can reach in the reachability matrix. Dependence indicates the number of elements that

Fig. 2. Hierarchical structure model.

can reach that element in the reachability matrix. This study sums the corresponding rows and columns in the reachability matrix to obtain the driving power and dependence of each element. Based on the average levels of driving power and dependence, this study classifies all transaction cost elements into four MICMAC categories: driver elements, autonomous elements, linkage elements, and dependent elements (see Fig. 3).

By integrating the ISM hierarchical structure with the MICMAC clustering results, this study groups the ten ISM levels into three functional zones based on their driving power and dependence characteristics, as shown in Fig. 4. Elements from Level 10 to Level 7 form the bottom driving zone. This zone mainly consists of driver elements with high driving power and low dependence, such as TC1 and TC2. It lies at the base of the hierarchical structure, and elements at this level show broad reachability to upper-level elements.

Transaction cost elements from Level 6 to Level 5 form the middle connecting zone. This zone mainly includes linkage and autonomous elements, such as TC10 and TC13. It connects the lower driving zone and the upper dependent zone and plays a connecting role in the structural model. Elements at this level show both driving power and dependence.

TCs from Level 4 to Level 1 form the upper dependent zone. This zone mainly consists of dependent elements and some autonomous

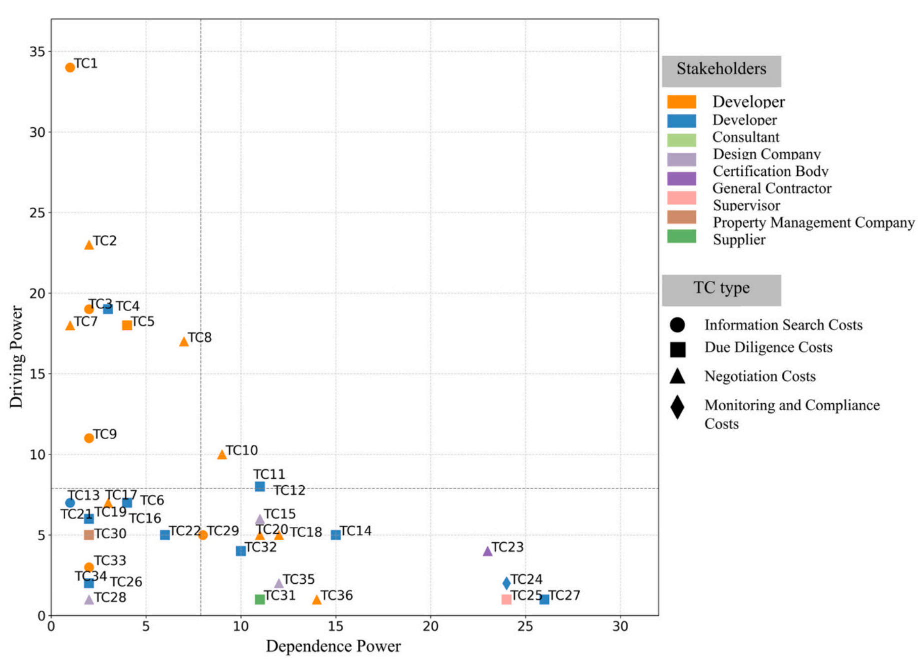

Fig. 3. Driving power–dependence diagram of transaction cost elements.

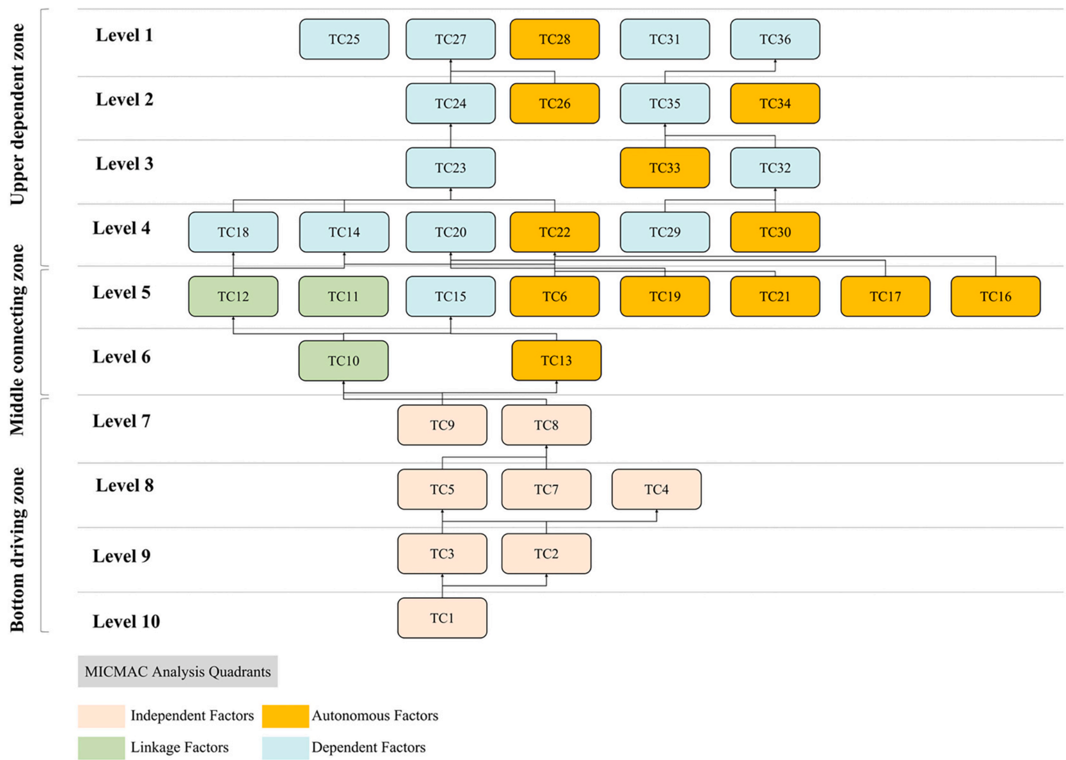

Fig. 4. Three-Zone Hierarchical Structure of Transaction Cost Elements Derived from ISM–MICMAC.

elements, such as TC23 and TC25. Elements at this level have low driving power and high dependence.

4.1.3. Characteristic distribution across transaction cost functional zones

To further examine heterogeneity across zones, Table 4 reports the distribution of characteristics across four dimensions: Stage, TC type, TC determinant, and stakeholder. The results show clear differences across the three zones.

First, the Bottom driving zone (L10–L7) is dominated by the concept stage (87.5%). In this zone, transaction costs are mainly associated with information search and negotiation (each 37.5%), followed by due diligence (25.0%). In terms of determinants, this zone is entirely driven by asset specificity (100.0%), mainly reflecting specific project requirements (50.0%) and professional personnel (25.0%). Stakeholder bearing is concentrated in the developer.

Second, transaction costs in the middle connecting zone (L6–L5) mainly occur in the design stage (50.0%) and the construction stage (40.0%). The dominant TC type is due diligence (40.0%), while information search and negotiation each account for 30.0%. Determinants are still predominantly asset-specific (90.0%), especially expertise (30.0%) and contract- and information-related specificity (each 20.0%), with only a small share of technological uncertainty (10.0%). Stakeholder involvement is more dispersed, led by consultants and developers, with additional contributions from design companies and certification bodies.

