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Mapping barriers to strategies: A dynamic stakeholder–stage framework for nearly zero energy buildings

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ABSTRACT

Although Nearly Zero Energy Buildings (NZEB) offer a clear path to reducing energy use and carbon emissions, different stakeholder groups face numerous barriers at four stages of implementation. Existing reviews catalog these barriers but lack precise stakeholder–stage alignment and fail to match each barrier with its most effective mitigation strategy. We reviewed 89 publications, identified 42 barriers and nine strategy categories, and applied Simple Correspondence Analysis (SCA) to quantify the couplings between barriers and strategies based on the consensus in the literature. We then developed a barrier–strategy mapping and prioritization framework to identify the dominant academic strategies associated with each barrier. The results show: (1) barriers shift from early financing–policy frictions to later human–technology frictions; (2) 90 % of barriers link to at least one highly significant strategy; (3) information coordination gaps and frequent design changes show no significant coupling with any mitigation strategy. The framework offers three values: (1) Practical guidance: it provides clear, stage-specific guidance for barrier identification and strategy selection; (2) Theoretical foundation: it lays a structured basis for context-sensitive empirical studies across regions, project types, and scales, enabling localized validation and optimization of the NZEB barrier–strategy model; (3) Mapping paradigm: this study proposes a strategy–barrier mapping paradigm grounded in systematic literature consensus. It provides a structured basis for selecting and prioritizing strategies across diverse regional conditions, project typologies, and real-world applications.

1. Introduction

The global building sector consumes 30–40 % of final energy and directly or indirectly generates 40 % of carbon dioxide emissions [1]. If current emission trends continue, buildings could account for up to 50 % of global carbon emissions by 2050 [2]. Reducing building energy use is crucial in mitigating climate change [3–5]. In recent years, Nearly Zero Energy Buildings (NZEBs) have emerged as a feasible solution to address energy and carbon challenges in the building sector. Researchers widely acknowledge NZEBs for their benefits in energy savings, emission reduction, environmental protection, and indoor comfort [6–9]. Many developed countries have set NZEB targets and introduced incentive policies to support adoption [10,11]. For example, Germany [12], Denmark [13], Japan [13], and the UK [14] have developed NZEB roadmaps and enacted supporting regulations. Since 2020, the European Union has mandated NZEB standards for all new buildings and plans to adopt Zero Energy Buildings (ZEBs) across the board by 2028 [15].

Recognizing the necessity and benefits of NZEBs, many countries have introduced technical standards, financial subsidies, and policy incentives to encourage stakeholder participation and accelerate implementation [16]. Despite these policies and economic and societal efforts, NZEB implementation still faces complex and persistent challenges [17,18]. At each development stage—concept, design, construction, and operation—stakeholders, including government, developers, designers, contractors, and end-users, assume new responsibilities and roles, often encountering significant barriers [19,20]. For example, developers must integrate multiple resources during the concept stage and make NZEB project decisions. Still, high capital pressures, policy uncertainty, and information asymmetry significantly increase the complexity and risk of their decision-making [17,21]. In the design stage, designers must integrate complex systems to meet energy performance targets, but limited technical expertise and insufficient tool support often lead to design discrepancies [22]. In the construction stage, contractors demand precise execution of high-performance components, placing pressure on technical capabilities constraints [23]. In operation, end users' lack of awareness and training in energy management often undermines

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building performance [24]. The barriers faced by these stakeholders evolve throughout the project stages—from high investment costs and policy uncertainty, to challenges in technology integration and information disconnection, and further to difficulties in controlling construction quality and gaps in operational performance—creating cumulative constraints that severely hinder the large-scale development of NZEB.

Previous studies have identified numerous barriers to achieving NZEB from various perspectives [17,25–30], providing essential insights into NZEB implementation challenges. However, three critical gaps remain: 1) Existing research categorizes barriers statically by type, lacking dynamic matching of "specific stakeholders × specific project stages", which limits the accurate identification of challenges faced by stakeholders across different project stages. This reduces the precision of barrier recognition and hinders the targeted selection of mitigation strategies, ultimately weakening resource allocation efficiency and policy implementation effectiveness; 2) Although many mitigation strategies have been proposed—either addressing specific technical bottlenecks or focusing on macro-level policy incentives—these strategies are largely fragmented and lack systematic synthesis; 3) Current studies have failed to establish structured linkages between barriers and corresponding strategies, have not proposed highly significant mitigation strategies targeted at specific barriers, and have not identified gaps in strategy coverage. As a result, critical barriers remain inadequately addressed over time, leading to resource misallocation and diminishing the overall coherence and effectiveness of NZEB promotion efforts.

This study addresses these gaps by adopting a dynamic perspective to develop a contextualized barrier–strategy matching framework. The framework reflects stakeholders' roles and responsibilities across different stages of NZEB implementation, aiming to provide more targeted and actionable guidance for practice. To achieve this goal, we conduct a systematic literature review to identify and synthesize the main barriers and corresponding strategies reported in existing studies. The study focuses on three core research questions (RQs):

RQ1

What barriers do stakeholders face across NZEB's four implementation stages—concept, design, construction, and operation?

RQ2

What mitigation strategies have been proposed in the existing literature to address these barriers?

RQ3

Which strategies significantly mitigate each barrier according to the literature consensus?

Unlike previous static reviews, this study linked each barrier to specific stakeholders and project stages and identified matching mitigation strategies to offer a comprehensive overview of NZEB implementation barriers. We applied Simple Correspondence Analysis (SCA) to quantify barrier–strategy couplings from the literature, then used these results to build a mapping and prioritization framework that highlights the highly significant mitigation strategies for each barrier. We visualized these dynamic couplings across stages and stakeholder groups, integrating them into a unified conceptual framework. By shifting from static aggregation to dynamic association and from fragmented lists to precise coupling, we provided actionable guidance for targeted decision-making, resource allocation, and context-sensitive empirical research. Furthermore, in light of the identified gap in highly significant strategies, we outlined future research directions to bridge this divide and further advance NZEB implementation.

This paper is organized into five sections. Section 2 outlines the research methodology and scope. Section 3 presents the results, including stakeholder-specific barriers at each implementation stage, nine categories of mitigation strategies, the SCA coupling analysis, and validation through two demonstrator case studies. Section 4 discusses the evolution patterns of these barriers, the characteristics of high-consensus strategies, future research directions based on the identified gaps, and the distinction between "literature popularity" and "empirical validity." Finally, section 5 concludes with a summary of the key findings, theoretical and practical contributions, study limitations, and implications for promoting NZEB adoption.

2. Research methodology

This study adopts a systematic review approach [31], refined from the five-step process proposed by Khan et al. [32], to construct an integrated research design (Fig. 1). In the first step, we define the scope by identifying stakeholder barriers across NZEB stages and the corresponding mitigation strategies. Next, we systematically search multiple databases using preset keywords and inclusion/exclusion criteria to collect the initial literature. Then, we apply independent double-blind screening and consensus checks to remove irrelevant or low-quality studies, ensuring a high-quality sample. During synthesis, we code and categorize barriers and strategies, then use SCA to quantify their association patterns [33]. To address methodological limitations, we integrate qualitative review insights with SCA's objectivity, creating a mixed-method approach [34]. Specifically, qualitative analysis enriches the statistics with context. Quantitative analysis minimizes coding bias and provides a more comprehensive and reliable view of NZEB barriers and solutions [35].

The first stage is to develop the research question (RQ) outlined in Section 1.

2.1. Search criteria

The second stage involves literature retrieval, including database selection and keyword identification, to ensure a comprehensive and unbiased review. We selected Scopus and Web of Science (WoS) as the primary databases. These platforms offer extensive coverage of high-impact journals, complement one another, and are widely used in bibliometric research [17,36,37]. They also serve as key sources for NZEB-related studies, with many influential reviews in this field drawing on their data [17,38,39]. Previous research indicates that NZEB publications have steadily increased since 2006 [38]. We therefore included articles published between 2006 and 2025 that examine barriers to NZEB implementation and corresponding mitigation strategies. This period captures the evolution of NZEB technologies and policy transformations, along with the emergence of more recent strategic responses.

To ensure that the search was both comprehensive and focused, this study started from the core concepts of the NZEB field, incorporating existing reviews and empirical studies, and categorized the search terms into four groups: (1) NZEB-related terms, covering synonyms and derivative expressions such as "Nearly Zero Energy Building" and "Net Zero Energy Building" [38]; (2) Stakeholder terms, including different role descriptors such as "developer," "contractor," and "end user" [19]; (3) Barrier/challenge terms, such as "barrier," "risk," and "obstacle" [17]; (4) Strategy terms, centred around "strategy," to capture various mitigation measures [40]. To differentiate between the searches for barriers and strategies, NZEB terms were first combined with stakeholder terms, then paired separately with barrier/challenge terms and strategy terms, forming two sets of search logics: one for identifying stakeholder-specific barriers, and another for capturing corresponding mitigation strategies. Table 1 lists the specific search terms for each category.

In practice, synonyms within each category were connected using OR logic to ensure coverage of multiple expressions of the same concept. In contrast, categories were combined using AND logic to ensure that search results contained all necessary elements. Furthermore, the search scope was strictly limited to article titles, abstracts, and author keywords (using TITLE-ABS-KEY in Scopus and TS in Web of Science) to enhance the relevance and precision of the search results. Full search strings and implementation details are provided in Appendix A.

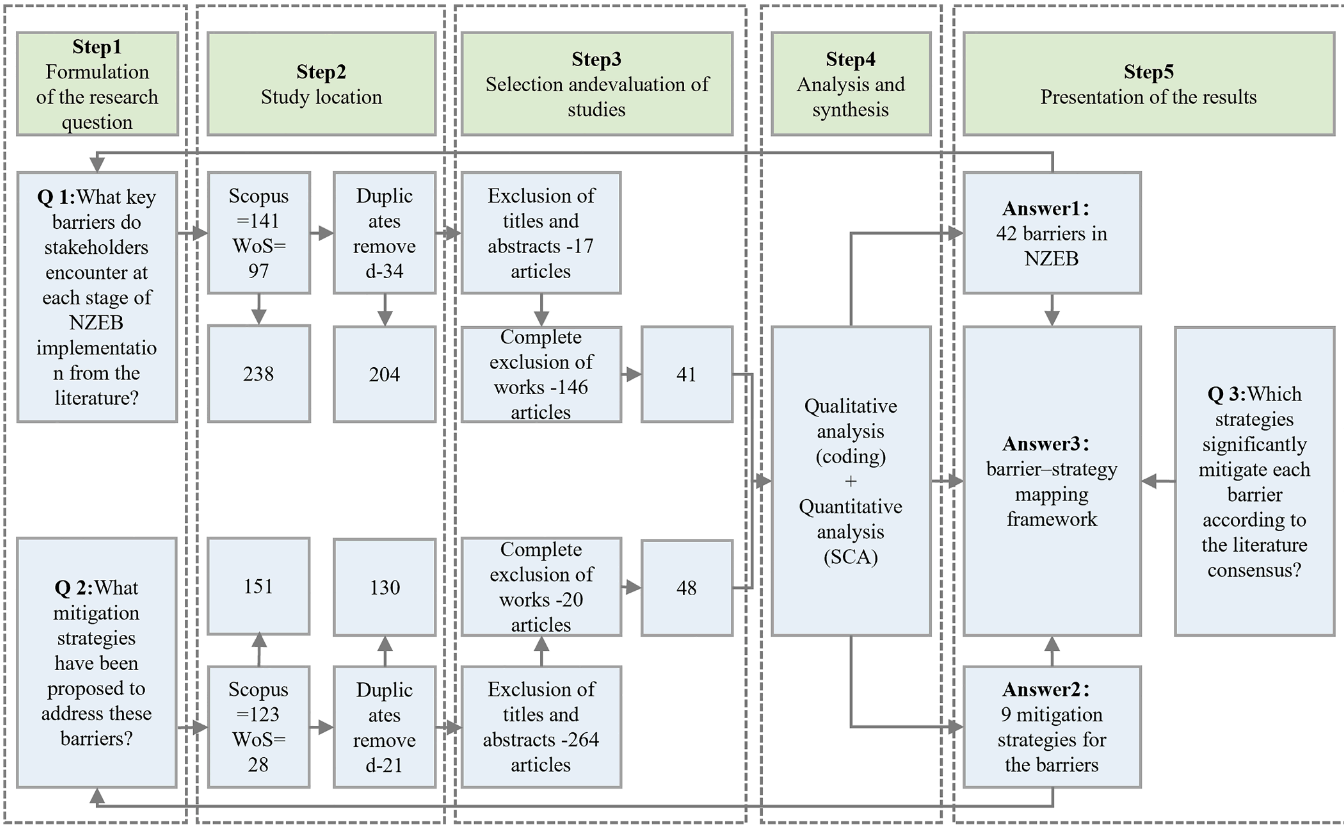

Fig. 1. Systematic review approach.

