

Article

Implementing Zero-Carbon Buildings: A Technological Index and an Innovative Strategic Roadmap

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Abstract

Implementing zero-carbon buildings (ZCBs) can serve as a promising approach to reducing unsustainable emissions and decreasing the effects of climate change on the Earth. However, many countries face technological barriers that hinder the successful implementation of ZCBs. To end this, this study develops a technological index for implementing ZCBs and provides strategies with actionable examples to advance the implementation. Therefore, the study identified 17 technological barriers that hinder the implementation of ZCBs from previous studies, which were then used to create a survey for distribution to construction professionals through an online platform. A survey of 272 usable responses was collected and analyzed via principal component analysis, fuzzy synthetic evaluation, and sensitivity assessment. These analysis techniques were harnessed to develop the technological index of 3.50, which is inclined to be highly influenced. To reduce this index, the study proposes an innovative strategic roadmap based on insights from the literature, providing a practical guide for implementing strategies with actionable examples. The developed index, in conjunction with an innovative strategic roadmap, will help researchers optimize the current knowledge. It will also guide practitioners and policymakers to enable sustainable decisions in building construction projects.

Keywords: sustainable building; zero-carbon buildings; fuzzy synthetic evaluation; technological index; strategic roadmap



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1. Introduction

The construction sector has reached a critical turning point, as the greenhouse gas emissions from building construction will continue to accelerate climate change unless immediate action is taken [1]. The building industry is still emitting billions of tons of CO₂ each year and will make it impossible to limit global warming to 1.5 °C while exposing future generations to a dangerously unstable climate [2]. The Organization for Economic Co-operation and Development (OECD) indicated that nearly all new buildings must achieve zero-carbon building (ZCB) standards by 2030, and the existing buildings must undergo deep decarbonization by 2050 to prevent environmental collapse [3]. Therefore, the

transition to zero-carbon buildings (ZCBs) is not a matter of preference but a fundamental necessity for a sustainable future.

The OECD defined the concept of ZCBs as the way to achieve a zero-carbon or net-zero emission building, which requires adopting a whole life-cycle approach [3]. The UK Green Building Council defines ZCBs as a state where zero-carbon emissions from building construction and operations are either nonexistent or offset to a net-negative level [4]. Meanwhile, several previous studies defined the ZCBs as the sustainable path for buildings without emissions from either operational carbon or embodied carbon [5–7]. The operational carbon is emissions resulting from the buildings' use, and embodied carbon refers to the emissions that come from materials, construction, and demolition [3].

The implementation of ZCBs offers significant advantages for both society and biodiversity. However, challenges hinder their widespread adoption in the building construction sector. Osuizugboet et al. [8] noted that the integration of emerging technologies for ZCBs remains limited and is hindered by various barriers. The limitation is due to an unstable indicator that provides a clear scenario for the barriers that hinder the adoption of technology in implementing ZCBs. Therefore, this indicates a lack of indexes that introduce the importance of the technologies necessary for ZCB implementation. This issue may stem from the scarcity of research addressing the indexes associated with ZCB implementation [9]. As a result, further studies are needed to determine the technological index for advancing the implementation of ZCBs.

In the construction sector, an index is a numerical metric used to monitor economic trends, material costs, and market fluctuations that influence various projects [10,11]. This index primarily functions as a benchmarking tool, enabling industry professionals to make informed decisions regarding project planning, resource distribution, and financial management. In this regard, the significance of the technological index lies in its ability to convert complex data into standardized, easily interpretable metrics applicable to construction management and planning. In this context, while it is recognized that achieving the benefits of ZCBs depends on the availability of adequate technology, existing research has not yet established a technological index for ZCB implementation, and there is also a lack of a roadmap that can be harnessed to support adopting technology in order to implement ZCBs. Therefore, the research questions of the present study are as follows:

- What is the technological index for implementing ZCBs?
- What is the roadmap that can be used to reduce the technological index in order to implement ZCBs?

To address these questions, this study develops a technological index for implementing ZCBs and proposes an innovative strategic roadmap based on insights from previous studies to reduce the technological index in order to implement ZCBs. The technological index with an innovative strategic roadmap can help policymakers to have an in-depth understanding of the current status of technological barriers that hinder the implementation of ZCBs. Also, the policymakers will be knowledgeable enough to generate proactive and post-action plans to advance the implementation of ZCBs. The practitioners will be enabled to harness the technology for implementing ZCBs. Meanwhile, the academics can also be provided with a technological index and an innovative strategic roadmap, which can be used to extend the current knowledge on the implementation of ZCBs worldwide. The next section demonstrates the relevant literature regarding technological index development aligned with the point of departure of this study, followed by the section that highlights the methodology and then the section that presents the results of the applied data analysis techniques. Subsequently, the discussion section discussed the technological index for the construction of ZCBs, followed by a section that provides an innovative strategic roadmap to lower the developed index based on previous studies. The implications of this study

are also discussed and provided in a separate section. The last section introduces the conclusion and limitations as well as future research directions.