Third, the upper dependent zone (L4–L1) concentrates in the operation stage (44.4%) and the construction stage (38.9%). Transaction costs are dominated by due diligence (44.4%) and negotiation (33.3%), followed by information search (16.7%) and a small share of monitoring (5.6%). While asset specificity remains dominant (61.1%), uncertainty increases substantially (38.9%), including both technological (22.2%) and behavioral uncertainty (16.7%). Stakeholder bearing remains centered on consultants and developers.

4.2. Key node identification based on SNA

Based on the relational matrix in the Chinese context, this study applies Social Network Analysis (SNA) to identify the relative importance of nodes in the network of transaction cost elements. Table 5 reports the ranking of each node under three indicators: out-status, in-

Table 4
Characteristic Distribution Across Transaction Cost Functional Zones.

Functional zones	Stage distribution	TC type distribution (category %)	TC determinant distribution (source %)	MICMAC classification	Stakeholder bearing rate (%)
Bottom driving zone (L10–L7)	Concept: 87.5% Design: 12.5%	Information search: 37.5% Negotiation: 37.5% Due diligence: 25.0%	Asset specificity: 100.0%	Independent (IV): 100.0%	Developer: 100.0% Consultant: 37.5% Government: 25.0% Financial institution: 12.5%
Middle connecting zone (L6–L5)	Design: 50.0% Construction: 40.0% Concept: 10.0%	Due diligence: 40.0% Information search: 30.0% Negotiation: 30.0%	Asset specificity: 90.0% Uncertainty: 10.0%	Autonomous (I): 60.0% Linkage (III):30.0% Dependent (II): 10.0%	Consultant: 80.0% Developer: 70.0% Design company: 40.0% Certification body: 30.0%
Upper dependent zone (L4–L1)	Operation: 44.4% Construction: 38.9% Design: 16.7%	Due diligence: 44.4% Negotiation: 33.3% Information search: 16.7% Monitoring: 5.6%	Asset specificity: 61.1% Uncertainty: 38.9%	Dependent (II): 66.7% Autonomous (I): 33.3%	Consultant: 72.2% Developer: 66.7% General contractor, property management company, and supervisor: periodic involvement

Table 5
Ranking of Transaction Cost Elements Based on SNA.

Rank	TC ID	Status-out centrality	TC ID	Status-in centrality	TC ID	Node betweenness centrality
1	**TC1**	0.5623	**TC23**	0.2842	**TC8**	0.0344
2	**TC2**	0.0811	**TC24**	0.2521	**TC10**	0.0234
3	**TC17**	0.0712	**TC25**	0.2482	**TC12**	0.0215
4	TC12	0.0441	TC27	0.2142	TC29	0.0193
5	TC16	0.0441	TC14	0.1852	TC14	0.0173
6	TC21	0.0441	TC20	0.1684	TC32	0.0134
7	TC6	0.0438	TC36	0.1421	TC20	0.0125
8	TC3	0.0384	TC10	0.1321	TC23	0.012
9	TC4	0.0384	TC8	0.1245	TC35	0.0067
10	TC10	0.0381	TC12	0.1182	TC5	0.0051
11	TC14	0.0384	TC31	0.1121	TC6	0.0045
12	TC18	0.0384	TC35	0.1121	TC11	0.0029
13	TC22	0.0384	TC18	0.1121	TC17	0.0027
14	TC20	0.0312	TC11	0.1065	TC18	0.0023
15	TC5	0.0302	TC15	0.1062	TC24	0.0021
16	TC7	0.0302	TC32	0.1062	TC9	0.0008
17	TC9	0.0302	TC22	0.0921	TC2	0.0004
18	TC11	0.0302	TC6	0.0842	TC3	0.0004
19	TC13	0.0302	TC29	0.0841	TC16	0.0003
20	TC19	0.0302	TC5	0.0614	TC21	0.0003

status, and betweenness centrality. Following Rajeh and Cherifi [84], this study defines the top three nodes under each indicator as key nodes. Fig. 5 illustrates the network structure of transaction cost elements.

Specifically, the top three nodes in out-status centrality are TC1 (searching for experienced consultants), TC2 (signing consultancy contracts), and TC17 (partner contract negotiation). Out-status centrality reflects a node's outward reachability within the consensus-based network. Higher scores indicate a more outward-oriented structural position [48]. The top three nodes by betweenness centrality are TC8 (Financing), TC10 (drafting design contracts), and TC12 (performance simulation). Betweenness centrality captures a node's bridging position in network paths. Higher scores indicate that the node more frequently lies on structural pathways between other nodes [85]. The top three nodes in in-status centrality are TC23 (change and dispute resolution), TC24 (construction process monitoring), and TC25 (collection and verification of construction inspection results). In-status centrality reflects the extent to which a node receives incoming structural links from other nodes. Higher scores suggest that the node occupies a structurally dependent position where multiple perceived dependencies converge [48]. Meanwhile, as shown in Fig. 6, the community detection results indicate that TC23, TC24, and TC25 belong to Community 2. This community has the highest internal-to-external edge ratio (1.0455), indicating that it exhibits the strongest internal cohesion among all communities [99]. This community is mainly concentrated in the construction stage, suggesting that these transaction cost elements are embedded in a tightly connected construction-stage subnetwork.

To further examine the structurally antecedent elements associated with the three transaction cost elements with the highest status-in centrality, this study follows the approach of He and Chen [38] to extract structural influence pathways connected to these top three nodes. In