Table 1
Search strings used in scopus and web of science.

Keyword Category	Search Strings
NZEB	"Nearly-Zero Energy building" OR "Net-Zero Energy building" OR "Net-Zero Emissions building" OR "Zero Carbon building" OR "Zero Energy building" OR "Zero Emissions building" OR "Low Energy building" OR "Low Carbon building" OR "Net-Zero Carbon building" OR "Carbon Neutral building" OR "Carbon Positive building" OR "Energy Positive building" OR "Climate Neutral building" OR "Zero-Net-Energy building" OR "NZEB" OR "NZCB" OR "NZE" OR "ZEB" OR "ZCB" OR "nZEB"
Stakeholders	"supply group" OR "contractor*" OR "developer*" OR "energy producer*" OR "energy supplier*" OR "demand group" OR "client*" OR "end-user*" OR "regulation group" OR "government" OR "institution*" OR "professional bod*" OR "financier*"
Barriers	"barrier*" OR "challenge*" OR "obstacle*" OR "risk*"
Strategies	"strategy*"

2.2. Selection and eligibility

We screened titles, abstracts, and full texts against predefined inclusion and exclusion criteria to make final inclusion decisions. To capture any studies missed in the previous stage, we used forward and backward snowballing [41] and repeated it until no new studies appeared [42]. We included only journal articles and review papers, excluding conference proceedings, book chapters, and brief survey reports to maintain focus and consistency [38]. Additionally, we also excluded non-English publications and studies outside the NZEB field (e.g., biology, water management, and oncology). In total, we extracted 89 bibliographic records from the databases, forming our study dataset.

2.3. Analysis and synthesis

In the fourth stage (analysis and synthesis), we read all selected articles and performed content analysis. Specifically, the analysis consisted of two complementary steps: qualitative and quantitative [43]. In the first step (qualitative analysis), we open-coded articles to identify barriers faced by different stakeholders and mitigation strategies at each NZEB stage, then grouped these themes. In the second step (quantitative analysis), we applied SCA to the categorized data and plotted the variables in two dimensions to reveal barrier–strategy structures [44].

SCA has previously been applied by Vignon et al. [43] in similar studies on renewable energy. Following this approach, we constructed a barrier–strategy co-occurrence matrix with numerous categories, limited samples, sparse data, and complex interactions, thereby enabling the extraction of a holistic structure. Compared to other correspondence analysis techniques, such as Multiple Correspondence Analysis (MCA) and Multidimensional Scaling (MDS), SCA more closely aligns with our data and analysis goals. Although MCA and MDS offer advantages, they do not meet the specific needs of our study. Although both MCA and MDS offer advantages, neither satisfies our study's particular requirements. Specifically, MCA can manage joint distributions that fail with sparse, high-category data: it creates many dimensions, disperses inertia, and reduces [45]. Furthermore, MCA is unable to quantify the strength of barrier–strategy co-occurrences in paired entries [46]. By contrast, MDS can embed similarity matrices into a low-dimensional space, but it cannot model categorical associations or test their significance and direction [47].

In comparison, SCA overcomes these limitations by constructing contingency tables for two pairs and accommodating datasets with many categories, even when sample sizes are small [48]. It offers chi-square tests and standardized residuals for inference, and visualizes category clusters and separations in low-dimensional plots [49,50]. In our mixed-review method, SCA is the core quantitative module. It integrates qualitative coding themes with rigorous statistics. By using chi-square tests and residuals, it validates and extends our coding results. This approach streamlines the logic and strengthens interpretability and persuasiveness.

2.3.1. Qualitative analysis

Since barriers have mature classifications but strategies lack a framework [38], we used deductive coding for barriers [51] and inductive coding for strategies [52] on 89 articles in NVivo 13. The first stage focused on deductive coding of barriers. We predefined four project stages [53], seven stakeholder categories [19], and six barrier dimensions [38] into an a priori coding scheme based on authoritative reviews and policies. We coded all barrier statements per this scheme to ensure comparability and consistency. The second stage applied an inductive approach to mitigation strategies. Two researchers independently reviewed texts, identified strategy nodes describing NZEB responses, and merged similar items to refine themes. We derived nine strategy categories after open coding, clustering, and labeling. We derived nine strategy categories through open coding, clustering, and labeling, and confirmed that theoretical saturation was reached when five consecutive articles yielded no new strategies [54]. To enhance reliability and validity, the entire process adopted double independent coding: initial Cohen's $\kappa \geq 0.82$, improved to above 0.90 after reconciliation. Moreover, an external NZEB expert blind-reviewed node definitions and semantics, achieving over 90 % agreement. This process produced a structured barrier–strategy list and rigorous matrix data for SCA, guiding the transition from text to structured evidence.

2.3.2. Quantitative analyses

2.3.2.1. Constructing the contingency table. First, we categorized the identified barriers and strategies by dimension or subcategory. Then, we recorded how often each barrier–strategy pair co-occurred in the context of mitigation across all articles to build a two-dimensional contingency table [43]. In the table, rows list barrier categories, columns list strategy categories, and cells show co-occurrence frequencies. This table, based on consensus in the literature, facilitates the precise matching of co-occurrence relationships between barriers and strategies.

2.3.2.2. Chi-Square test and association strength. To evaluate barrier–-strategy relationships, we performed a chi-square test and determined its significance level. A high chi-square value implies a strong association, indicating the frequent co-occurrence or co-absence of certain barrier–strategy pairs across studies. The chi-square statistic is computed as follows:

$$\chi^2 = \sum_i \sum_j \frac{(O_{ij} - E_{ij})^2}{E_{ij}}$$

Where O_{ij} denotes the observed frequency in row i and column i of the contingency table, and E_{ij} represents the expected frequency under the assumption of independence between rows and columns.

2.3.2.3. Standardized residuals and significance assessment. After establishing overall significance, we used standardized residuals to identify which specific barrier–strategy combinations show the most substantial positive or negative associations. The standardized residual is calculated using the following formula.

$$r_{ij} = \frac{O_{ij} - E_{ij}}{\sqrt{E_{ij}}}$$

When it exceeds a critical threshold (e.g., 1.96 for $p < 0.05$, or 2.58 for $p < 0.01$), the observed co-occurrence frequency can be considered significantly higher or lower than what would be expected by chance. Larger positive residuals indicate more frequent co-occurrence of the barrier–strategy pair than expected. In comparison, larger negative residuals suggest the pair appears significantly less often than expected under the independence assumption.

2.3.2.4. SCA visualization and interpretation. After confirming statistical associations, we projected the row and column coordinates into a low-dimensional space for visualization. SCA clusters frequently co-occurring barrier–strategy pairs in close proximity within the plot, allowing intuitive exploration of similarities and differences among categories [43]. After confirming the statistical associations, we projected the row and column coordinates of the contingency table into a low-dimensional space for visualization. SCA clusters frequently co-occurring barrier–strategy pairs into nearby regions in the plot, facilitating the intuitive observation of similarities and differences across categories. We then interpreted the spatial distribution patterns revealed by the analysis.

3. Results

3.1. NZEB implementation barrier identification

A systematic literature review identified 40 barriers to NZEB implementation, involving seven stakeholders and seven different barrier types. These barriers were mapped across the four stages concept, design, construction, and operation, resulting in 42 "barrier–-stakeholder" nodes (with some barriers recurring across multiple stakeholder groups). To facilitate subsequent quantitative analysis, each node was coded as "B_aS_b," where "a" refers to the specific barrier number and "b" corresponds to the stakeholder category. Details of these nodes, including their classifications, stages, and associated stakeholders, are presented in Table 2.

3.2. Identification of mitigation strategies for NZEB barriers

Through open coding, multiple rounds of clustering, and anonymous expert validation, this study identified nine major strategy categories and sixty-three subcategories. For ease of subsequent quantitative analysis, each strategy node was coded in the format "ST_c", where "c" corresponds to the specific strategy number. Details of each subcategory and its description are provided in Table 3.

The nine major strategy categories are: 1) Active–Passive and renewable energy optimization, addressing early-stage climate adaptability concerns, and peak load risks. High-performance envelopes combined with photovoltaic, heat pump, and energy storage systems can help architects reduce design loads without increasing operational complexity, thereby lowering design difficulty and improving system stability [102,118,119]; 2) BIM+ Enhancing Efficiency can improve the long-standing issue of information silos by integrating BIM platforms, enabling clash detection, schedule coordination, and seamless post-assessment data transfer across design, construction, and operation stages, significantly reducing changes and rework [120–122]; 3) Design simulation and optimization technologies use GIS–BIM–LCA integration and multi-objective algorithms to provide investors with quantitative "energy–cost" indicators for early-stage decision-making, thereby mitigating uncertainty [123–125]; 4) Construction quality assurance technologies can help contractors detect hidden defects early, reducing the performance gap between design specifications and actual construction [126–129]; 5) Operational management system technologies - including model predictive control, integrated energy management systems, and artificial intelligence-based fault detection - enables facility managers to minimize energy performance deviations and lower the required skill level, all while ensuring occupants maintain a comfortable indoor environment [130,131]; 6) Incentive policies and regulatory measures, such as subsidies, tax credits, and efficiency obligations, transform high upfront costs and policy uncertainties into predictable returns,

Table 2
Classification of stakeholder-specific challenges across the NZEB project stages.