2. Research Background

2.1. Concept and Definition of ZCBs

The idea of ZCBs has become a central element in international efforts to cut emissions and address climate change, with the goal of reaching net-zero targets by the mid-century. A ZCB achieves equilibrium between the carbon it emits and the carbon it offsets or avoids, primarily through energy efficiency measures, the use of renewable energy sources, and the reduction of embodied carbon throughout its life cycle [3]. The UK Green Building Council specifies that ZCBs must achieve both “net-zero operational carbon” and “net-zero embodied carbon,” indicating a transition from focusing solely on energy use to considering the entire building life cycle [12]. The pressing need for this transition stems from the fact that the built environment accounts for about 37% of global energy-related CO₂ emissions [13]. Therefore, the concept of ZCBs extends beyond enhancing efficiency—it reframes sustainable construction as a pursuit of total carbon neutrality [14,15]. This can cover material extraction, design, operation, and end-of-life stages [16]. Thus, ZCBs represent a technological development as well as a sustainable direction for construction systems that align with environmental limits.

2.2. An Overview of Implementing ZCBs

ZCBs play a vital role in lowering carbon emissions, addressing the growing concerns of greenhouse gas emissions and high energy consumption in the construction sector [17]. These buildings strive to maintain an equilibrium between carbon emissions and carbon absorption, ultimately achieving net-zero-carbon output [18]. As noted by Zhao et al. [19], the concept of ZCBs was first introduced in the UK in 2002 with the creation of the world’s first “zero-carbon dwellings” and “zero-carbon community.” Generally, ZCBs operate using renewable energy sources, incorporate rainwater harvesting or reclaimed water systems, and prioritize waste recycling and treatment [20]. The advantages of ZCBs include improved energy efficiency, reduced energy consumption, minimized waste, enhanced building performance, controlled carbon emissions, lower environmental impact, climate change mitigation, and a substantial decrease in greenhouse gas emissions over the building’s life cycle [21]. However, the global adoption of ZCB practices remains uneven, with many countries encountering obstacles that hinder their implementation [22]. Despite the various advantages of ZCBs, technological challenges continue to slow progress in the sector. For example, Ohama et al. [23] emphasized that the integration of renewable energy technologies in African buildings is still limited. Fouly and Abdin [9] attributed this slow adoption to a lack of awareness and understanding of the technologies essential for ZCBs, highlighting the need for further research in this area. Thus, implementing ZCBs is a sustainable solution to reduce energy consumption in construction projects.

2.3. Role of Technology in Implementing ZCBs

Achieving zero-carbon performance relies heavily on technological advancements in both active and passive systems. Earlier studies highlighted the integration of renewable energy technologies for advancing ZCBs. For example, Zhao et al. [24] indicated that building-integrated photovoltaics, hybrid geothermal systems, and smart energy management platforms are the key enablers for implementing ZCBs. These technologies can help with passive design measures, high-performance envelopes, and adaptive façades [25]. Digital tools such as Building Information Modeling (BIM), life-cycle assessment (LCA), and digital twins have become essential for quantifying and minimizing embodied carbon

throughout design and operation [14,26]. The convergence of these technologies advances the paradigm of smart and sustainable building [27,28]. However, these technologies are contingent on various technological barriers.

2.4. Technological Barriers for Implementing ZCBs

Previous studies have identified several technology-related barriers that impede the advancement of ZCBs. Gaining insight into these challenges can help organizations, policymakers, governments, and construction stakeholders develop strategies to mitigate these issues and support ZCB adoption within the construction industry. These barriers include a lack of research in technological applications, a lack of accessible technologies, the high cost of maintenance on ZCB, the availability of renewable energy technologies, a lack of clients' understanding of technologies, and less technical knowledge in new technological advancements [9,23,29–38]. The literature review identified 17 technology-related barriers that influence the construction of ZCBs based on findings from previous studies. Table 1 presents the list of technological barriers to the implementation of ZCBs.

Table 1. Technological barriers to implementing ZCBs.

No	Barriers	1	2	3	4	5	6	7	8	9	10	11	12	Sum
B01	Insufficient research on technological applications	■		■			■							3
B02	Limited access to available technologies	■			■	■						■		4
B03	Elevated maintenance costs for zero-carbon buildings (ZCB)	■						■				■		3
B04	Insufficient client understanding of technological solutions	■	■				■	■	■	■				6
B05	Limited technical expertise in emerging technologies	■		■		■			■	■	■	■		7
B06	Inadequate knowledge of renewable technologies		■				■	■	■	■				5
B07	Limited availability of renewable energy technologies						■					■		2
B08	Insufficient technological infrastructure	■			■		■					■		4
B09	Limited technical knowledge in recent technological advancements	■				■	■	■	■	■	■	■		8
B10	Cost of ZCB technology	■			■			■				■		4
B11	The industry's capacity to adopt ZCB technologies, including policy initiatives and industry practices		■			■	■	■			■	■	■	7
B12	Research findings are not effectively transformed into technological innovations						■				■			2
B13	Practical challenges related to the maintainability and operability of ZCB										■			1
B14	Conflicts with new technologies arising from the current condition of existing buildings						■				■			2
B15	Complexity of ZCB technology		■								■	■		3
B16	Insufficient space for the installation of on-site renewable energy technologies					■					■			2
B17	Underdeveloped technology							■					■	2

Notes: 1 = [23]; 2 = [9]; 3 = [29]; 4 = [30]; 5 = [31]; 6 = [32]; 7 = [33]; 8 = [34]; 9 = [35]; 10 = [36]; 11 = [37]; 12 = [38].