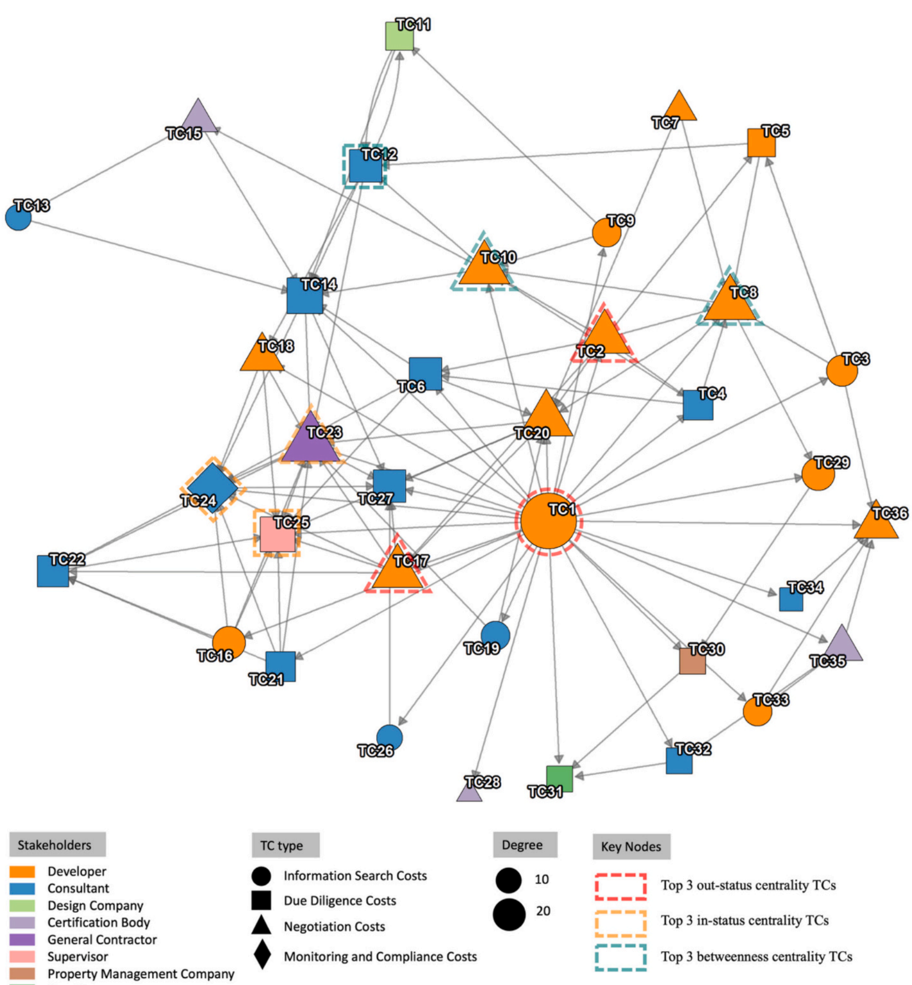

Fig. 5. SNA-based network structure of transaction cost elements.

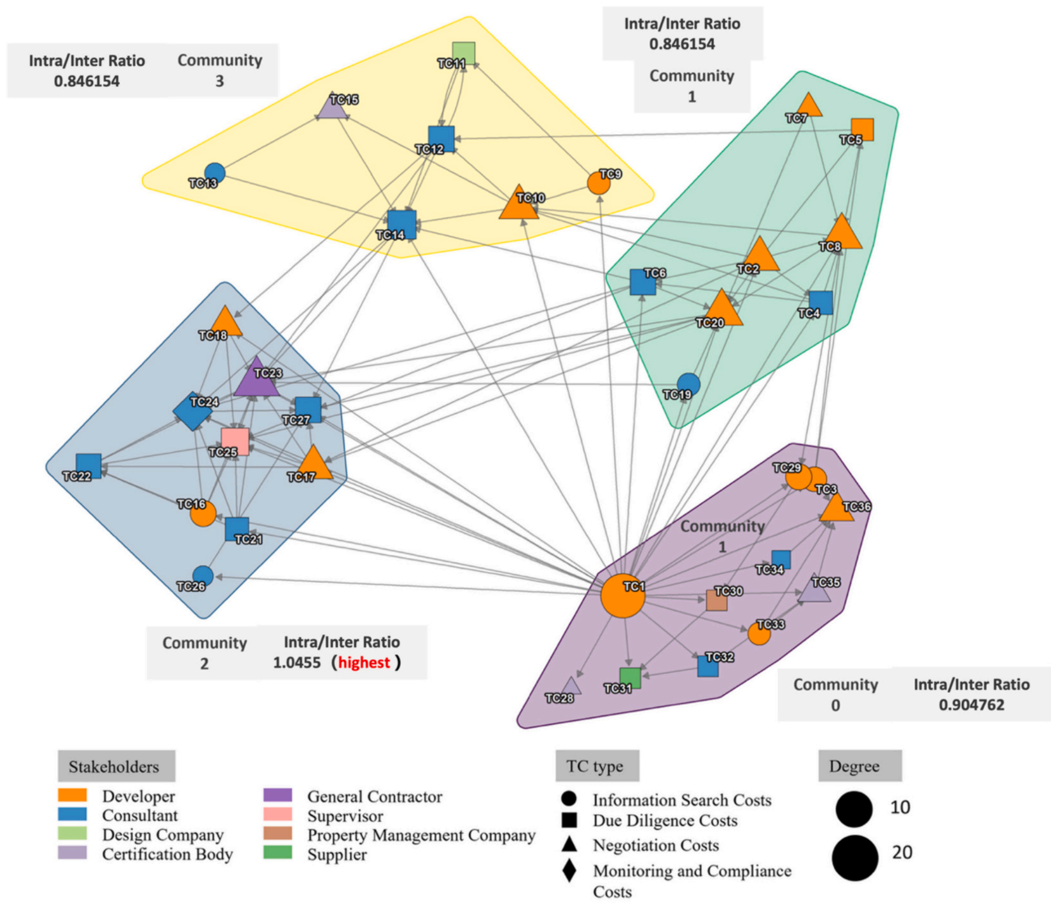

Fig. 6. Community Structure of the Transaction Cost Network Based on SNA.

addition to the nine nodes identified by the three centrality indicators, path tracing further highlighted the important pathway positions of TC14, TC17, and TC22. Because TC14, TC17, and TC22 repeatedly appeared in pathways leading to high in-status nodes, they were treated as path-relevant nodes.

4.3. Integrated ISM–MICMAC–SNA interpretation of key transaction cost nodes

Based on the role-specific criteria defined in Section 3.2, the key transaction cost nodes were further interpreted by integrating the SNA results with the ISM–MICMAC structure. The centrality results were not treated as a single ranking of key nodes. Instead, different indicators were used to clarify different structural roles.

First, TC1 and TC2 were interpreted as structurally antecedent key nodes. Both nodes are located in the bottom driving zone of the ISM hierarchy and show high MICMAC driving power and low dependence power. They also rank first and second in SNA out-status centrality. This consistency suggests that these nodes occupy upstream structural positions, have broad structural reachability, and show strong outward network positions.

Second, TC23, TC24, and TC25 were interpreted as structurally dependent key nodes. These nodes are located in the upper dependent zone of the ISM hierarchy, show high MICMAC dependence power and low driving power, and rank as the top three nodes in SNA in-status centrality. This consistency indicates that they occupy downstream dependent positions where multiple perceived structural dependencies converge.

Third, TC8, TC10, and TC12 were interpreted as bridging key nodes because they rank highest in SNA betweenness centrality. In this study, these nodes help connect different structural pathways across early project decisions, contractual arrangements, technical simulation, and later construction-stage governance activities.

Fourth, TC14, TC17, and TC22 were interpreted as path-relevant key nodes. These nodes repeatedly appeared in directed pathways leading to the high in-status nodes TC23, TC24, and TC25, indicating that they occupy important pathway positions in the structural relationships toward downstream dependent nodes.

Based on this integrated interpretation, the key transaction costs were grouped into four categories, as shown in Fig. 7.

5. Discussion

5.1. Stakeholder perspective: Developer-borne transaction costs related to consultants at the base of the hierarchy

As shown in Section 4.1.3, the results show that the developer bears most transaction costs in the bottom driving zone (L10–L7). This finding aligns with Wang et al. [14], who identify the developer as a key bearer of transaction costs. More importantly, the structural hierarchy shows that the developer's transaction costs are not only high in share but also concentrated at the base of the transaction cost element network.