Stage	Composite Code	Barrier	Stakeholder	Classification	Reference
Concept Stage	B1S1	B1 High upfront costs	S1 Developers	Economic barrier	[21,38,55–57]
	B2S1	B2 Lack of financing information	S1 Developers	Economic barrier	[17,21,58]
	B3S1	B3 Lack of systematic understanding of costs and benefits	S1 Developers	Economic barrier	[59–61]
	B4S1	B4 Lack of expertise	S1 Developers	Professional/Technical barrier	[55,62–64]
	B5S1	B5 Insufficient stakeholder coordination	S1 Developers	Professional/Technical barrier	[17,55,65,66]
	B6S6	B6 Ambiguous definitions & inconsistent standards for low/zero-carbon buildings	S6 Government	Legislative barrier	[57,67–70]
	B7S1	B7 Limited market demand & high market uncertainty	S1 Developers	Market barrier	[26,55,69–72]
	B8S1	B8 Resistance to change	S1 Developers	Social-cultural barrier	[17,27,73,74]
	B9S1	B9 Policy uncertainty	S1 Developers	Legislative barrier	[26,28,57,72,75,76]
	B10S7	B10 Limited public awareness & publicity	S7 End-users	Social-cultural barrier	[17,28,77,78]
	B11S1	B11 Lack of incentives	S1 Developers	Legislative barrier	[15,21,28,57,64,79]
	B12S1	B12 Geographical & climatic constraints	S6 Government	Geographical barrier	[17,28,57,70,74,79]
Design Stage	B13S1	B13 Lack of information coordination & sharing	S1 Developers	Professional/Technical barrier	[11,61,62,80,81]
	B13S2	B13 Lack of information coordination & sharing	S2 Designer	Professional/Technical barrier	
	B14S1	B14 Lack of technical knowledge	S1 Developers	Professional/Technical barrier	[26,27,73,81]
	B14S2	B14 Lack of technical knowledge	S2 Designer	Professional/Technical barrier	
	B15S1	B15 Lack of experienced partners	S1 Developers	Professional/Technical barrier	[28,81,82]
	B16S2	B16 Context-specific challenges across regions	S2 Designer	Geographical barrier	[83,84]
	B17S2	B17 Lack of standardized tools & LCA methodology support	S2 Designer	Technological barrier	[26,28,57,77,85]
	B18S2	B18 Poor robustness of design systems	S2 Designer	Technological barrier	[66,86,87]
	B19S2	B19 Neglect of component degradation	S2 Designer	Technological barrier	[84,86,88,89]
	B20S2	B20 Conflicts between conventional structures & new processes	S2 Designer	Professional/Technical barrier	[25,90]
	B21S2	B21 Unspecified design details	S2 Designer	Professional/Technical barrier	[83,91]
	B22S2	B22 Resistance to change	S2 Designer	Social-cultural barrier	[17,27,92,93]
	B23S2	B23 Lack of practical guidelines	S2 Designer	Legislative barrier	[21,29,94–97]
	B24S2	B24 Difficulty in technology integration & lack of feasible solutions	S2 Designer	Technological barrier	[28,82,89,93]
Construction Stage	B25S1	B25 Lack of relevant & experienced partners	S1 Developers	Professional/Technical barrier	[65,81,82]
	B26S1	B26 Misalignment of design objectives among suppliers	S1 Developers	Professional/Technical barrier	[81,98–100]
	B27S1	B27 Lack of timely information sharing among stakeholders	S1 Developers	Professional/Technical barrier	[62,81,99–101]
	B28S3	B28 Insufficient real-time information exchange	S3 Contractors	Professional/Technical barrier	[21,90]
	B29S3	B29 Lack of experience & knowledge	S3 Contractors	Professional/Technical barrier	[17,28,55,77]
	B30S3	B30 Poor workmanship & improper construction techniques	S3 Contractors	Professional/Technical barrier	[24,102–107]
	B31S3	B31 Failure to identify latent issues	S3 Contractors	Professional/Technical barrier	[108,109]
	B32S4	B32 Low quality of equipment or materials	S4 Suppliers	Technological barrier	[105,106,110]
	B33S2	B33 Drawings fail to guide construction	S2 Designer	Professional/Technical barrier	[111]
	B34S2	B34 Frequent design changes	S2 Designer	Professional/Technical barrier	[109]
Operation Stage	B35S1	B35 Lack of experienced partners	S1 Developers	Professional/Technical barrier	[112,113]
	B36S1	B36 Complex certification systems & processes	S1 Developers	Legislative barrier	[29,89]
	B37S5	B37 Lack of technical & system management skills	S5 Facility managers	Professional/Technical barrier	[24,86,114]
	B38S5	B38 Performance gaps & inadequate energy monitoring	S5 Facility managers	Technological barrier	[57,85,115,116]
	B39S7	B39 Lack of operational knowledge & skills	S7 End-users	Professional/Technical barrier	[24,62]
	B40S7	B40 Insufficient financial rewards & incentives	S7 End-users	Economic barrier	[103,117]

Table 3
Refined mitigation strategies for NZEB implementation.

Strategy Category	Sub-Strategy (Code + Name)	Subcategory Description	Reference
ST1 Active–Passive and Renewable Energy Optimization	ST1–1 Passive Shading and Facade Design	Reduce solar heat gains and mitigate indoor overheating using adjustable louvers, double-skin facades, etc. (typical payback 5–7 years)	[119,139]
	ST1–2 Hybrid Ventilation	Reduce cooling loads by directing airflow through wind towers, vents, or window opening strategies. (typical payback 8 years)	[119,140,141]
	ST1–3 High Heat Storage Envelope	Use thermally massive walls or floors to store heat at night and release it during the day. (typical payback 7–43 years)	[119,142,143]
	ST1–4 Efficient Heat Recovery and Energy-Saving Appliances	Reduce primary energy use through total heat exchange ventilation and energy-efficient appliances. (typical payback <3 years)	[102,118,144]
	ST1–5 Advanced Materials and Innovative Design	Enhance thermal control with electrochromic glass and PCM-based composite materials. (typical payback <3 years)	[145,146]
	ST1–6 Climate-Specific Active + Passive Integration	Customize passive, active, and renewable system integration for regional climate adaptability.	[147,148]
	ST1–7 Genetic Algorithms and Lifecycle Optimization	Optimize design and maintenance strategies using genetic algorithms and LCA to cope with material degradation.	[149,150]
	ST1–8 Roof/Facade PV and BIPV/T	Integrate PV or solar thermal modules into roofs or facades for dual energy supply, self-generation, and self-consumption. (roof PV payback 4–8 years; BIPV/T 6–12 years)	[142,151]
	ST1–9 Solar–Multisource Heat Pump Coupling	Combine solar thermal systems with multi-source heat pumps and switch seasonally to improve COP. (typical payback 3 years)	[152]
	ST1–10 PV–Battery–Thermal Storage Integration	Coordinate PV, battery, and thermal storage to balance energy loads and enhance self-consumption rates. (typical payback 9–14 years)	[142,153]
ST2 BIM+ Enhancing Efficiency	ST2–1 BIM-Based Design Coordination and Information Sharing	Use BIM for clash detection, design optimization, and data sharing during the design stage.	[120–122]
	ST2–2 BIM–EnergyPlus–Machine-Learning Integration	Integrate BIM with EnergyPlus and machine learning to rapidly and accurately predict energy consumption.	[116]
	ST2–3 BIM-VR-Based Construction Simulation	Integrate VR and BIM to visualize the construction process and reduce rework and errors.	[116]
	ST2–4 BIM-BEMS-WSN/RFID Integration	Integrate BEMS, WSN, and RFID into BIM for unified energy monitoring and data management.	[154,155]
	ST2–5 WSN Real-Time Indoor Environment Monitoring	Deploy wireless sensor networks to collect real-time temperature and humidity data for better operational control.	[156]
ST3 Design Simulation Optimization Technology	ST3–1 GIS–BIM–LCA Integration	Integrate GIS and BIM data to enable spatialized lifecycle assessments of carbon and energy performance.	[157,158]
	ST3–2 Heuristic and Multi-Objective Optimization	Use algorithms such as Glowworm and NSGA to optimize multi-objective energy and cost performance.	[91,159]
	ST3–3 Residential Archetype Modeling	Develop representative residential archetypes for large-scale retrofit assessment and optimization.	[160]
	ST3–4 Multi-Tool Coupled Simulation (CFD/FEA/ANN)	Apply coupled tools (CFD, FEA, ANN) to evaluate building systems under multiple physical conditions.	[123–125]
	ST3–5 Degradation Modelling & AI Data Mining	Model material and equipment degradation, and use AI to explore lifecycle performance patterns.	[161,162]
	ST3–6 Climate-Responsive Simulation with Predictive Models	Improve simulation accuracy under extreme weather by integrating historical and projected climate data.	[163]
ST4 Construction Quality Assurance Technologies	ST4–1 Industrialized High-Performance Facades and Panels	Use prefabricated high-performance curtain walls or panels to ensure consistent insulation and airtightness.	[126–129]
	ST4–2 Low-Cost VIP Insulation Panels	Adopting a natural, lightweight core material instead of silica gel results in a lower cost and higher thermal insulation efficiency. (typical payback 2.5 – 17 years)	[164]
	ST4–3 Integrated Quality Inspection and Infrared Acceptance	Combine infrared imaging with airtightness testing for fast, non-invasive on-site defect detection.	[165–167]
	ST4–4 Pulse Method for Airtightness Testing	Perform low-pressure (2–15 Pa) airtightness tests quickly without structural damage or specialized operators.	[126,128,129]
	ST4–5 Rapid Defect Detection via Infrared Thermography	Use infrared thermography to detect thermal bridges and insulation failures quickly.	[166]
	ST4–6 SLAM/LiDAR/Drone + AI	Use SLAM, LiDAR, and drones with AI to detect thermal leaks across large areas with high precision.	[165]
ST5 Operational Management System Technologies	ST5–1 Model Predictive Control (MPC)	Predict future loads and dynamically optimize control to reduce energy consumption by up to 40 %.	[168]
	ST5–2 Integrated Energy Management System (EMS)	Integrate PV, storage, load, and pricing data for intelligent scheduling and control. (typical payback 0.7–5.4 years)	[130]
	ST5–3 User Feedback and Thermal Comfort	Dynamically adjusts control strategies based on user behavior and feedback to improve comfort.	[81,169]
	ST5–4 Predictive Modelling (Black/Grey/White Box)	Select model types based on data availability to balance accuracy and computational cost.	[164]
	ST5–5 Demand-Side Management and Smart Metering	Apply smart meters and time-of-day tariffs to optimize peak and valley shifting and tariffs.	[168]
	ST5–6 Robust and Stochastic Optimization	Handle uncertainty through robust/stochastic methods to ensure robust system operation.	[130,131]
	ST5–7 Fault Detection and Diagnosis (FDD)	Combine AI and expert rules to detect and isolate real-time BEMS faults. (typical payback 0.7–5.4 years)	[170,171]
ST6 Incentive Policies and Regulatory Measures	ST6–1 Subsidies and Incentives	Government subsidies reduce initial investment costs and improve ROI for NZEBs. (Empirical analysis of Italy's Superbonus 110 % indicates a mean payback period of approximately 13.8 years; supplementary grants equating to 30 percent of project costs may reduce this to 8–9 years.)	[30,172–175]

(continued on next page)

Table 3 (*continued*)