2.5. Developed Indexes in Building Construction

The index serves as a strategic framework that can empower construction organizations with a practical tool to integrate scarce organizational resources, effectively enhancing their competitive edge in business [39]. Alnaser et al. [40] developed a model that calculates the sustainable building index that ranges between 0.1 and 1.00; the greater the value, the greater the chance for building projects that seek to integrate photovoltaic or wind turbines. Similarly, Li et al. [41] also developed a model to estimate the construction waste generation index for building projects. Also, Liu et al. [42] established a model to calculate the building energy efficiency evaluation index. Afshar Ali et al. [43] developed a modified information and communication technology maturity level index in buildings. Hong et al. [44] determined indexes for the real-time monitoring of environmental pollutants in building construction projects. O'Grady et al. [45] presented a new circular economy-based index for the built environment, including design for disassembly, deconstruction, and resilience. Recently, Qasem and Almohassen [46] developed a virtual reality-based constructability index for building construction projects. Thus, these studies illustrate that developing an index is a crucial measure to accelerate the growth of the industry of sustainable building construction.

2.6. Developed Indexes Using Fuzzy Synthetic Evaluation in Construction Studies

Fuzzy set theories utilize mathematical logic to derive objective inferential conclusions from subjective statements [47]. In this regard, the fuzzy synthetic evaluation (FSE) enhances the handling of uncertainties for construction professionals' decisions [10]. The FSE was commonly applied in previous studies in the field of construction management to develop an index for a particular matter. Gaur and Tawalare [48] developed a performance index to evaluate the building information modeling-based stakeholder management in mega-construction projects. Oluleye et al. [49] determined a significance index using FSE for barriers to circular economy adoption in the construction industry towards zero waste. Chen et al. [50] developed the readiness model index by applying the FSE for adopting digital technologies in construction organizations. Nguyen and Ha [39] used the FSE to develop an implementation index for corporate social responsibility in architectural design organizations. Similarly, Nguyen et al. [51] developed a climate for innovation index by applying FSE for the development purpose of architectural design organizations. Tetteh et al. [52] conducted the FSE technique to develop the overall index and sub-indexes for the critical drivers for the adoption of wearable sensing technologies for construction safety monitoring. Moyo et al. [53] used the FSE for evaluating the index and sub-indexes for the technical support system for sustainable construction indicators. Omer et al. [54] developed workplace indexes at construction sites using the FSE technique. The previous studies in construction underscore the importance of FSE in developing the indexes for different purposes.

2.7. Roadmaps in Building Construction

Phaal et al. [55] stated that the roadmap can offer an innovative representation of information. Zhang et al. [56] proposed a staged roadmap to advance the zero-energy building technologies at the urban scale, which was divided into three stages for effective implementation. Arachchi et al. [57] provided a roadmap for construction professionals to promote sustainability by integrating the principles of the circular economy in passive tropical building designs. Bahgat et al. [58] designed a life-cycle roadmap to achieve a net-zero built environment in the MENA and South Africa regions. Öberg et al. [59] developed a roadmap of actions to support the implementation of design for structural adaptation in timber buildings in Sweden and Australia. Heidari et al. [60] established an energy retrofit

roadmap to achieve a net-zero energy and carbon footprint for Canadian single-family houses. Nasirzadeh et al. [61] introduced a roadmap to improve the labor productivity in building construction projects in Australia. Skarning et al. [62] mapped out a roadmap for enhancing roof and façade windows in nearly zero-energy homes across Europe.

2.8. Points of Departure

This study concludes with a summary of reviewing the previous studies in key elements to create a path for the points of departure. The key elements can be found as follows:

- Implementing ZCBs is a sustainable practice to address the negative impacts on the environment and society.
- Implementing technology in building construction is a promising solution. However, there is a research gap in addressing the technological barriers slowing the global population, particularly developing regions, from implementing ZCBs.
- Several indexes were developed in the field of building construction. However, there is a research gap in developing a technological index for implementing ZCBs.
- Previous studies advocated that FSE is an optimal technique to develop indexes.
- Previous studies lack a strategic roadmap to advance the implementation of ZCBs.

Therefore, this study seeks to address the points of departure by developing a technological index for implementing ZCBs. Additionally, this study proposes an innovative strategic roadmap based on the earlier literature.