Further analysis shows that the transaction costs the developer bears in the bottom driving zone mainly focus on consultant selection and contract formation, policy and subsidy information search and feasibility assessment. This pattern suggests that, in the early stage, the developer invests transaction costs to access professional expertise and form collaborative relationships. These costs are located at the base of

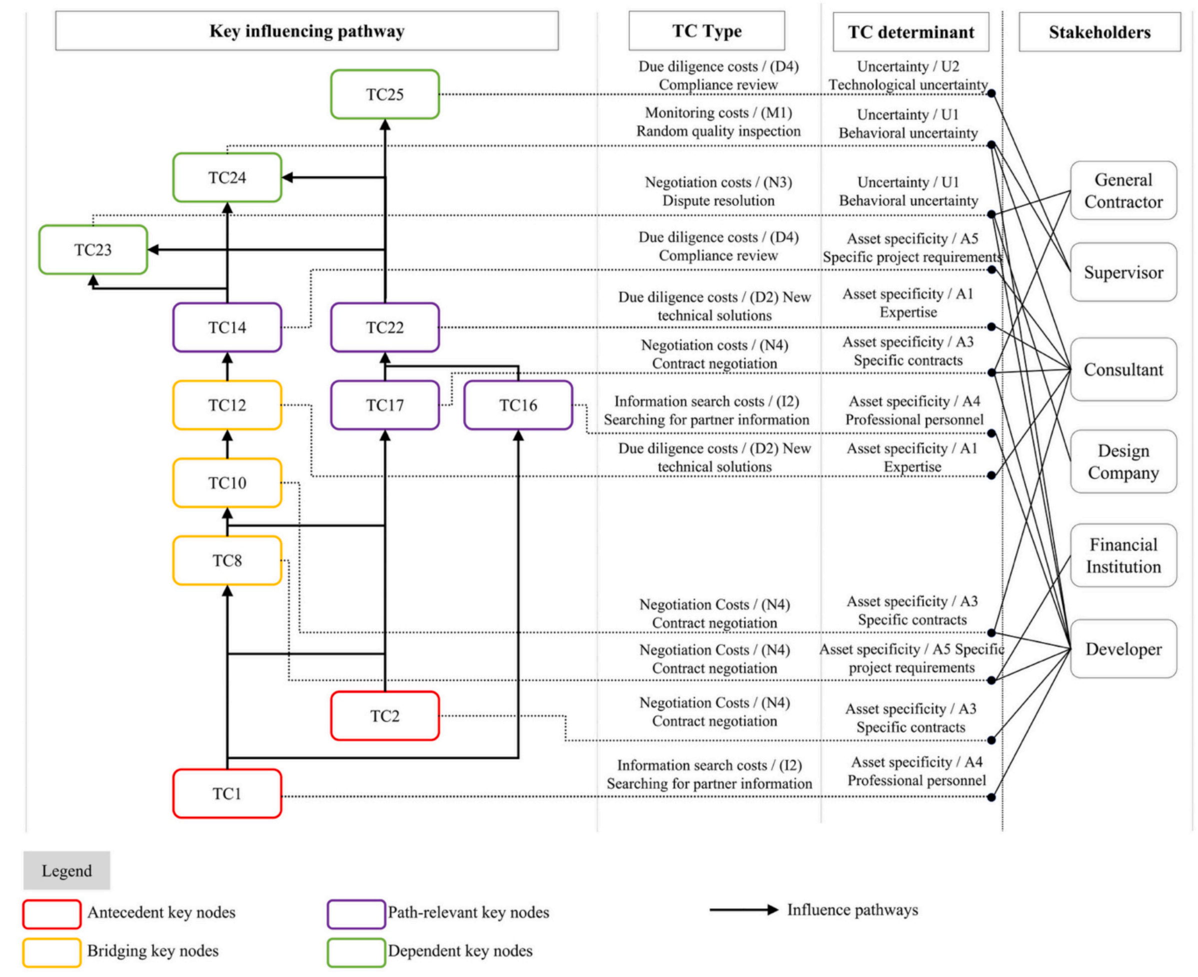

Fig. 7. Structural Pathways of Key Transaction Cost Elements and Their Associated Types, Determinants, and Stakeholders.

the hierarchy and are perceived by experts as having structural influence on downstream transaction cost elements.

Compared with conventional building projects, the developer often lacks NZEB-related knowledge and information. In this context, engaging experienced consultants becomes a key way for the developer to reduce project uncertainty. Prianto et al. [86] note that consultants provide technical coordination and information integration in sustainable building implementation and play an important role in reducing uncertainty. However, the developer faces disadvantages in information and knowledge. As a result, the developer needs to invest more resources in information search and communication during consultant selection and contract formation to reduce risks in later stages [87]. Therefore, improving the developer's NZEB-related knowledge and information can reduce information search and communication costs during consultant selection and contract formation. This improvement may help reduce opportunistic risks and uncertainty related to information asymmetry in later stages, thereby potentially lowering downstream transaction cost burdens.

5.2. TC type and determinant perspective: Bottom-layer TCs are mainly driven by asset specificity

As shown in Section 4.1.3, the functional zones exhibit a clear hierarchical pattern: asset specificity drives the lower levels, while uncertainty becomes more prominent in the upper layers. The bottom driving zone (Level 10–7) reflects the asset-specific investments required to initiate NZEB projects. These include early commitments to project requirements, key professionals, and non-standardized information and contractual arrangements. In the middle connecting zone (Level 6–5), these early investments are translated into executable technical choices and inter-organizational coordination processes. During this process, expertise remains central, while technological uncertainty begins to emerge. In the upper dependent zone (Level 4–1), uncertainty becomes more prominent, primarily manifesting as additional efforts in verification, coordination, and dispute resolution.

This hierarchy suggests that information search and contract-related communication associated with asset specificity occupy structurally antecedent positions in relation to later transaction cost elements. Their structural influence is represented through perceived dependency pathways involving technical decisions, compliance review, coordination, and negotiation. These pathways are associated with upper-level cost types such as dispute coordination, compliance confirmation, and process monitoring, which are more closely related to uncertainty. In the Chinese NZEB context, this result supports Williamson [23]: insufficient ex ante arrangements for contract drafting and negotiation increase ex post efforts in monitoring and enforcement, adjustment, and dispute handling.

5.3. Stage evolution perspective: Cross-stage perceived dependencies across the lifecycle

As shown in Section 4.1.3, the distribution across project stages reveals clear cross-stage perceived dependencies. The bottom driving zone is dominated by transaction costs in the concept stage. The middle connecting zone mainly involves transaction costs in the design and construction stages. The upper dependent zone concentrates on transaction costs in the construction and operation stages. This pattern indicates that transaction costs are structurally linked across lifecycle stages through consensus-based directional relationships.

Existing studies often treat the construction stage as the primary stage of transaction cost occurrence and attribute this to technical and organizational complexity within that stage [88]. However, this study shows that construction-stage transaction costs are linked to earlier transaction cost elements in the concept and design stages. In the expert-consensus model, they should not be viewed only as construction-stage issues, but also as elements embedded in broader cross-stage perceived dependencies.