Strategy Category	Sub-Strategy (Code + Name)	Subcategory Description	Reference
	ST6–2 Carbon Taxes and Penalties	Increases emissions costs through penalties to encourage energy efficiency and renewable energy.	[176]
	ST6–3 Tax Reductions and Deductions	Offers tax incentives to attract private and corporate investment in energy-saving projects. (Evaluations of the Superbonus 110 % framework reveal payback durations near 13.8 years.)	[175,177,178]
	ST6–4 Mandatory Retrofits and Renewable Quotas	Regulations mandate retrofitting and renewable integration for existing old buildings.	[179,180]
	ST6–5 Green Finance	Use tools such as low-interest loans and green bonds to share project financing risks. (In India, a 30 percent subsidy plus an ESCO shared-savings model yields a 3–4 year payback. Introducing 20–30 percent risk guarantees in Italy could cut a 13.8 year payback down to 8–9 years.)	[174,175,181]
	ST6–6 Training and Quality Standards	Develops certification and training programs to improve design, construction, and O&M quality.	[132–135]
	ST6–7 Information Platforms	Publish guidelines, white papers, and consultancy services to enhance industry awareness.	[182]
	ST6–8 EEOS & White Certificates	Encourages supply chain energy savings through obligations and tradable certificates.	[24,183]
	ST6–9 Government-Led Decarbonization of Public Assets	Government demonstration projects that drive market adoption and showcase low-carbon pathways.	[184]
ST7 Certification Systems, Benchmarking, and Standards	ST7–1 International/National LCA Standards	Use ISO 14,044 and EN 15,978 to assess lifecycle carbon emissions.	[157,185]
	ST7–2 Net Zero Energy/Carbon Certification	Labels such as LEED Zero or CTS nZEB should be achieved to indicate net-zero performance.	[136,137]
	ST7–3 Equipment Efficiency Thresholds	Raise minimum COP standards for equipment such as HRVs and HVACs to ensure efficiency.	[186]
	ST7–4 Whole-Life Performance Certification	Dynamic certification across design, construction, and operation stages to ensure consistency.	[187]
	ST7–5 Certification-Based Market Trust Mechanism	Certification increases financing or transaction value, reducing end-user uncertainty.	[182]
ST8 Innovative Business Models	ST8–1 Shared-Savings Contracts / Energy Performance Services	Share costs and savings through performance-based contracts to mitigate investment risk.	[188]
	ST8–2 Building Renovation Passport (BRP)	Step-by-step renovation roadmap and financing aligned with economic capacity.	[189]
	ST8–3 DSRI Multi-Loop Partners	Closed-loop collaboration among demand, supply, regulatory, and institutional actors.	[19,190]
	ST8–4 Lifecycle Value Framework	Value proposition based on lifecycle cost-benefit optimization.	[188]
	ST8–5 Service-Oriented Revenue Model	Shift from one-time sales to recurring EPC or O&M service revenue.	[184]
	ST8–6 Collaborative Design Partnerships	Share technical risks through cooperation with suppliers, consultants, and research bodies.	[191,192]
	ST8–7 Green Finance and Carbon Trading	Use performance-based payments and carbon trading to incentivize green investment.	[193]
	ST8–8 Monetisation of Non-Energy Benefits	Monetize additional benefits such as health, comfort, and productivity.	[190]
	ST8–9 Institutional and Contractual Support	Strengthen regulatory and contractual systems to support emerging business models.	[192]
ST9 Integrated Project Delivery	ST9–1 IPD/IDP Processes	Adopt IPD/IDP contracts to distribute risks and responsibilities among stakeholders.	[81,98]
	ST9–2 Full-Cycle Owner Engagement	Frequent owner involvement across stages is needed to ensure the alignment of goals and execution.	[81,138]
	ST9–3 Cost and Risk Management Tools	Use change management and risk registers to support collaboration and project control.	[194]
	ST9–4 Integrated Project Delivery Guidelines	Reference implementation templates from AIA and IEA for collaborative delivery frameworks.	[195,196]
	ST9–5 Performance Contracts with Monitoring Mechanisms	Multi-party contracts and monitoring systems to ensure compliance and deter opportunism.	[195,196]
	ST9–6 Green Procurement Mechanisms	Provide incentives or scoring advantages for low-carbon technologies in procurement processes..	[179]

improving adoption rates among developers and end users [132–135]; 7) Certification systems, benchmarking, and standards offer can provide transparent performance metrics for financial institutions and buyers, strengthening market confidence [136,137]; 8) Innovative business models—such as energy performance contracting, building renovation passports, and green finance instruments—restructure risk-sharing mechanisms within the supply chain to enhance capital flows and shorten payback periods [136,137]; 9) Integrated project delivery frameworks, embedding shared-risk contracts and full-lifecycle owner engagement, break down functional silos and enhance goal alignment and collaboration among stakeholders [81,138].

3.3. Relationships between NZEB barriers and mitigation strategies

After identifying barriers and mitigation strategies, we employed SCA to explore their interrelationships. To support this analysis, we developed a contingency matrix that records the frequency of co-occurrence between each barrier and strategy. The matrix shown in Table 4 formed the basis of the SCA analysis, detailing the number of times each strategy (ST1–ST9) was referenced as a response to specific barriers (B1S1–B40S7).

The SCA process began with a chi-square test on the $B \times S$ contingency table to assess the overall association strength between barriers (B_aS_b) and mitigation strategies (ST_c). The test result ($x^2 = 960.76$, df = 328, $p < 0.001$) confirmed that the two sets of variables were not independently distributed [197].

3.3.1. Macro-level analysis

To reveal the overall structure of barriers and mitigation strategies across different stages of NZEB implementation, we first applied

Table 4
Barrier–strategy co-occurrence matrix.

Barrier	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	ST9
B1S1	3	0	0	0	0	5	3	3	0
B2S1	0	0	0	0	0	4	0	0	0
B3S1	0	0	3	0	0	3	4	0	0
B4S1	0	3	2	0	0	0	0	0	0
B5S1	0	4	0	0	0	0	0	0	3
B6S6	0	0	0	0	0	0	2	0	0
B7S1	0	0	0	0	0	3	0	5	0
B8S1	0	0	0	0	0	2	0	3	2
B9S1	0	0	0	0	0	3	0	0	0
B10S7	0	0	0	0	0	2	3	2	0
B11S1	0	0	0	0	0	5	0	0	0
B12S6	0	0	0	0	0	0	2	0	0
B13S1	0	2	0	0	0	3	0	0	2
B13S2	0	2	0	0	0	3	0	0	3
B14S1	3	0	0	0	0	2	0	0	0
B14S2	3	3	0	0	0	2	0	0	0
B15S1	0	0	0	0	0	2	0	0	2
B16S2	5	0	5	0	0	0	0	0	0
B17S2	3	0	5	0	0	0	0	0	0
B18S2	3	0	5	0	0	0	0	0	0
B19S2	4	0	5	0	0	0	0	0	0
B20S2	0	3	1	0	0	0	0	0	3
B21S2	0	5	0	0	0	0	0	0	3
B22S2	0	0	0	0	0	3	0	0	3
B23S2	0	0	0	0	0	4	3	0	0
B24S2	3	0	4	0	0	0	0	0	0
B25S1	0	0	0	0	0	3	0	0	0
B26S1	0	3	0	0	0	3	0	4	3
B27S1	0	3	0	0	0	3	0	0	3
B28S3	0	3	0	0	0	3	0	0	3
B29S3	1	2	0	0	0	3	0	0	5
B30S3	0	0	0	3	0	0	3	0	0
B31S3	0	0	2	4	0	0	3	0	0
B32S4	2	0	0	2	0	0	0	0	0
B33S2	0	0	0	3	0	0	0	0	0
B34S2	0	0	0	1	0	0	0	0	0
B35S1	0	0	0	0	3	0	0	0	0
B36S1	0	0	0	0	0	0	5	0	0
B37S5	0	1	0	0	2	3	0	0	0
B38S5	0	0	0	0	3	0	0	0	0
B39S7	0	0	0	0	4	3	0	0	0
B40S7	0	0	0	0	3	3	2	1	0

Correspondence Analysis (CA) to the $B \times S$ contingency table. By performing singular value decomposition (SVD) on the standardized residual matrix, we extracted the first two principal dimensions, which account for 52.9 % and 47.1 % of the total inertia, respectively. These dimensions were then projected onto a two-dimensional plane (Fig. 4) to visually present the spatial distribution and clustering patterns between strategies (ST_c) and barriers (B_aS_b).

In Fig. 2, barrier points are labeled as "B_aS_b," representing stage-specific barriers stakeholders face in the concept, design, construction, and operation stages. Strategy points are marked with red triangles ("ST_c"), and colored convex hulls enclose clusters corresponding to different lifecycle stages. This visualization presents the overall structure and clustering patterns of barriers and strategies during NZEB implementation.

3.3.1.1. Spatial and Temporal Evolution of Barrier–Strategy Relationships. The two-dimensional correspondence analysis in Fig. 2 reveals the complex distribution of barriers and the spatial positioning of mitigation strategies ("ST_c'') throughout the NZEB implementation process. By integrating chi-square distance metrics, the study identifies two key dimensions across the project lifecycle: spatial transitions from macro-level decision-making to micro-level implementation, and temporal evolution from early planning to late-stage operation. This framework precisely examines barrier–strategy alignments across stages.

Along the spatial dimension (Dimension 1), the left side (negative axis) is dominated by macro-economic and institutional barriers located in the concept stage and raised mainly by Developers (S1). Specifically, B1S1 (high upfront costs) and B2S1 (lack of financing information) show standardized residuals above +3, indicating that financial pressure and limited funding access are critical barriers to project initiation. B11S1 (lack of incentives) and B8S1 (resistance to change) also lie in this zone, highlighting the impact of weak policy support and cultural inertia on investment decisions. Nearby strategy points ST6 (Incentive Policies & Regulatory Measures) and ST8 (Innovative Business Models) imply that these external drivers can effectively mitigate early-stage economic and institutional risks.

Moving rightward along Dimension 1, barriers shift toward the design and construction stages. Designers (S2) face B13S2 (lack of information coordination and sharing) and B14S2 (lack of technical knowledge), while Contractors (S3) report B30S3 (poor workmanship and improper construction techniques) and B31S3 (failure to identify latent issues). These reflect process- and technology-related deficiencies at both cross-departmental collaboration and on-site execution levels. Nearby strategies — ST2 (BIM + Enhancing Efficiency), ST3 (Design-Simulation Optimization Technology), and ST4 (Construction Quality-Assurance Technologies) — underscore the growing importance of digital modelling, validation, and quality control in project delivery.

Along the temporal dimension (Dimension 2), the lower half (negative axis) captures structural weaknesses in the concept and design stages. B13S2 (information asymmetry) and B18S2 (poor robustness of design systems) highlight planning and data integration challenges, while B8S1 (resistance to change) indicates limited investor confidence stemming from unclear business propositions. Proximate strategies ST2 (BIM + Enhancing Efficiency) and ST8 (Innovative Business Models) suggest that although digital and financial tools are being employed, more targeted development is required to resolve early-stage uncertainties.

In contrast, the upper half (positive axis) is dominated by typical barriers from the construction and operation stages. B36S1 (complex certification systems and processes), B38S5 (performance gaps and inadequate energy monitoring), and B39S7 (lack of operational knowledge and skills) reflect post-delivery management and behavioral-adaptation issues. Adjacent strategies ST5 (Operational Management-System Technologies) and ST7 (Certification, Benchmarking & Standards) indicate emerging monitoring and evaluation mechanisms. However, challenges like B40S7 (low returns and insufficient incentives) remain under-addressed, implying that economic and training measures for the later stages are still incomplete.

3.3.1.2. Stage Clustering and Stakeholder Differences. In Fig. 2, four colored convex hulls clearly outline the clusters of barriers across the concept, design, construction, and operation stages, with stakeholder labels indicating the core challenges associated with each stage. At the concept stage (developer S1), economic and regulatory barriers—B1S1 (high up-front costs), B2S1 (lack of financing information), B5S1 (insufficient stakeholder coordination), B9S1 (policy uncertainty), and B11S1 (lack of incentives)—are clustered in the lower-left quadrant, suggesting that financial constraints and unstable policy environments are primary bottlenecks for project initiation.

In the design stage (designer S2), technical and process-related issues—B13S2 (lack of information coordination and sharing), B14S2 (lack of technical knowledge), B17S2 (lack of standardized tools and LCA methodology support), and B24S2 (difficulty in technology integration and lack of feasible solutions)—concentrate in the lower-right quadrant. This distribution highlights ongoing limitations in interdepartmental communication, methodological support, and integrated design capabilities.