3. Methodology

This study employed a multiphase methodology to address the objectives of this study, as illustrated in Figure 1. To this end, the figure shows that the study contains 5 phases, where phase 1 is used to identify 17 technological barriers for the literature review, phase 2 is focused on procedures of the survey and data collection, and phase 3 is assigned for analyzing the collected data. Meanwhile, phase 4 is dedicated to discussing the outputs from the analysis techniques, and phase 5 is harnessed to synthesize the findings to create an innovative strategic roadmap as well as provide a practical guide to foster the implementation of ZCBs. Figure 1 presents the workflow of the methodology for the present study.

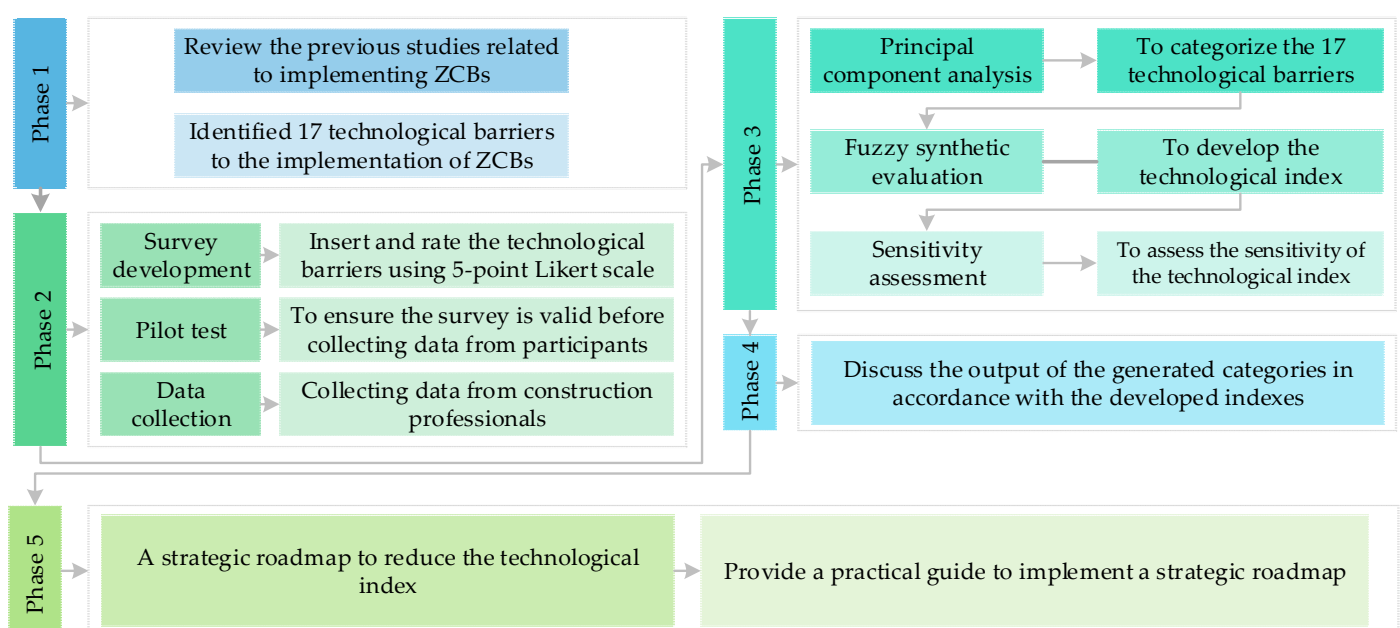


Figure 1. The workflow of a multiphase methodology.

3.1. Survey Development

The 17 technological barriers to the construction of ZCBs were extracted from a comprehensive literature review of previous similar studies and were used to develop the questionnaire. The questionnaire comprised two sections. The first section withdrew closed-ended demographic information related to gender, age, professional background, academic qualification, work experience, and the type of organization associated with it. The second section requested respondents to indicate their agreement with the identified technological barriers to the construction of ZCBs, using the Likert scale: 1 strongly disagree, 2 disagree, 3 fairly agree, 4 agree, and 5 strongly agree. The use of the Likert scale is supported by Joshi et al. [63], as it can reduce the ambiguity of results.

3.2. Pilot Test

A pilot test was undertaken to ensure the validity of the questionnaire survey [64]. Purposively selected construction professionals (10) with at least 5 years' experience and university lecturers (10) were requested to participate in the pilot test [65]. The feedback of selected participants on the minor aspects of content quality and wording was incorporated into the actual survey instrument. After ensuring the clarity and readability of the survey, it was distributed to the target population to receive their thoughts regarding the technological barriers to the construction of ZCBs.