Construction-stage transaction costs are located mainly in the middle and upper layers of the hierarchical structure and remain structurally associated with transaction costs in earlier stages. Antoniou and Tsioulpa [93] also show that unclear technical and performance requirements in the design stage lead to frequent changes and disputes in the construction stage and significantly increase downstream coordination costs.

The construction stage also shows dense internal dependencies. Because construction processes follow a strict sequence, deviations from earlier decisions may be associated with change and dispute-resolution costs (TC23). To correct deviations and ensure compliance, the project team must also increase investment in construction process monitoring and result collection (TC24) and in evaluation document preparation and confirmation (TC27). Love et al. [89] also show that early quality defects often surface during construction and amplify through rework, disputes, and supervision.

Overall, this study moves beyond approaches that treat transaction costs in different stages as isolated [21]. It further reveals cross-stage structural relationships and deepens understanding of the formation conditions associated with transactiz on cost burdens in different stages.

5.4. *Structural perspective: Key transaction cost elements and related sources*

As shown in Section 4.3, this study identifies 12 key transaction cost elements, grouped into four structural roles. Based on transaction cost determinants and transaction cost types, this study further organizes the key transaction cost elements into five groups: (1) selection of consultants and construction partners; (2) negotiation of consultancy, design, and construction contracts; (3) formulation of design and construction technical solutions; (4) preparation of design and construction certification documents and (5) construction changes and dispute handling, as well as process inspection. Table 6 lists the specific transaction cost elements in each group.

This study further summarizes the main factors associated with these key transaction cost elements and identifies five related sources: (1) limited access channels for NZEB consultants and construction partners and low market transparency; (2) insufficient NZEB-related knowledge among project participants and a lack of standardized contract clauses; (3) the presence of non-conventional technical activities and cross-actor collaboration in NZEB projects; (4) inconsistencies between certification and evaluation documentation requirements and on-site implementation criteria; (5) significant technological and behavioral uncertainty in the construction stage. This study responds to Wang et al. [14], who call for further examination of interactions among transaction costs. Compared with prior studies that focus on identifying transaction cost elements or describing static distributions, this study locates key nodes within the transaction cost element structure and discusses their related formation conditions. By grouping key transaction cost elements and clarifying their related sources, this study contributes to a systematic understanding of the formation conditions associated with transaction cost burdens in Chinese NZEB projects and provides a basis for identifying priority transaction cost types and key nodes for governance.

5.5. *Implications and limitations*

5.5.1. *Theoretical implications*

This study provides theoretical implications for Transaction Cost Theory (TCT). First, this study does not merely use TCT to classify the determinants of transaction costs. Instead, it extends its application from isolated transactions to a networked and multi-stage NZEB project system. Classical TCT commonly focuses on a core transaction and its governance structure, such as market, hierarchy, or hybrid governance [92]. In contrast, NZEB projects involve multiple interdependent transactions across project stages, organizations, and stakeholder interfaces. Therefore, transaction cost governance in NZEB projects cannot be understood only as the selection of an appropriate governance

Table 6
Grouping and explanation of key transaction cost elements.

Key TCs	Main category	TC type	Determinant(s)	Rationale
TC1, TC16	Consultant and construction partner selection(A)	I2 Partner information search	Asset specificity (professional personnel)	Limited access to qualified professional services and low market transparency increase the costs of partner search and screening [90].
TC2, TC8, TC10, TC17	Negotiation of consultancy, design, and construction contracts(B)	N4 Contract negotiation	Asset specificity (specific contracts and specific project requirements)	In complex projects, contract incompleteness and unclear clauses and interface boundaries increase renegotiation costs [26].
TC12, TC22	Formulation of design and construction technical solutions(C)	D2 New technical solutions	Asset specificity (expertise)	NZEB implementation involves extensive active and passive technical activities and cross-actor collaboration. This increases uncertainty in technical pathways and performance delivery and raises the costs of technical solution decisions [15].
TC14, TC25	Preparation of design and construction certification documents(D)	D4 Compliance review	Asset specificity (specific project requirements) and uncertainty (technological uncertainty)	Evaluation requirements are often not aligned with project technical outputs and site records. As a result, evidence documents often require supplementation, revision, and reconfirmation during submission and review, which creates repeated work [54].
TC23, TC24	Construction changes, dispute handling, and process inspection(E)	N3 Dispute resolution (TC23) and M1 Random quality inspection (TC24)	Uncertainty (behavioral uncertainty)	When deviations or changes occur during construction, dispute handling and quality verification often rely on site inspection records as evidence. If records are fragmented, inconsistent, or incomplete, information gaps trigger repeated verification and communication, increasing transaction costs related to disputes and inspections [91].

structure for a single transaction. It should also be understood as the cross-stage coordination of multiple interrelated transaction relationships.

Second, the findings show that transaction cost elements in NZEB projects have structural dependencies across different project stages. This extends the classical ex ante–ex post logic in TCT [23]. Traditional TCT emphasizes that incomplete ex ante arrangements may generate ex post governance costs within the same transaction, such as monitoring, enforcement, adaptation, and dispute-resolution costs. This study further shows that, in networked and multi-stage NZEB projects, insufficient ex ante arrangements may not only affect ex post governance within the same transaction, but may also be structurally connected to downstream transaction cost elements across different stages and stakeholder interfaces.

Third, the findings further enrich the understanding of governance structure, contract completeness, and alignment mechanisms in TCT. In networked and multi-stage NZEB projects, governance structure should not be understood only as the choice among market, hierarchy, and hybrid forms for a single transaction. It should also be understood as a governance arrangement for coordinating multiple transaction relationships across organizations and project stages. Contract completeness should not only refer to whether legal terms are sufficiently specified in a single contract. It should also include whether performance targets, technical responsibilities, certification evidence, construction records, and handover requirements are aligned across different project stages. In this sense, alignment mechanisms are theoretically important because they explain why transaction costs may become structurally connected across actors, contractual interfaces, and project stages. Therefore, this study extends transaction cost governance in TCT from the governance choice of a single transaction relationship to the explanation of structural dependencies among multiple actors, multiple contracts, and multiple project stages.

5.5.2. Practical implications

First, prioritize and mitigate transaction costs borne by the developer during consultant selection.

The results show that most transaction costs in the bottom driving zone are borne by the developer and concentrate on consultant selection and consultancy contract formation. This finding suggests that transaction costs differ across stakeholders. Governance should therefore prioritize key stakeholders and key stages. This means project managers should first identify and reduce information search and communication costs during consultant selection. Tan et al. [87] show that targeted NZEB training and education can improve the developer's understanding of NZEB and reduce opportunistic risks caused by information asymmetry, thereby lowering transaction costs related to consultant selection.

Second, prioritize controlling early-stage transaction costs driven by asset specificity.

The results show clear differences in the hierarchical structure of transaction costs. In the bottom driving zone, transaction costs are mainly driven by asset specificity and often take the form of information search, contract negotiation, and key decision-making activities. In the upper dependent zone, transaction costs are more closely related to uncertainty and often manifest as dispute coordination, compliance confirmation, process monitoring, and result verification. This pattern indicates that transaction costs driven by different determinants occupy different positions in the hierarchical structure. Project managers should prioritize managing early-stage transaction costs driven by asset specificity, as these costs are structurally linked to later-stage transaction cost burdens driven by uncertainty.