During the construction stage (contractors S3 and suppliers S4), a cluster of barriers—B30S3 (poor workmanship and improper construction techniques), B31S3 (failure to identify latent issues), and B32S4

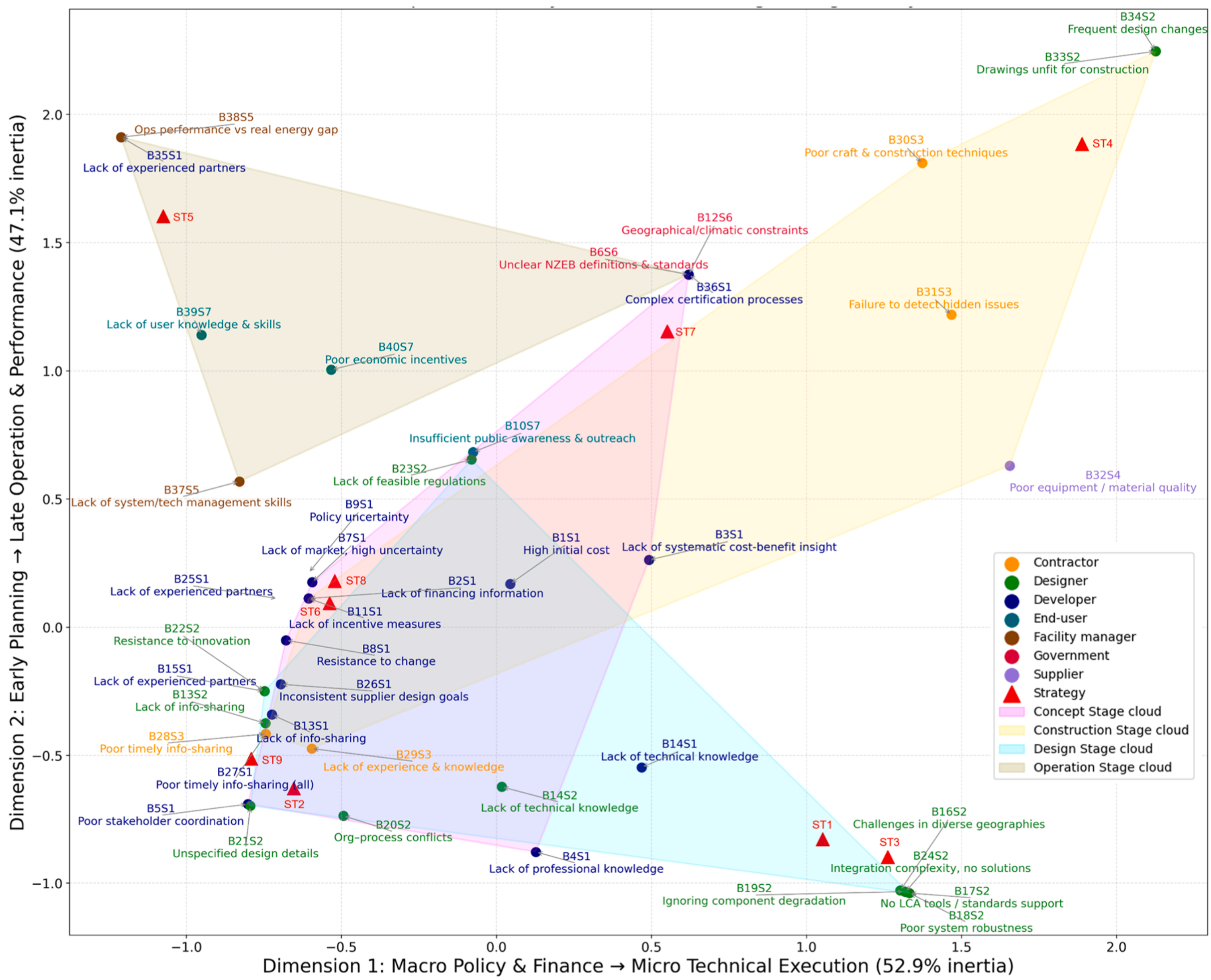

Fig. 2. Two-dimensional mapping of NZEB barriers and strategies based on correspondence analysis.

(low quality of equipment or materials)—appears in the upper-central region. These reflect deficiencies in construction process maturity, quality control, and on-site execution accuracy.

At the operation stage (developer S1, facility managers S5, and end users S7), a final group of regulatory, technical, and behavioral barriers—B35S1 (lack of experienced partners), B36S1 (complex certification systems and processes), B38S5 (performance gaps and inadequate energy monitoring), B39S7 (lack of operational knowledge and skills), and B40S7 (insufficient financial rewards and incentives)—is concentrated in the upper section. This highlights how post-occupancy performance is compromised by inadequate operational capacity, user-side knowledge gaps, and misaligned economic incentives.

3.3.2. Micro-level analysis

After confirming the global clustering patterns, this section examines the local significance of "barrier–strategy" combinations. We implemented the standardized residual matrix analysis in Python (see Appendix C for full code) and used the resulting residuals (Appendix B) to generate the heatmap in Fig. 3, where color intensity indicates each combination's deviation from the expected frequency under an independence model. Black contour lines indicate the statistical significance threshold of $|r_{ij}| = 2$, highlighting combinations where the strategy has a significant mitigating effect on the barrier according to the literature.

In the heatmap analysis of Fig. 3, we further examined the specific significance differences of each barrier–strategy combination at the micro level. First, we can intuitively identify which strategies are particularly prominent in mitigating specific barriers according to the literature. For example, ST4 (Construction Quality Assurance Technologies) shows residuals as high as +5 to +8 for B30S3 (Poor workmanship and improper construction techniques), B31S3 (Failure to identify latent issues), and B33S2 (Drawings fail to guide construction), highlighting its strong alignment with on-site technical deficiencies. ST5 (Operational Management System Technologies) displays residuals around +7 for B35S1 (Lack of experienced partners), B38S5 (Performance gaps and inadequate energy monitoring), and B39S7 (Lack of operational knowledge and skills), highlighting the central role of operational platforms and user training in sustaining long-term performance. ST8 (Innovative Business Models) shows positive residuals exceeding +3 for B7S1 (Limited market demand and high market uncertainty) and B8S1 (Resistance to change), emphasizing its effectiveness in reducing early-stage economic and cultural resistance.

Second, through this micro-level perspective, we validated the global patterns revealed by the Correspondence Analysis (CA) and captured local details that are difficult to discern in the low-dimensional projection. Specifically, at the policy and practice levels, barriers without significant positive deviations in the heatmap (e.g., B27S1, B28S3) indicate critical gaps where new strategies are urgently needed.

The application of SCA revealed the overall structure and clustering

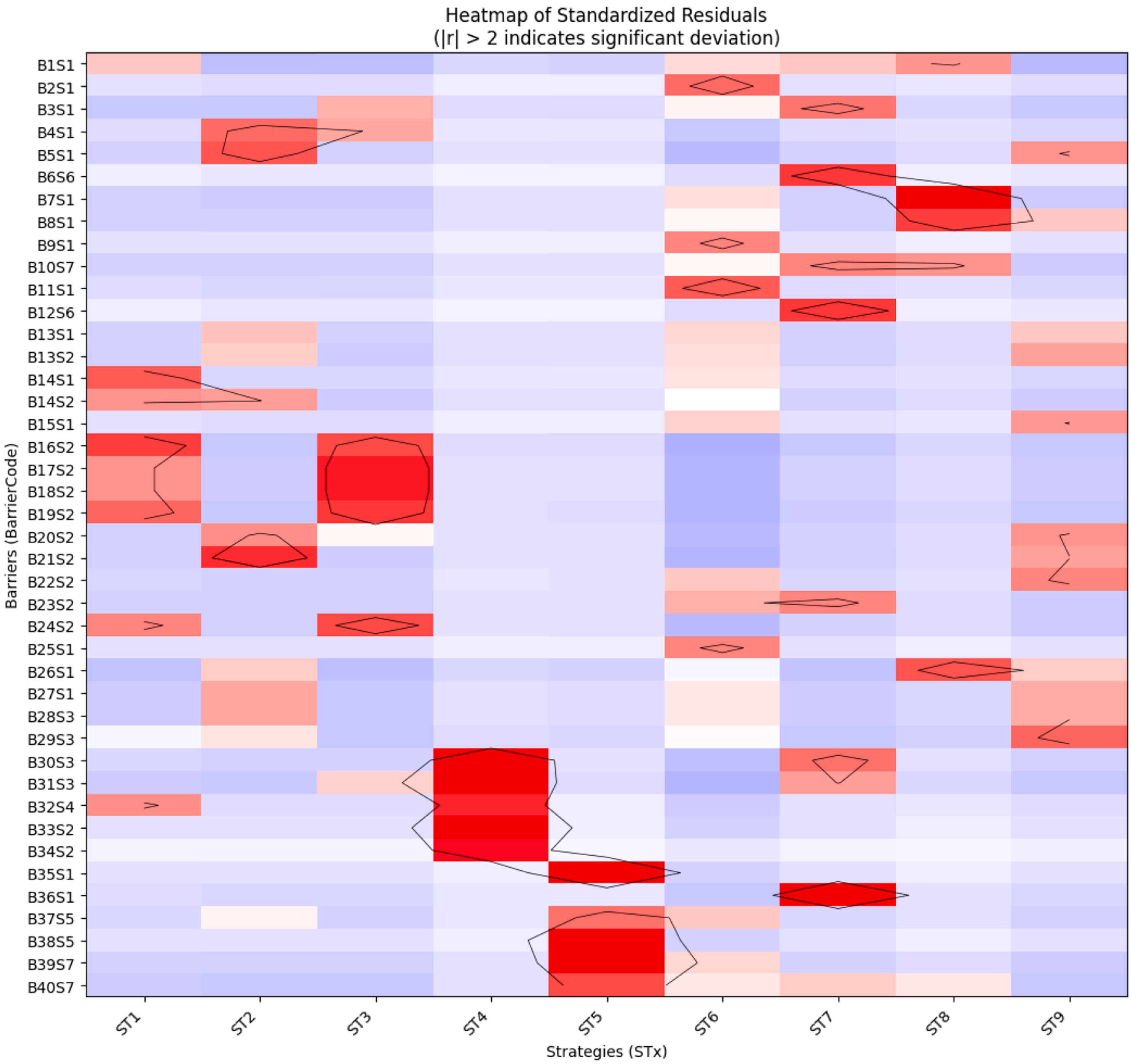

Fig. 3. Heatmap of barrier–strategy standardized residuals in NZEB implementation.

of barriers and mitigation strategies, precisely identifying "high-efficiency matches" between barrier–strategy pairs. This enabled stakeholders to implement NZEB in a more efficient and targeted manner. The findings can inform decision-making and public policy development to overcome identified challenges and promote the broader implementation of NZEB.

3.4. Case validation

This section validates the guidance and adaptability of our barrier–strategy mapping framework in NZEB projects under different conditions through case studies. To enhance representativeness and generality, we selected two internationally demonstrative NZEB cases that span different climate zones and project types, as shown in Table 5. Case A (NREL–RSF, USA) represents an advanced office building in North America and highlights the close link between contracts, incentives, and performance. Case B (ZERO-PLUS, EU) focuses on

Table 5
Case study profiles.