3.3. Data Collection

A broad spectrum of construction professionals was targeted to participate in the survey. These included architects, mechanical engineers, structural engineers, builders, quantity surveyors, electrical engineers, urban and regional planners, and land surveyors. These profiles were selected based on their likelihood of knowledge and experience related to ZCBs. Due to the uniqueness of the area of study, non-random sampling was instituted. Specifically, purposive and snowball sampling were undertaken to identify knowledgeable and experienced construction professionals in ZCBs. Such sampling techniques can generate representative samples as intimately as [65].

An online survey was administered to purposively identified construction professionals in Nigeria, and they were requested to share the survey instrument with other potential participants with the requisite academic and professional experience [66]. To enhance the response rate, follow-up emails were sent out at two-week intervals within a three-month period. A total of three hundred and twenty-five (325) questionnaires were distributed to survey participants. After a thorough screening of the returned instruments, only 272 were deemed valid for analysis, representing a response rate of 83.69%. Lakens [67] stated that a benchmark of at least 100 valid samples is needed to conduct the analytical techniques and provide a credible conclusion. The resulting 272 valid responses are consistent with acceptable sample thresholds for several earlier survey-based studies that developed an index using FSE in the field of construction, which have a smaller number of responses compared to the present study. For example, Oluleye et al. [49] developed an index with 140 responses; a sample size of 55 responses was used by [48] in order to develop a performance index, and recently, Seidu et al. [47] recorded a dataset of 62 valid responses to develop an index. Therefore, a sample of 272 responses was considered adequate for drawing meaningful and indicative conclusions for the technological index for implementing ZCBs.

In summary, the data collection process for this study followed these steps: (1) Preparation phase: The research instruments were developed based on a review of relevant literature and pre-tested for clarity and reliability. (2) Ethical consideration: Ethical considerations were duly observed throughout the study. Participation was voluntary, and respondents were briefed on the study's objectives, their rights to withdraw at any stage

without penalty, and the assurance of anonymity and confidentiality. Informed consent was acquired from all survey participants before data collection. (3) Administration phase: Questionnaires were distributed to participants through an online platform. (4) Data retrieval verification: The process of data collection for this study took place over a three-month period.

3.4. Data Analysis

The Statistical Package of Social Sciences version 27 and Microsoft Excel spreadsheet were used for data analysis. Principal component analysis (PCA) serves as a statistical technique for simplifying and condensing large datasets by identifying the subgroups within the intercorrelations of technological barriers [68,69]. The PCA was conducted to streamline the numerous technological barriers associated with constructing ZCBs and ascertain construct validity. In general, PCA is adequate for a dataset with at least 100 responses [70]. Several earlier studies related to construction management used a sample size lower than the current study. For example, Omer et al. [71,72] used a sample size of 133 and 120, respectively; Moyo et al. [73,74] collected a total of 151 and 121 usable responses, respectively, and a total of 122 responses were collected by [75,76], respectively. Hence, the 272 valid responses were adequate for this analysis.

PCA with the varimax rotation technique was performed to determine suitable components for the current study. Prior to conducting PCA, the Kaiser–Meyer–Olkin (KMO) test and Bartlett’s test of sphericity were applied to assess the model’s suitability [77,78]. The KMO value, which ranges from 0 to 1, indicates the adequacy of the factor solution, with higher values suggesting better suitability. Furthermore, Bartlett’s test of sphericity determines whether the variables exhibit significant correlations, thereby justifying the use of PCA [79].

Next, the FSE technique was conducted to develop the index of each subdivision structure of technological barriers. As the construction of ZCBs overlaps between the dimensions of environment and social domain, it is complex to articulate and measure [80]. Unclear information and subjective human interpretation in data collection can introduce uncertainty. To address this, fuzzy logic provides a suitable framework for capturing human reasoning and managing ambiguity [81,82]. As a subset of fuzzy logic, the FSE method enhances the handling of uncertainties and aids in interpreting the linguistic characteristics of random phenomena. Prior studies have spanned into different research areas, including green infrastructure projects [47,83], climate for innovation in construction organizations [51], green building projects [84], and sustainable construction [53,85,86].

In this context, the FSE enables the evaluation of complex assessments with multiple levels and attributes. The fuzzy membership function provides a structured way to model intricate decision-making processes. Moreover, expert opinions and subjective perceptions can be effectively integrated. Utilizing the FSE technique helps minimize imprecision and uncertainty associated with practitioners’ experiential knowledge [87]. As a result, the FSE method is considered an appropriate choice for this study to develop the technological index for the construction of ZCBs. The following steps illustrate the procedure of the FSE technique:

Define the basic set of items or subdivisions as $T = (t_1, t_2, t_3, \dots, t_i)$, where: t_i = the number of items or subdivisions of the technological barriers of the construction of ZCBs.

Establish a set of grading alternatives as $A = (a_1, a_2, a_3, \dots, a_j)$. The scale measurement follows a 5-point Likert scale, where a_1 = Very low; a_2 = Low, a_3 = Moderate, a_4 = High, and a_5 = Very high.