Third, shift transaction cost governance upstream to the concept and design stages to manage construction-stage transaction cost burdens.

The results show that construction-stage transaction cost burdens are structurally related to earlier arrangements in the concept and design stages. If technical and coordination uncertainty are not addressed in the concept and design stages, the construction stage is more likely to experience frequent changes and disputes, which significantly increase coordination costs [93]. Therefore, project managers should link construction-stage transaction costs with earlier-stage costs and move key governance efforts to the concept and design stages.

Fourth, key transaction cost mitigation should align with the types and determinants of transaction costs.

Based on the classification of key transaction cost elements in Table 5 and their related sources, this study proposes five targeted mitigation strategies. At the industry level, stakeholders can improve the accessibility and verifiability of information on consultants and construction partners to reduce repeated search and screening costs (Strategy A) [94]. They can also standardize contract clauses and clarify key boundaries early to reduce repeated negotiation and downstream monitoring and dispute-related efforts (Strategy B) [95]. In parallel, harmonized technical evaluation methods and regional standardization of technical pathways can reduce uncertainty in solution selection and limit implementation deviations and rework risks (Strategy C) [96]. For certification-related costs, systematizing documentation and aligning it with technical outputs can reduce supplementary documentation and repeated confirmation (Strategy D) [97]. At the project level, standardized procedures for construction changes and dispute handling, together with formalized inspection records, can reduce information gaps, repeated verification, and communication burdens (Strategy E) [98].

5.5.3. Research limitations and future research directions

This study integrates the Delphi method, ISM–MICMAC, and Social Network Analysis (SNA) to identify structural relationships among transaction cost elements in Chinese NZEB projects. However, several limitations remain.

First, this study relies on expert consensus to identify transaction cost relationships, which inevitably introduces subjectivity. Two rounds of anonymous Delphi surveys, controlled feedback, and a predefined consensus threshold helped reduce authority effects and conformity bias. This study also examined disagreement patterns, response dispersion and distribution, and the stability of dominant judgments between the two rounds. However, expert judgments may still reflect personal experience, professional background, anchoring effects, institutional norms, and path dependence. In addition, snowball sampling ensured professional depth but may also have produced network homogeneity and reduced diversity of perspectives. The expert panel was also embedded in the Chinese NZEB institutional context, which may shape how experts perceive transaction cost relationships. Future research can broaden expert sources, increase diversity in expert composition, and compare results across different stakeholder groups and institutional contexts. When larger-scale empirical datasets become available, future research may also employ alternative analytical approaches, such as Structural Equation Modeling (SEM) or Bayesian network analysis, to further test and validate the structural relationships identified in this study.

Second, binary modeling of relationships is a major limitation of this study. The SSIM-to-adjacency-matrix transformation records only whether a perceived directional relationship exists, using 0/1 coding. This approach is useful for constructing an interpretable ISM–MICMAC–SNA model, but it inevitably leads to a loss of relational information. It cannot distinguish between strong and weak relationships, frequent and rare interactions, or critical and marginal dependencies. This simplification may affect the interpretation of the results. For example, SNA centrality measures may be distorted because all identified relationships are treated as equal. A weak relationship and a strong relationship both receive the same value of 1. This may influence the identification of key nodes among transaction cost elements. Similarly, the interpretation of path dominance may be affected, because the model shows whether a structural pathway exists, but not whether that pathway is stronger, more frequent, or more important than other pathways. Therefore, the results should be interpreted as structural patterns based on consensus-based directional relationships, rather than as quantitative measures of influence strength or path dominance. Future research can address this limitation by using fuzzy ISM, weighted SNA, and probabilistic graph models to capture relationship strength, uncertainty, and the probability of interaction more precisely.

Third, the structural model developed in this study is static. ISM–MICMAC–SNA captures relational structures under a given context but cannot fully reflect the dynamic evolution of transaction costs during project implementation. In addition, the applicability of the framework to larger and more complex projects requires further examination. In projects with longer delivery periods or more diverse stakeholder configurations, relationships among transaction cost elements may evolve further and produce denser and more heterogeneous network structures. Future research can therefore combine dynamic network analysis, system dynamics, or agent-based modeling to test both the temporal evolution of structural relationships and the applicability of the framework under larger project scales and more differentiated stakeholder systems.

Fourth, this study lacks contextual validation through detailed project processes. Although expert judgments integrate multi-project experience, the mechanisms of key paths and key nodes require further validation through process tracing or multi-case comparison to assess stability and variation across project conditions.

Finally, this study is grounded in the Chinese NZEB context, which substantially shapes the empirical findings. NZEB implementation in China is characterized by government-led promotion, policy-driven incentives, multi-level regulation, demonstration projects, and certification-heavy procedures. These features increase the importance of policy information search, compliance review, certification documentation, construction-stage monitoring, and inspection-related verification. Therefore, the specific structural results identified in this study should be interpreted mainly within China's policy-driven and certification-oriented implementation system, rather than directly generalized to all NZEB contexts.

The generalizability of this study should therefore be understood at two levels. At the methodological level, the Delphi–ISM–MICMAC–SNA analytical pathway is transferable because it provides a systematic procedure for identifying consensus-based directional relationships, hierarchical structures, driving–dependence roles, and key transaction cost nodes. At the empirical level, however, the specific hierarchy, functional zones, and key transaction costs are context-specific. This distinction is important because NZEB and zero-energy building frameworks differ across countries. In the European Union, implementation is embedded in the Energy Performance of Buildings Directive and its transposition by Member States. In the United States, zero-energy building practice is more decentralized and is often shaped by voluntary programs, market incentives, and state or local policy variation. Therefore, transaction cost structures may differ between government-driven, certification-heavy systems and more decentralized or market-driven systems. Future research can conduct cross-country comparisons to test the boundary conditions and robustness of the structural findings.

6. Conclusion

NZEBs play a key role in the global transition toward carbon neutrality and net-zero emissions. It reduces operational energy use through passive design, high-performance systems, and renewable energy integration. Therefore, scaling up NZEB implementation has important practical value for the low-carbon transition in the building sector. However, the diffusion of NZEB in China remains slow. Beyond incremental investment, transaction costs arising from multi-stage certification, multi-actor collaboration, and information asymmetry constitute a critical yet often underestimated barrier. Compared with prior studies that focus on listing transaction costs and describing static distributions, this study adopts a structural-interaction perspective to examine how transaction cost elements are hierarchically organized and structurally related across stages. It uses a two-round Delphi survey and an integrated ISM–MICMAC–SNA approach to reveal the hierarchical structure, driving–dependence features, and key nodes among 36 transaction cost elements in Chinese NZEB projects.