Attribute	Case1-NREL–RSF	ZERO-PLUS
Location / Climate Zone	Golden, Colorado, USA (ASHRAE Climate Zone 5B)	Pegeia (Cyprus), Voreppe (France), Nova Ferentillo (Italy), York (UK) – four zones
Building Type	Office building	Residential community
Scale	22 200 m²	156 units (across four settlements)
Certification	LEED Platinum (2011); LEED Zero Energy (2020)	Net Zero Energy Building (NZEB)
Key Energy Performance Metrics	EUI: 35 kBtu/ft²·yr (50 % below comparable new office buildings)	Net regulated energy ≤ 20 kWh/m²·yr; annual renewable generation ≥ 50 kWh/m²·yrk.
Data Sources	[191,198]	[81,199,200]

community housing under EU policy leadership. It covers multiple climate zones and user groups and shows the interplay among policy, market, and technology. We follow a uniform five-step procedure: (1) Barrier identification: Collect project literature, technical reports, and operational data. Extract key barrier nodes according to the categories in Table 2; (2) Based on the strategy types with significant positive residuals in Fig. 3, we determine the "Recommended Strategy Categories" (ST1–ST9) for each barrier in the framework, reflecting mitigation strategies that show strong coupling relationships in the literature; (3) Extract case strategies: Identify the effective strategies adopted in the project by analyzing case literature and data, and categorize them into the corresponding strategy types; (4) Check consistency: Compare the framework's preferred strategy categories with those applied in each case. Count three outcomes: full match (exact alignment), partial match (project adds other strategies on top), and miss (project does not use any recommended strategy in the framework); 5. Summarize consistency results.

Table 6 summarizes, for each key barrier in the two demonstrator cases—the office project (NREL–RSF) and the residential community (ZERO-PLUS)—the framework's recommended strategy categories, the Strategy implemented in the Case, and the degree of consistency between recommendation and practice.

Table 6
Alignment between recommended strategies and implemented measures for key barriers in NZEB demonstrator projects.

Case No.	Stage	Barrier Code & Description	Recommended Strategy Categories in the framework	Strategy in Case	Consistency
Case1	Concept	B1S1 High upfront costs B2S1 Lack of financing information	ST6 Incentive Policies and Regulatory Measures ST8 Innovative Business Models	ST6 Incentive Policies and Regulatory Measures (DOE grants; federal funding; green credit schemes) ST8 Innovative Business Models (Energy Performance Contracts / PPAs)	Fully consistent
	Concept	B7S1 Limited market demand & uncertainty B10S7 Limited public awareness	ST7 Certification Systems, Benchmarking, and Standards ST8 Innovative Business Models	ST7 Certification Systems, Benchmarking, and Standards (LEED Platinum/Zero certification; real-time energy dashboards) ST8 Innovative Business Models (demonstration value showcasing)	Fully consistent
	Design	B4S1 Lack of expertise B15S1 Lack of experienced partners	ST2 BIM+ Enhancing Efficiency ST9 Integrated Project Delivery	ST9 Integrated Project Delivery (design-competition RFP + performance-driven design-build delivery)	Fully consistent
	Construction	B20S2 Conflict between conventional structure & new processes B26S1 Misaligned supplier objectives	ST2 BIM+ Enhancing EfficiencyST9 Integrated Project Delivery ST8 Innovative Business Models	ST9 Integrated Project Delivery (fixed-price contracts + performance-based incentives)	Fully consistent
	Operation	B40S7 Insufficient financial rewards & incentives B8S1 Resistance to change	ST5 Operational Management System Technologies ST8 Innovative Business Models	ST8 Innovative Business Models (US$2 M annual operations incentive fund; tenant energy-savings sharing scheme)	Fully consistent
Case2	Concept	B6S6 Ambiguous definitions & inconsistent standards for low/zero-carbon buildings	ST7 Certification Systems, Benchmarking, and Standards	ST7 Certification Systems, Benchmarking, and Standards (ISO 14,044 LCA standard + Net Zero Energy/Carbon certification) ST6 Incentive Policies and Regulatory Measures (Cyprus renewables subsidies + EIB low-interest loans)	Partial match (ST7 ✓, ST6 not recommended)
	Concept	B1S1 High upfront costs B3S1 Lack of systematic understanding of costs & benefits	ST8 Innovative Business Models ST7 Certification Systems, Benchmarking, and Standards	ST3 Design Simulation Optimization Technology (multi-scenario LCCA decision optimization) ST1 Active–Passive & Renewable Energy Optimization (high-reflectance roof coating + PV–battery storage integration)	No match
	Concept	B7S1 Limited market demand & uncertainty	ST8 Innovative Business Models	ST8 Innovative Business Models (community-scale bulk procurement + shared energy hub) ST6 Incentive Policies and Regulatory Measures (Horizon 2020 ZERO-PLUS grants + green bond issuance)	Partial match (ST8 ✓, ST6 not recommended)
	Operation	B38S5 Performance gaps & inadequate energy monitoring B37S5 Lack of technical & system management skills	ST5 Operational Management System Technologies	ST5 Operational Management System Technologies (Model Predictive Control + rooftop PV–lithium battery integration)	Fully consistent
	Design	B20S2 Conflict between conventional structure & new processes	ST2 BIM+ Enhancing Efficiency ST9 Integrated Project Delivery	ST9 Integrated Project Delivery (multi-party, full-lifecycle risk-sharing contracts + change-control board)	Fully consistent
	Design	B12S1 Geographical & climatic constraints B16S2 Context-specific regional challenges	ST7 Certification Systems, Benchmarking, and StandardsST1 Active–Passive & Renewable Energy Optimization ST3 Design Simulation Optimization Technology	ST1 Active–Passive & Renewable Energy Optimization (high-reflectance façade paint + adjustable passive shading) ST3 Design Simulation Optimization Technology (microclimate wind-environment modeling & simulation)	Fully consistent
	Operation	B39S7 Lack of operational knowledge & skillsB40S7 Insufficient financial rewards & incentives	ST5 Operational Management System Technologies	ST5 Operational Management System Technologies (resident mobile energy-monitoring portal + time-of-use tariff response) ST8 Innovative Business Models (health & comfort credit incentives + tradable carbon-credit schemes)	Partial match (ST5 ✓, ST8 not recommended)

Across the two demonstration cases, we identified 19 distinct barriers that cover all major phases of the NZEB (Nearly Zero Energy Building) lifecycle, including conceptual planning, design, construction, and operation. We analyzed the degree of alignment between these barriers and the strategies applied in practice. The results show that approximately 78.9 % of the barriers (15 out of 19) were fully addressed using strategies that align precisely with those recommended by the framework. About 10.5 % of the barriers (2 out of 19) were addressed by combining the recommended strategies with additional actions tailored to specific project needs, resulting in more effective strategy packages. The remaining 10.5 % of the barriers (2 out of 19) were not addressed using any of the strategy categories recommended in the framework.

4. Discussing the barriers and strategies

4.1. Barrier patterns and stakeholder differences across NZEB implementation stages

Section 3.1 identified 42 barriers across four NZEB stages and seven stakeholder groups. Building on this, Mapping (Fig. 4) shows stakeholder challenges evolving from finance–policy frictions to personnel–technology frictions. The concept stage focuses on economic and legislative barriers, including capital pressures, policy uncertainty, and low market acceptance. These reflect high upfront costs, unclear policies, and limited public awareness in early decisions. Technical complexity spikes during the design and construction stages. Most barriers are professional or technical, highlighting integration challenges [194]. Despite recent advances and the availability of NZEB technologies [38], adoption still relies on stakeholders' technical skills and practices [38]. In the operation stage, performance gaps and weak incentives intensify, revealing investment–return discontinuities and lifecycle sensitivity of NZEB [29]. It also reflects end-users' concerns about cost-effectiveness, health, and energy benefits [26]. This progression across stages illustrates that NZEB adoption is not a static technical issue but a dynamic transformation, shifting from early policy and financial support to later-stage quality control and user engagement. Equally significant is the differentiation in the barriers faced by stakeholders. Developers (S1) and designers (S2) account for over 70 % of barriers, mainly in the concept and design stages. This emphasizes the importance of early decision-making and design in achieving NZEB success. By contrast, governments (S6) and end-users (S7) report fewer barriers; however, addressing their policy and economic issues boosts the confidence of other stakeholders [27]. Studies confirm the need to identify stakeholder barriers and quantify the extra effort required to overcome them [73,201]. These extra efforts—gathering financing data, negotiating design changes, and tracking certification—represent transaction costs [202,203]. Therefore, in addition to identifying barriers, recognizing the extra efforts required from stakeholders to overcome them helps reduce both the obstacles and their associated burdens, thus promoting the adoption and diffusion of NZEBs.

Fig. 4. Distribution of stakeholder-specific barriers across NZEB implementation stages.

4.2. High-consensus barrier–strategy characteristics in NZEB implementation

Section 3.3 applied SCA to examine relationships between 42 barriers and nine strategy categories. The results showed that 38 barriers (approximately 90 %) presented significant positive residuals ($|r_{ij}| \geq 2$) with at least one strategy. In other words, the literature has shown consensus on mitigation strategies for most identified barriers. Fig. 5

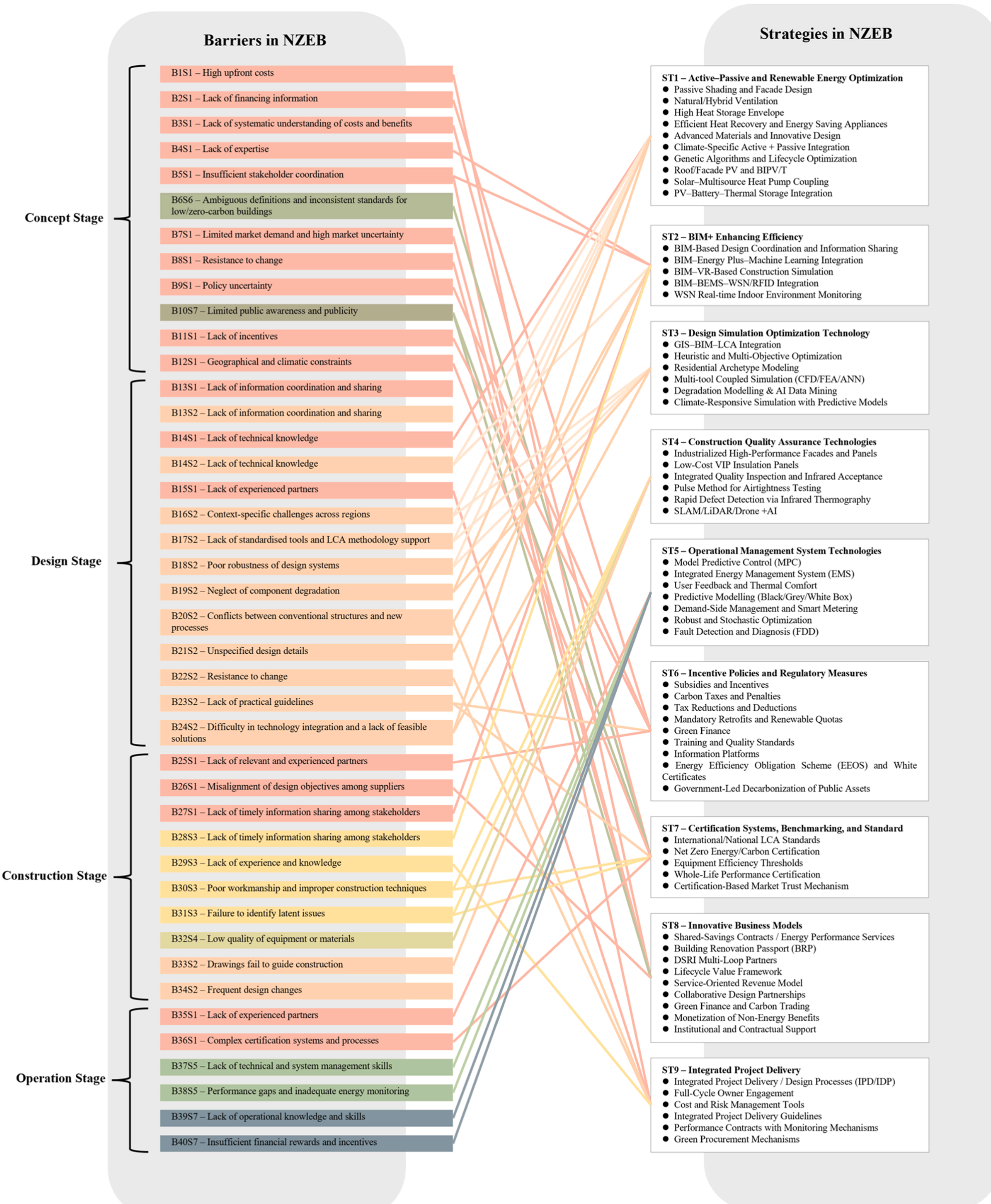

Fig. 5. Mapping of stakeholder-specific NZEB barriers to highly significant mitigation strategies across implementation stages.

maps each barrier to the highly significant mitigation strategies across implementation stages.