Determine the weightings for each item or subdivision using the following formulation:

$$W_i = \frac{M_i}{\sum_{i=1}^n M_i} \quad (1)$$

where M_i = the mean score value of the corresponding item or subdivision, $\sum M_i$ = the sum of the mean ratings, and W_i = weighting.

Compute the final evaluation matrix result for each item and subdivision using the following equation:

$$F = W_i \bullet E_i \quad (2)$$

where F = the final evaluation matrix; W_i = the weighting; E_i = the fuzzy evaluation matrix; and ' $\bullet$ ' refers to the fuzzy composite operator.

Develop the technological index for implementing ZCBs using the following equation:

$$I = \sum_{i=1}^5 D \times A \quad (3)$$

where I = the technological index; D = the final evaluation matrix; and $A = \frac{1}{5}$, representing the linguistic item.

4. Results

4.1. Demographic Information

Table 2 presents the demographic information of a total of 272 respondents. Builders (26.5%) were the most represented profession, and this is significant since they experience the barriers as they undertake their projects. In addition, 84.3% of the respondents with ≥ 5 years of experience demonstrate competence and exposure to the barriers under study. The types of organizations are adequately represented, potentially contributing to holistic perspectives.

Table 2. Demographic information of respondents.

Characteristics	Categories	Frequency	Percentage (%)
Professional background	Architect	45	16.5
	Structural Engineer	36	13.2
	Mechanical Engineer	13	4.8
	Electrical Engineer	18	6.6
	Builder	72	26.5
	Quantity Surveyor	54	21.3
	Surveyor	14	5.1
Years of experience	Less than 5 years	43	15.8
	5–10 years	72	26.5
	11–15 years	51	18.8
	16–20 years	28	10.3
	21–25 years	41	15.1
	26–30 years	25	9.2
	31 years or above	12	4.3
Type of organization	Client	28	10.3
	Consulting	111	40.8
	Contracting	133	48.9

4.2. Principal Component Analysis

The output of PCA was considered suitable, as it achieved the following criteria. The KMO with a value > 0.800 and Bartlett's test of sphericity, with $p < 0.05$, was used to establish the validity of extracted components [77,78]. As a result, the extracted subdivisions were considered suitable for analysis as detected by the value of KMO equal to 0.834, leading to adequacy for further analysis. The produced value of Bartlett's test of sphericity of 0.000 suggests that the correlation matrix is statistically significant at $p < 0.05$, signifying that it is not an identity matrix. Table 3 provides a summary of KMO and Bartlett's test of sphericity.

Table 3. Results for KMO and Bartlett's test of sphericity.

Kaiser–Meyer–Olkin measure of sampling adequacy		0.834
Bartlett's test of sphericity	Approx. Chi-Square	1288.913
	Df	136
	Sig.	0.000

Consequently, 5 subdivisions were extracted from the 17 technological barriers through a factor analysis. The values of the communities range between 0.5 and 0.6, which can be considered as an acceptable range with low to moderate values [87]. The factor loadings for all barriers within each component were higher than the minimum of 0.4, yielding an adequate level of importance [67]. The eigenvalue for all components is >1 , which allows for the retention of these components [87]. A total of 60.425% of the variance was explained by all components, which achieved a satisfactory level for the sample adequacy criterion of higher than 50% [88]. According to Hinton et al. [89] and Taber [90], the components with a Cronbach's alpha value of at least 0.6 should be retained for exploratory studies. From the results, all but one of the components had a reliability of >0.600 . Hence, the remaining four components were analyzed further. These components are named and presented in Table 4.

Table 4. Results for principal component analysis.

Code	Subdivisions	Extraction	Factor Loading	Eigenvalues	% of Variance	Cumulative %	Cronbach's Alpha
—	Inadequate technical support	—	—	5.030	29.591	29.591	0.766
B02	Lack of accessible technologies	0.649	0.753	—	—	—	—
B04	Lack of the client's understanding of technologies	0.628	0.735	—	—	—	—
B03	High cost of maintenance on ZCB	0.602	0.733	—	—	—	—
B01	Lack of research in technological applications	0.594	0.572	—	—	—	—
B05	Less technical expertise in new technological advancements	0.488	0.559	—	—	—	—
—	Insufficient knowledge and infrastructure	—	—	1.648	9.693	39.284	0.678

Table 4. Cont.