The findings address Research Question 1 and describe the hierarchical structure, driving–dependence relationships, and coupling patterns of transaction cost elements in Chinese NZEB projects. First, from a stakeholder perspective, transaction costs in the bottom driving zone and the middle connecting zone are borne mainly by the developer. The developer's early investments in consultant selection and consultancy contract formation lie at the base of the hierarchical structure and are associated with later transaction cost burdens. Second, from the perspective of transaction cost types and determinants, search, negotiation, and decision-related costs associated with asset specificity mainly fall within the bottom-driving zone and occupy important lower-level positions. Dispute coordination, compliance confirmation, and process monitoring and verification costs associated with uncertainty mainly appear in the upper dependent zone and are structurally associated with the former. Third, from a stage perspective, transaction costs show cross-stage directional relationships from the concept stage to the design and construction stages, and then to the construction and operation stages.

The findings also address Research Question 2. This study identifies 12 key transaction cost elements in the modeled structural network. It further groups them into five categories based on transaction cost types and determinants and discusses their related sources. Based on these findings, this study proposes four managerial implications. These implications offer a new analytical lens and practical pathway for understanding structural relationships among transaction cost elements in Chinese NZEB projects and for designing targeted governance and mitigation strategies.

CRediT authorship contribution statement

Hanbing Wang: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Bo Shu:** Writing – review & editing, Supervision. **Henk Visscher:** Writing – review & editing, Supervision. **Queena K. Qian:** 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 influenced the work reported in this paper.

Appendix A. Table A.1. Transaction Costs in the Implementation Process of NZEB in China.

Stage	Transaction Cost	Stakeholders	TC type	TC determinant
Concept Stage	TC1 Searching for experienced consultants	Developer	I2 Searching for partner information	Asset Specificity(Professionals)
	TC2 Signing consultancy contracts	Developer	N4 Contract negotiation	Asset Specificity(Specific Contracts)
	TC3 Policy search	Developer	I4 Searching for policy and subsidy info	Asset Specificity(Specific Information)
	TC4 Feasibility Assessment	Consultant	D1 Feasibility assessment	Asset Specificity(Specific Project Requirements)
	TC5 Decision-making costs	Developer	D3 Decision-making costs	Asset Specificity(Specific Project Requirements)
	TC6 Compliance review	Consultant	D4 Compliance review	Asset Specificity(Specific Project Requirements)
	TC7 Land bidding	Developer	N2 Licensing fees	Asset Specificity(Specific Project Requirements)
	TC8 Financing	Developer	N4 Contract negotiation	Asset Specificity(Specific Project Requirements)
Design Stage	TC9 Searching for experienced design companies	Developer	I2 Searching for partner information	Asset Specificity(Professionals)
	TC10 Drafting design contracts	Developer	N4 Contract negotiation	Asset Specificity(Specific Contracts)
	TC11 Design-technology training for energy-oriented design	Design Company	D2 New technical solutions	Asset Specificity(Expertise)
	TC12 Performance simulation	Consultant	D2 New technical solutions	Asset Specificity(Expertise)
	TC13 Information on design evaluation requirements	Consultant	I1 Searching for specifications and certification requirements	Asset Specificity(Specific Information)
	TC14 Preparation and confirmation of design evaluation documents	Consultant	D4 Compliance review	Asset Specificity(Specific Project Requirements)
	TC15 Communication of design evaluation information	Certification Body	N1 Coordination costs	Uncertainty(Technological Uncertainty)
Construction Stage	TC16 Searching for experienced partners	Developer	I2 Searching for partner information	Asset Specificity(Professionals)
	TC17 Partner contract negotiation	Developer	N4 Contract negotiation	Asset Specificity(Specific Contracts)
	TC18 Construction instructions	Developer	N3 Dispute resolution	Uncertainty(Behavioral Uncertainty)
	TC19 Material and equipment selection	Consultant	I3 Searching for case studies and technical information	Asset Specificity(Specific Information)
	TC20 Material and equipment contract negotiation	Developer	N4 Contract negotiation	Asset Specificity(Specific Contracts)
	TC21 Demonstrating construction processes	Consultant	D2 New technical solutions	Asset Specificity(Expertise)
	TC22 Construction process optimization	Consultant	D2 New technical solutions	Asset Specificity(Expertise)
	TC23 Change and dispute resolution	General Contractor	N3 Dispute resolution	Uncertainty(Behavioral Uncertainty)
	TC24 Construction monitoring	Consultant	M1 Random quality inspection	Uncertainty(Behavioral Uncertainty)
	TC25 Collecting inspection results during construction	Supervisor	D4 Compliance review	Uncertainty(Technological Uncertainty)
	TC26 Information on construction evaluation requirements	Consultant	I1 Searching for specifications and certification requirements	Asset Specificity(Specific Information)
	TC27 Preparation and confirmation of construction evaluation documents	Consultant	D4 Compliance review	Asset Specificity(Specific Project Requirements)
	TC28 Construction evaluation review	Certification Body	N1 Coordination costs	Uncertainty(Technological Uncertainty)
Operation Stage	TC29 Searching for experienced property management companies	Developer	I2 Searching for partner information	Asset Specificity(Professionals)
	TC30 Training on NZEB building usage	Property Management Company	D2 New technical solutions	Asset Specificity(Expertise)
	TC31 Training on NZEB building maintenance	Supplier	D2 New technical solutions	Asset Specificity(Expertise)
	TC32 Energy consumption optimization	Consultant	D2 New technical solutions	Asset Specificity(Expertise)
	TC33 Information on operational evaluation requirements	Developer	I1 Searching for specifications and certification requirements	Asset Specificity(Specific Information)
	TC34 Preparation and confirmation of operational evaluation documents	Consultant	D4 Compliance review	Asset Specificity(Specific Project Requirements)
	TC35 Operational evaluation review	Certification Body	N1 Coordination costs	Uncertainty(Technological Uncertainty)
	TC36 Certification communication	Developer	N1 Coordination costs	Uncertainty(Technological Uncertainty)

Source: H. Wang et al. [14].

Appendix B.