Based on this figure, we propose a staged set of combined mitigation strategies for NZEB implementation. The concept stage focuses on breaking financial and policy barriers through financial instruments and institutional tools. The design stage relies on digital collaboration and integration to reduce information and technology disconnection. The construction stage emphasizes on-site quality assurance, using inspection and standardization measures to prevent process failures. The operation stage aims to close the gap between performance and incentives through intelligent operation and maintenance combined with continuous certification.

Financing and institutional barriers—like high costs, low incentives, and market hesitation—dominate the concept stage. Almost all studies cite subsidies, regulations, and new business models as key to overcoming these barriers. "Green Finance + Shared-Savings Contracts/Energy Performance Services + BRP" are the most commonly cited methods to alleviate developers' capital pressure and increase end-user demand [204,205]. Furthermore, Net Zero Energy/Carbon Certification and national/international LCA standards—over technical specs—are stressed for providing a clear regulatory framework for early NZEB decisions [136,137].

In the design stage, gaps in information sharing and design tools grow more apparent. Existing studies focus on the solution of a "digital collaboration package"—comprising BIM-based design coordination and Information Sharing, Multi-tool Coupled Simulation (CFD/FEA/ANN), and GIS-BIM-LCA integration. BIM integration connects design details with construction execution, while the simulation and integration tools optimize passive design and renewable system deployment at the conceptual level. This multi-tool coupling approach is widely recognized as essential for reducing design complexity and improving efficiency, as it demonstrates consensus on the importance of digital collaboration [206].

During construction, studies emphasize the importance of an on-site quality control measure. Construction defects and mismatches between plans and execution are addressed through inspection methods, including infrared thermography, pulse airtightness tests, SLAM/LiDAR/Drone, and AI, as well as whole-life performance certification. These tools quickly identify defects, reduce rework, and establish a performance baseline [165–167]. Experts agree that inspection and standardization are the primary methods for preventing performance loss in construction [207].

In operation, attention shifts to performance gaps and weak incentives. Many studies combine Model Predictive Control (MPC)-driven Energy Management Systems (EMS) with whole-life performance certification. MPC-driven EMS narrows the gap between planned and actual energy use via load forecasting, scheduling, and feedback loops. Meanwhile, whole-life certification enforces transparent, ongoing constraints on building performance [208]. WSN real-time indoor environment monitoring and stage certification are also key for energy efficiency and asset value [209].

Although the high-consensus strategies form a progressive cycle across the four stages—covering financing, coordination, quality, and operation—this study identifies a persistent gap at the design–construction interface. Specifically, lack of information coordination and sharing, and frequent design changes show no significant coupling with any mitigation strategy.

4.3. Future research directions

Mapping 42 obstacles to nine categories reveals three NZEB implementation bottlenecks: concept-stage finance–policy friction, design–construction coordination gaps, and operation-stage performance–incentive misalignment. Most barriers have highly significant mitigation strategies, except at the design–construction interface, where insufficient coordination and frequent design changes lack any consensus approach. This gap increases rework risk, fragments performance data, and raises hidden transaction costs, ultimately weakening early-stage incentives. To address the design–construction bottleneck—poor information coordination, and frequent design changes causing rework, data fragmentation, and high transaction costs—and proposes a progressive solution path: (1) **Rebuild Data and Trust**—Ensure seamless information flow and clear accountability to support subsequent coordination and optimization; (2) **Enhance Technology and Efficiency**—Build on trusted data to improve design and construction coordination and systematically reduce hidden costs; (3) **Activate Capital and Incentives**—Leverage technical and efficiency gains to align performance with returns and unlock market potential. Based on this, the agenda is structured into three tiers and five research thrusts, ordered by priority:

Tier 1. **Rebuild data and trust** (highest priority)

1. Building complete and trustworthy information channels: Develop a cross-stage, one-stop digital platform integrating technical parameters, energy-consumption data, policy regulations, and collaborative resources [210]; enhance information credibility, intuitiveness, and coverage through visual dashboards and intelligent recommendations [211]; introduce new indicators such as indoor climate, health, and resilience to bridge the information gap between design and construction stages, thereby turning fragmented hand-offs into a continuous data thread that prevents rework and data loss at the design–construction interface.
2. Developing intelligent certification and assessment processes: Utilize a BIM-GIS integrated platform to modularize data collection [212–214], automated checking [215], simulation validation [216], and third-party certification [217]; improve assessment transparency, shorten approval cycles, and reduce compliance costs, creating a single, trusted record that discourages late-stage design changes and the transaction costs they trigger.

Tier 2. **Enhance technology and efficiency** (second priority)

3. Standardizing safe and compliant AI applications: Develop an NZEB-specific algorithm suite and a comprehensive data-governance framework; harmonise BIM, energy-use, and environmental data formats; apply causal inference, reinforcement learning, and federated learning for adaptive optimisation [218]; extend AI to the design–construction interface via blockchain-enabled smart contracts [219] (scan-to-BIM verification [220], on-chain payment triggers) while ensuring traceability, interpretability, and cybersecurity, so that design updates are instantly reflected on-site and coordination gaps are closed in real time.
4. Reducing transaction costs across the project process: Identify and quantify the hidden costs of learning, negotiation, monitoring, and enforcement incurred by stakeholders at each stage [203]; quantify the proportion of transaction costs (TCs) borne by different stakeholders [221]; and reduce non-technical costs through shared training, standardized contract management, and lean collaboration models, directly attacking the hidden frictions that discourage proactive coordination between designers and constructors.

Tier 3. **Activate capital and incentives** (third priority)

5. Developing diverse and sustainable revenue mechanisms: Beyond traditional subsidies, identify and monetize external benefits such as indoor comfort, health, and carbon reduction [191]; establish long-term market incentives centred on carbon trading, green REITs, differentiated electricity pricing [222], and performance-based contracts to ensure that NZEBs outperform conventional buildings in terms of cash flow and risk profiles, so stakeholders who invest in

early, high-quality coordination across the design–construction divide are financially rewarded.

4.4. From literature popularity to empirical validity

This study applied simple correspondence analysis (SCA) to quantitatively describe the co-occurrence strength between barriers and strategies at each project stage. Based on this analysis, we developed a barrier–strategy mapping and prioritization framework grounded in the consensus of the literature. This framework functions as a tool for screening strategies rather than predicting performance outcomes. It reflects the dominant academic view on recommended strategies for specific barriers—what we refer to as "literature popularity". However, this does not mean that these strategies are always the most effective or universally applicable in practice, which we define as "empirical validity".

To explore the gap between academic recommendations and real-world outcomes, we introduced two case studies in Section 3.4: the NREL–RSF office building and the ZERO PLUS residential community. We compared the strategies recommended by the framework with those implemented in the case. For most barriers, the strategy categories recommended by our framework match those implemented in the case studies. For a small number of barriers, the implemented strategies overlap with the recommended categories but include context-specific additions or substitutions. Only for a very small number of barriers do the implemented categories diverge entirely from our framework's recommendations. Together, these two cases show that while literature popularity provides a valuable guide for prioritizing strategies, empirical validity must still be confirmed and refined through local adaptation and on-site application.

Although the case validations corroborate the framework's strategic guidance, they also reveal its limited adaptability across diverse project settings and institutional contexts. First, by relying solely on published literature, this study may be subject to potential biases in literature selection. Second, SCA captures "literature popularity" rather than “empirical validity,” which may lead to an overestimation of strategy effectiveness or an underestimation of implementation challenges. Third, by focusing on explicit barriers, this study overlooks pervasive implicit institutional resistances—"transaction cost barriers"—such as information search costs, stakeholder coordination overhead, and certification compliance expenses. Although infrequently reported, these transaction cost barriers are widespread in NZEB projects and directly impact strategy feasibility and implementation outcomes.

To improve the explanatory power and real-world applicability of the framework, we propose four recommendations for future empirical research:

1. Conduct field validation involving multiple stakeholders: Researchers should use semi-structured interviews, focus groups, and surveys to empirically test the SCA-identified barriers and strategies across different regions and project contexts. Particular attention should be given to identifying execution challenges during the design–construction phase.
2. Integrate a transaction cost analysis framework: Future studies should identify and quantify non-technical costs associated with information asymmetry, coordination frictions, and certification procedures. These factors often shape how and whether strategies are implemented, and understanding their systemic impact can inform institutional-level improvements.
3. Develop a mixed-method validation mechanism: Building on the proposed barrier–strategy–stage–actor model, researchers could integrate Delphi methods, case studies, and text mining to create a multi-source, multi-method validation system. This would enhance the model's adaptability to diverse project settings and help reveal low-frequency but high-impact mechanisms that current frequency-based methods might overlook.
4. Conduct comparative studies across regions and institutional systems: By systematically comparing policy frameworks, market mechanisms, and implementation pathways in different countries and regions, researchers can identify the boundary conditions that affect strategy applicability. These insights will support the development of context-sensitive strategy packages and enable more effective and adaptable implementation approaches.

By pursuing these research directions, future studies can address the current limitations of SCA in capturing strategy adaptability and behavioural mechanisms. This will help advance both the theoretical and practical development of NZEB implementation.

5. Conclusion

This systematic literature review identified and analysed the barriers faced by stakeholders during different stages of NZEB implementation and the corresponding mitigation strategies. The findings addressed the initial research questions and provided important insights:

In response to RQ1, this study identified 42 major barriers across the concept, design, construction, and operation stages of NZEB implementation, spanning seven dimensions: economic, professional/technical, legislative, market, socio-cultural, geographical, and technological. These barriers involve seven core stakeholder groups, including developers, government authorities, designers, and others.

In response to RQ2, the literature review summarized nine major categories comprising 63 subcategories of mitigation strategies, including active/passive and renewable energy optimization, rating systems, benchmarks and standards, and incentive policy mechanisms. These strategies aim to comprehensively address the identified barriers and reflect the evolving landscape of NZEB technologies and policy environments.

In response to RQ3, this study employed SCA to explore the association patterns between 42 identified barriers and nine categories of mitigation strategies, revealing the overall structure and clustering of barriers and mitigation strategies and identifying highly significant mitigation strategies for each barrier. Additionally, the study uncovered barriers that existing strategies have not significantly mitigated.

Moreover, case validations demonstrate that, while the framework reliably guides the prioritization of strategy categories, "literature popularity" does not guarantee "empirical validity", and specific sub-strategies must be adapted to local policy, market, and technical constraints.