Code	Subdivisions	Extraction	Factor Loading	Eigenvalues	% of Variance	Cumulative %	Cronbach's Alpha
B07	Lack of renewable technologies	0.674	0.752	—	—	—	—
B06	Poor knowledge on renewable technologies	0.624	0.690	—	—	—	—
B08	Lack of technological infrastructure	0.564	0.530	—	—	—	—
—	Poor resources and immaturity	—	—	1.312	7.715	46.999	0.680
B16	Lack of space to install on-site renewable energy technologies	0.700	0.793	—	—	—	—
B17	Immature technology	0.603	0.676	—	—	—	—
B15	Complexity of ZCB technology	0.598	0.668	—	—	—	—
—	Insufficient readiness for ZCB technologies	—	—	1.183	6.958	53.957	0.586 ^a
B10	Cost of ZCB technology	0.530	0.681	—	—	—	—
B11	Industry's ability to embrace ZCB technologies	0.563	0.658	—	—	—	—
B09	Less technical knowledge in new technological advancements	0.645	0.587	—	—	—	—
—	Inadequate research and practical effort	—	—	1.100	6.468	60.425	0.657
B12	Research outcomes are not translated effectively into technology innovations	0.629	0.730	—	—	—	—
B13	Maintainability and operability practical problems of ZCB	0.603	0.689	—	—	—	—
B14	Incompatibilities with new technologies due to existing building condition	0.579	0.688	—	—	—	—

Note: ^a refers to the eliminated subdivision because the value of Cronbach's alpha is lower than 0.60.

4.3. Fuzzy Synthetic Evaluation

Table 5 outlines the results of procedures (1) to (6), providing details on the weights assigned to technological barriers and the weights and total weights for subdivisions using Equation (1). The table also includes membership functions for technological barriers and subdivisions across various construction project categories. Furthermore, the membership function for the overall subdivisions is also presented. Each membership function is accompanied by its respective level to indicate its classification level. The membership

function for each item and subdivision, as well as for all subdivisions, was computed using Equation (2).

Table 5. The results for membership functions and classification using FSE.

Items and Subdivisions	Mean	Weightings	Membership Functions						Classifications
B2	3.43	0.19	0.07	0.08	0.31	0.41	0.12		Level 3
B4	3.61	0.20	0.04	0.10	0.25	0.42	0.19		Level 3
B3	3.64	0.21	0.05	0.09	0.24	0.40	0.21		Level 3
B5	3.73	0.21	0.04	0.06	0.26	0.40	0.23		Level 3
B1	3.35	0.19	0.11	0.12	0.26	0.35	0.16		Level 3
Inadequate technical support	17.77	0.36	0.06	0.09	0.26	0.40	0.19		Level 2
B7	3.39	0.32	0.07	0.12	0.29	0.38	0.14		Level 3
B6	3.63	0.34	0.03	0.12	0.24	0.40	0.21		Level 3
B8	3.53	0.33	0.04	0.13	0.24	0.42	0.16		Level 3
Insufficient knowledge and infrastructure	10.55	0.22	0.05	0.12	0.25	0.40	0.17		Level 2
B16	3.11	0.31	0.18	0.13	0.24	0.30	0.15		Level 3
B17	3.55	0.35	0.07	0.09	0.27	0.36	0.21		Level 3
B15	3.40	0.34	0.07	0.13	0.28	0.36	0.16		Level 3
Poor resources and immaturity	10.06	0.21	0.10	0.12	0.27	0.34	0.17		Level 2
B14	3.45	0.32	0.04	0.15	0.29	0.35	0.16		Level 3
B13	3.53	0.33	0.03	0.11	0.31	0.39	0.15		Level 3
B12	3.67	0.34	0.03	0.10	0.25	0.41	0.20		Level 3
Inadequate research and practical effort	10.64	0.22	0.03	0.12	0.28	0.39	0.17		Level 2
All subdivisions	49.02	—	0.06	0.11	0.27	0.38	0.18		Level 1

Figure 2 displays the technological index for implementing ZCBs, derived using the FSE technique. Equation (3) was used to compute the sub-technological indexes and the final technological index. The results of the sub-technological indexes indicate slight differences between inadequate technical support, inadequate research and practical effort, and insufficient knowledge and infrastructure, with indexes of 3.55, 3.54, and 3.51, respectively. Meanwhile, the subdivision of poor resources and immaturity has the lowest sub-technological index, which is 3.35. On the other hand, the final technological index for implementing ZCBs is 3.50. This finding indicates that technological barriers pose a high obstacle to implementing ZCBs. This suggests that the implementation of ZCBs is relatively delayed and continues to face challenges related to technological aspects.

4.4. Sensitivity Assessment of the Technological Index

To assess the sensitivity of the technological index, a sensitivity analysis was conducted to evaluate how minor adjustments in the assigned weights affect the final technological index. This involved making minimal variations to the weights (coefficients) of the subdivisions and analyzing their impact on the technological index. In the present study, the sensitivity analysis explores potential coefficient changes within a range of 5% to 10% above and below the baseline values. The variations in the technological index results can be easily observed in the sensitivity analysis provided in Table 6. The findings indicate that weight adjustments have only a minimal influence on the final technological index. This can

suggest that the final developed technological index is robust against weight fluctuations and remains reliable. Table 6 provides the results for the sensitivity assessment.