Table B.1. Structural self-interaction matrix

SSIM	TC36	TC35	TC34	TC33	TC32	TC31	TC30	TC29	TC28	TC27	TC26	TC25	TC24	TC23	TC22	TC21	TC20	TC19	TC18	TC17	TC16	TC15	TC14	TC13	TC12	TC11	TC10	TC9	TC8	TC7	TC6	TC5	TC4	TC3	TC2	TC1
TC1	V	V	V	V	V	V	V	V	V	V	V	V	V	V	O	V	V	V	V	V	V	O	V	O	O	O	V	V	V	O	V	O	V	V	V	
TC2	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	O	V	O	O	O	O	O	O	V	O	V	O	V	V	V	O		
TC3	V	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	O	V	O			
TC4	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	V	O	V	O				
TC5	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	O	O	V	O	O					
TC6	O	O	O	O	O	O	O	O	O	O	O	V	V	O	O	O	V	O	O	O	O	O	V	O	O	O	O	O	O	O						
TC7	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	O	O	O	O	O	O	O	O	O	O	V							
TC8	O	O	O	O	O	O	O	V	O	O	O	O	O	O	O	O	V	O	O	O	O	O	O	O	O	O	V	O								
TC9	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	V									
TC10	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	V	O	V	O										
TC11	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	V											
TC12	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	O	O	O	V	O	O	O	V	O												
TC13	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	V													
TC14	O	O	O	O	O	O	O	O	O	V	O	O	V	V	O	O	O	O	O	O	O	A														
TC15	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O															
TC16	O	O	O	O	O	O	O	O	O	O	O	V	V	V	V	O	O	O	O	O																
TC17	O	O	O	O	O	O	O	O	O	V	O	V	V	V	V	O	V	O	O																	
TC18	O	O	O	O	O	O	O	O	O	O	O	V	V	V	O	O	O	O																		
TC19	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	O	V																			
TC20	O	O	O	O	O	O	O	O	O	V	O	V	O	V	O	O																				
TC21	O	O	O	O	O	O	O	O	O	O	O	V	V	V	V																					
TC22	O	O	O	O	O	O	O	O	O	O	O	V	V	V																						
TC23	O	O	O	O	O	O	O	O	O	V	O	V	V																							
TC24	O	O	O	O	O	O	O	O	O	V	O	O																								
TC25	O	O	O	O	O	O	O	O	O	O	O																									
TC26	O	O	O	O	O	O	O	O	O	V																										
TC27	O	O	O	O	O	O	O	O	O																											
TC28	O	O	O	O	O	O	O	O																												
TC29	O	O	O	O	V	V	O																													
TC30	O	O	O	O	V	O																														
TC31	O	O	O	O	A																															
TC32	O	V	O	O																																
TC33	V	V	O																																	
TC34	V	O																																		
TC35	V																																			
TC36																																				

Appendix C

Table C.1. Adjacency matrix

AM	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15	TC16	TC17	TC18	TC19	TC20	TC21	TC22	TC23	TC24	TC25	TC26	TC27	TC28	TC29	TC30	TC31	TC32	TC33	TC34	TC35	TC36
TC1	0	1	1	1	0	1	0	1	1	1	0	0	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
TC2	0	0	0	1	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC3	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TC4	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC5	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
TC7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC8	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
TC9	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC10	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC11	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
TC13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0
TC15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
TC17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0
TC18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
TC19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
TC20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0
TC21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
TC22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
TC23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0
TC24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
TC25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
TC27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
TC30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
TC31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TC32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
TC33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
TC34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TC35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TC36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix D

Table D.1. Reachability matrix.

RM	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15	TC16	TC17	TC18	TC19	TC20	TC21	TC22	TC23	TC24	TC25	TC26	TC27	TC28	TC29	TC30	TC31	TC32	TC33	TC34	TC35	TC36	Driving power
TC1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	34
TC2	0	1	0	1	1	1	0	1	0	1	0	1	0	1	1	0	1	1	0	1	0	1	1	1	1	0	1	0	1	0	1	1	0	0	1	1	22
TC3	0	0	1	0	1	0	0	1	0	1	0	1	0	1	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	1	0	0	1	1	18
TC4	0	0	0	1	0	1	0	1	0	1	0	1	0	1	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	1	0	0	1	1	18
TC5	0	0	0	0	1	0	0	1	0	1	0	1	0	1	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	1	0	0	1	1	17
TC6	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	7
TC7	0	0	0	0	0	0	1	1	0	1	0	1	0	1	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	1	0	0	1	1	17
TC8	0	0	0	0	0	0	0	1	0	1	0	1	0	1	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	1	0	0	1	1	16
TC9	0	0	0	0	0	0	0	0	1	1	1	1	0	1	1	0	0	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	11
TC10	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	9
TC11	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	8
TC12	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	7
TC13	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	7
TC14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	5
TC15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	6
TC16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	6
TC17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	7
TC18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	5
TC19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	6
TC20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	5
TC21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	6
TC22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	5
TC23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	4
TC24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	2
TC25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
TC26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2
TC27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
TC28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
TC29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	1	1	5
TC30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	5
TC31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
TC32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	4
TC33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	3
TC34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2
TC35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2
TC36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Dependent power	1	2	2	3	4	4	1	7	2	9	3	11	1	15	11	2	3	12	2	11	2	6	23	24	24	2	26	2	8	2	11	10	2	2	12	14	

Appendix E

Hierarchy level.

Table E.1
Reachability set, antecedent set, intersection set, and hierarchy level.

TC	Reachability set	Antecedent set	Intersection set	Level
TC1	1,2,3,4,5,6,8,9,10,11,12,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36	1	1	10
TC2	2,4,5,6,8,10,11,12,14,15,17,18,20,22,23,24,25,27,29,31,32,35,36	1,2	2	9
TC3	3,5,8,10,11,12,14,15,18,20,23,24,25,27,29,31,32,35,36	1,3	3	9
TC4	4,6,8,10,11,12,14,15,18,20,23,24,25,27,29,31,32,35,36	1,2,4	4	8
TC5	5,8,10,11,12,14,15,18,20,23,24,25,27,29,31,32,35,36	1,2,3,5	5	8
TC6	6,14,20,23,24,25,27	1,2,4,6	6	5
TC7	7,8,10,11,12,14,15,18,20,23,24,25,27,29,31,32,35,36	7	7	8
TC8	8,10,11,12,14,15,18,20,23,24,25,27,29,31,32,35,36	1,2,3,4,5,7,8	8	7
TC9	9,10,11,12,14,15,18,23,24,25,27	1,9	9	7
TC10	10,11,12,14,15,18,23,24,25,27	1,2,3,4,5,7,8,9,10	10	6
TC11	11,12,14,18,23,24,25,27	1,2,3,4,5,7,8,9,10,11,12	11,12	5
TC12	11,12,14,18,23,24,25,27	1,2,3,4,5,7,8,9,10,11,12	11,12	5
TC13	13,14,15,23,24,25,27	13	13	6
TC14	14,23,24,25,27	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	14	4
TC15	14,15,23,24,25,27	1,2,3,4,5,7,8,9,10,13,15	15	5
TC16	16,22,23,24,25,27	1,16	16	5
TC17	17,20,22,23,24,25,27	1,2,17	17	5
TC18	18,23,24,25,27	1,2,3,4,5,7,8,9,10,11,12,18	18	4
TC19	19,20,23,24,25,27	1,19	19	5
TC20	20,23,24,25,27	1,2,3,4,5,6,7,8,17,19,20	20	4
TC21	21,22,23,24,25,27	1,21	21	5
TC22	22,23,24,25,27	1,2,16,17,21,22	22	5
TC23	23,24,25,27	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23	23	3
TC24	24,27	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24	24	2
TC25	25	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,25	25	1
TC26	26,27	1,26	26	2
TC27	27	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,26,27	27	1
TC28	28	1,28	28	1
TC29	29,31,32,35,36	1,2,3,4,5,7,8,29	29	4
TC30	30,31,32,35,36	1,30	30	4
TC31	31	1,2,3,4,5,7,8,29,30,31,32	31	1
TC32	31,32,35,36	1,2,3,4,5,7,8,29,30,32	32	3
TC33	33,35,36	1,33	33	3
TC34	34,36	1,34	34	2
TC35	35,36	1,2,3,4,5,7,8,29,30,32,33,35	35	2
TC36	36	1,2,3,4,5,7,8,29,30,32,33,34,35,36	36	1

Data availability

Data will be made available on request.

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