These insights carry important implications for NZEB practitioners, policymakers, and researchers. Construction teams can leverage the stakeholder–barrier mapping model to identify stage-specific bottlenecks and deploy context-tailored mitigation measures, thereby systematically advancing NZEB adoption. Policymakers can target incentives toward the most critical stages and actors based on the barrier–strategy mappings to enhance policy precision and effectiveness. Ultimately, the proposed literature-consensus mapping paradigm provides a structured framework for selecting and prioritizing strategies across diverse regional, project, and application contexts.

Nevertheless, this study has several limitations: it relies on published literature and may be affected by potential biases in literature selection; the SCA framework reflects "literature popularity" rather than true "empirical validity"; and case validation is limited to two demonstrator projects, which constrains the generalizability of the findings. Future research should undertake in-depth field studies across diverse climate zones and project types to strengthen the framework's explanatory power and applicability, and to bridge the gap between "literature popularity" and "empirical validity", thereby laying a more robust theoretical and practical foundation for large-scale, reliable NZEB deployment.

CRediT authorship contribution statement

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

Declaration of competing interest

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

Appendix A

Table A
Keywords search string and results.

Category	Database	Search terms	Results
Barriers	Scopus	TITLE-ABS-KEY("net zero carbon building" OR "NZCB" OR "zero carbon building" OR "ZCB" OR "net zero energy building" OR "NZEB" OR "zero energy building" OR "ZEB" OR "net zero emissions building" OR "zero emissions building" OR "low energy building" OR "low carbon building" OR "LCB" OR "carbon neutral building" OR "climate neutral building" OR "nearly zero energy building" OR "nZEB" OR "net-zero building" OR "zero net energy" OR "ZNE") AND TITLE-ABS-KEY("barrier*" OR "challenge*" OR "obstacle*" OR "risk*") AND TITLE-ABS-KEY("stakeholder*" OR "supply group" OR "contractor*" OR "developer*" OR "energy producer*" OR "energy supplier*" OR "demand group" OR "client*" OR "end-user*" OR "regulation group" OR "government" OR "institution*" OR "professional bod*" OR "financier*")AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))	141
	Web of Science	TS=("net zero carbon building" OR "NZCB" OR "zero carbon building" OR "ZCB" OR "net zero energy building" OR "NZEB" OR "zero energy building" OR "ZEB" OR "net zero emissions building" OR "zero emissions building" OR "low energy building" OR "low carbon building" OR "LCB" OR "carbon neutral building" OR "climate neutral building" OR "nearly zero energy building" OR "nZEB" OR "net-zero building" OR "zero net energy" OR "ZNE") AND TS=("barrier*" OR "challenge*" OR "obstacle*" OR "risk*") AND TS=("stakeholder*" OR "supply group" OR "contractor*" OR "developer*" OR "energy producer*" OR "energy supplier*" OR "demand group" OR "client*" OR "end-user*" OR "regulation group" OR "government" OR "institution*" OR "professional bod*" OR "financier*")	97
Strategies	Scopus	TITLE-ABS-KEY("net zero carbon building" OR "NZCB" OR "zero carbon building" OR "ZCB" OR "net zero energy building" OR "NZEB" OR "zero energy building" OR "ZEB" OR "net zero emissions building" OR "zero emissions building" OR "low energy building" OR "low carbon building" OR "LCB" OR "carbon neutral building" OR "climate neutral building" OR "nearly zero energy building" OR "nZEB" OR "net-zero building" OR "zero net energy" OR "ZNE") AND TITLE-ABS-KEY("strategy*") AND TITLE-ABS-KEY ("stakeholder*" OR "supply group" OR "contractor*" OR "developer*" OR "energy producer*" OR "energy supplier*" OR "demand group" OR "client*" OR "end-user*" OR "regulation group" OR "government" OR "institution*" OR "professional bod*" OR "financier*")AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))	123
	Web of Science	TS=("net zero carbon building" OR "NZCB" OR "zero carbon building" OR "ZCB" OR "net zero energy building" OR "NZEB" OR "zero energy building" OR "ZEB" OR "net zero emissions building" OR "zero emissions building" OR "low energy building" OR "low carbon building" OR "LCB" OR "carbon neutral building" OR "climate neutral building" OR "nearly zero energy building" OR "nZEB" OR "net-zero building" OR "zero net energy" OR "ZNE") AND TS=("Strategy*") AND TS=("stakeholder*" OR "supply group" OR "contractor*" OR "developer*" OR "energy producer*" OR "energy supplier*" OR "demand group" OR "client*" OR "end-user*" OR "regulation group" OR "government" OR "institution*" OR "professional bod*" OR "financier*")	28
	Number of articles selected	Manual screening based on the elimination criteria in Section 2.2	89

Note: The Scopus and WoS searches were conducted in February 2025.

Appendix B

Table B
Standardized Residuals Matrix for Barrier–Strategy Combinations.

BarrierCode	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	ST9
B1S1	1.205	-1.311	-1.272	-0.811	-0.871	0.777	1.205	2.191	-1.330
B2S1	-0.658	-0.701	-0.680	-0.433	-0.465	2.973	-0.658	-0.510	-0.711
B3S1	-1.041	-1.108	1.716	-0.685	-0.736	0.297	2.803	-0.806	-1.124
B4S1	-0.736	3.046	1.872	-0.484	-0.520	-1.124	-0.736	-0.570	-0.795
B5S1	-0.871	3.388	-0.899	-0.573	-0.616	-1.330	-0.871	-0.674	2.249
B6S6	-0.465	-0.495	-0.481	-0.306	-0.329	-0.711	3.832	-0.361	-0.503
B7S1	-0.931	-0.991	-0.961	-0.613	-0.658	0.688	-0.931	6.214	-1.005
B8S1	-0.871	-0.927	-0.899	-0.573	-0.616	0.174	-0.871	3.774	1.186
B9S1	-0.570	-0.607	-0.589	-0.375	-0.403	2.575	-0.570	-0.442	-0.616
B10S7	-0.871	-0.927	-0.899	-0.573	-0.616	0.174	2.575	2.291	-0.940
B11S1	-0.736	-0.783	-0.760	-0.484	-0.520	3.324	-0.736	-0.570	-0.795

(continued on next page)

Table B (*continued*)

BarrierCode	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	ST9
B12S6	-0.465	-0.495	-0.481	-0.306	-0.329	-0.711	3.832	-0.361	-0.503
B13S1	-0.871	1.231	-0.899	-0.573	-0.616	0.926	-0.871	-0.674	1.186
B13S2	-0.931	1.027	-0.961	-0.613	-0.658	0.688	-0.931	-0.721	1.978
B14S1	3.341	-0.783	-0.760	-0.484	-0.520	0.655	-0.736	-0.570	-0.795
B14S2	2.292	2.037	-0.961	-0.613	-0.658	-0.015	-0.931	-0.721	-1.005
B15S1	-0.658	-0.701	-0.680	-0.433	-0.465	0.984	-0.658	-0.510	2.102
B16S2	3.764	-1.108	3.577	-0.685	-0.736	-1.590	-1.041	-0.806	-1.124
B17S2	2.292	-0.991	4.240	-0.613	-0.658	-1.422	-0.931	-0.721	-1.005
B18S2	2.292	-0.991	4.240	-0.613	-0.658	-1.422	-0.931	-0.721	-1.005
B19S2	3.064	-1.051	3.884	-0.650	-0.698	-1.508	-0.987	-0.765	-1.066
B20S2	-0.871	2.310	0.213	-0.573	-0.616	-1.330	-0.871	-0.674	2.249
B21S2	-0.931	4.055	-0.961	-0.613	-0.658	-1.422	-0.931	-0.721	1.978
B22S2	-0.806	-0.858	-0.833	-0.531	-0.570	1.205	-0.806	-0.624	2.575
B23S2	-0.871	-0.927	-0.899	-0.573	-0.616	1.677	2.575	-0.674	-0.940
B24S2	2.575	-0.927	3.549	-0.573	-0.616	-1.330	-0.871	-0.674	-0.940
B25S1	-0.570	-0.607	-0.589	-0.375	-0.403	2.575	-0.570	-0.442	-0.616
B26S1	-1.187	1.112	-1.225	-0.781	-0.839	-0.157	-1.187	3.433	1.059
B27S1	-0.987	1.803	-1.020	-0.650	-0.698	0.481	-0.987	-0.765	1.747
B28S3	-0.987	1.803	-1.020	-0.650	-0.698	0.481	-0.987	-0.765	1.747
B29S3	-0.175	0.559	-1.127	-0.719	-0.772	0.132	-1.091	-0.845	3.062
B30S3	-0.806	-0.858	-0.833	5.123	-0.570	-1.231	2.915	-0.624	-0.871
B31S3	-0.987	-1.051	0.942	5.505	-0.698	-1.508	2.051	-0.765	-1.066
B32S4	2.380	-0.701	-0.680	4.183	-0.465	-1.005	-0.658	-0.510	-0.711
B33S2	-0.570	-0.607	-0.589	7.620	-0.403	-0.871	-0.570	-0.442	-0.616
B34S2	-0.329	-0.350	-0.340	4.399	-0.233	-0.503	-0.329	-0.255	-0.355
B35S1	-0.570	-0.607	-0.589	-0.375	7.040	-0.871	-0.570	-0.442	-0.616
B36S1	-0.736	-0.783	-0.760	-0.484	-0.520	-1.124	6.059	-0.570	-0.795
B37S5	-0.806	0.307	-0.833	-0.531	2.939	1.205	-0.806	-0.624	-0.871
B38S5	-0.570	-0.607	-0.589	-0.375	7.040	-0.871	-0.570	-0.442	-0.616
B39S7	-0.871	-0.927	-0.899	-0.573	5.881	0.926	-0.871	-0.674	-0.940
B40S7	-0.987	-1.051	-1.020	-0.650	3.599	0.481	1.038	0.543	-1.066

Appendix C. Python script for SCA-based residual analysis

```
# ————————————————————————
# SCA Analysis: Chi-square Test & Standardized Residuals
# • Input: contingency table CSV (Barriers × Strategies)
# • Outputs:
# 1) Chi-square statistic, p-value, dof
# 2) Expected frequencies and standardized residuals
# ————————————————————————
import pandas as pd
import numpy as np
from scipy.stats import chi2_contingency
# ————————————————————————
# 1. Load contingency table
# ————————————————————————
# Replace with the actual path to the CSV file
data_path = "your_data_path/barrier_strategy_matrix.csv"
# Load the matrix with BarrierCode as row index
df = pd.read_csv(data_path).set_index("BarrierCode")
df = df.loc[~(df == 0).all(axis=1)] # drop all-zero rows if needed
# ————————————————————————
# 2. Chi-square test
# ————————————————————————
chi2, p, dof, expected = chi2_contingency(df.values)
print("Chi-square Test:")
print(f" Chi2 = {chi2:.2f}")
print(f" p = {p:.4f}")
print(f" dof = {dof}")
# ————————————————————————
# 3. Standardized Residuals
# ————————————————————————
obs = df.values
exp = expected
std_resid = (obs - exp) / np.sqrt(exp)
# Convert to DataFrame
resid_df = pd.DataFrame(std_resid, index=df.index, columns=df.columns)
print("\nStandardized Residuals:")
print(resid_df)
# Highlight residuals above/below threshold
threshold = 2
high_positive = resid_df[resid_df > threshold].stack()
```

(*continued on next page*)

(*continued*)

```
40. high_negative = resid_df[resid_df < -threshold].stack()
41. print(f"\nCells with residual > {threshold}:")
42. print(high_positive)
43. print(f"\nCells with residual < -{threshold}:")
44. print(high_negative)
```

Data availability

Data will be made available on request.

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