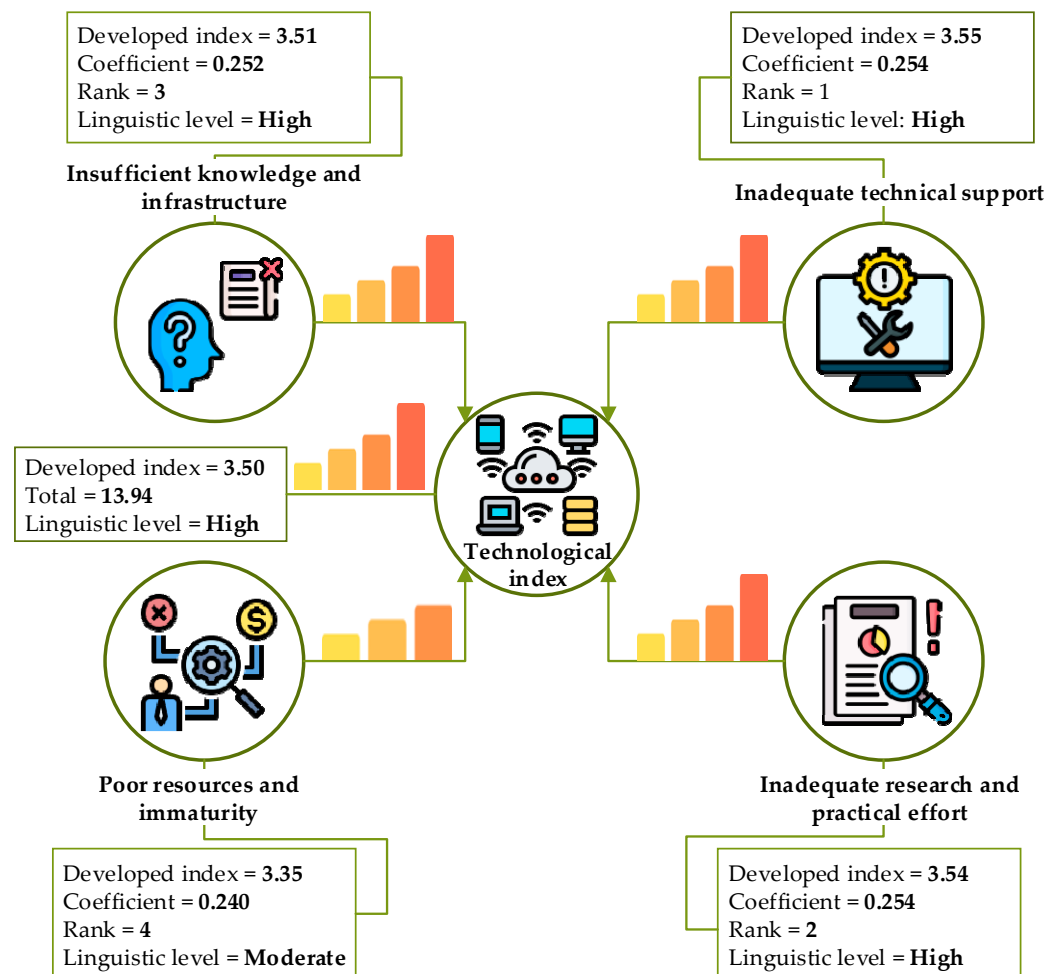


Figure 2. Developed a technological index for the implementation of ZCBs.

Table 6. Results for the sensitivity assessment.

Subdivisions	Coefficient Variance					Ranking Changes				
	−10%	−5%	0%	+5%	+10%	−10%	−5%	0%	+5%	+10%
Inadequate technical support	0.229	0.241	0.254	0.267	0.279	1	1	1	1	1
Insufficient knowledge and infrastructure	0.227	0.239	0.252	0.265	0.277	3	3	3	3	3
Poor resources and immaturity	0.216	0.228	0.240	0.252	0.264	4	4	4	4	4
Inadequate research and practical effort	0.229	0.241	0.254	0.267	0.279	2	2	2	2	2

5. Discussion

This section discusses the subdivisions of the technological barriers toward implementing ZCBs. In this regard, the subdivisions are arranged in developed index order. On the other hand, an innovative strategic roadmap to reduce the technological index is also proposed to advance the output and make the discussion section more informative.

5.1. Inadequate Technical Support (Developed Index: 3.55)

Inadequate technical support acquired the highest developed index and was introduced at a high linguistic level. It comprises five technological barriers, which are the highest compared to the remaining subdivisions. The concept of inadequate technical support denotes the insufficient availability of expertise, assistance, and maintenance services necessary for the effective deployment and operation of advanced technologies critical to ZCBs. In the absence of robust technical support, building operators will encounter difficulties in sustaining energy-efficient systems such as renewable energy installations, smart grids, and building management platforms. This absence will diminish the overall performance and sustainability of ZCBs in the future. For example, the restricted post-installation support for photovoltaic systems in developing countries frequently results in system inefficiencies or failures [91]. Darko et al. [92] indicated that a scarcity of professionals adequately trained in green building technologies can cause inefficient technical support toward implementing ZCBs. Also, Siva et al. [93] noted that insufficient governmental investment in training and certification programs specific to zero-carbon technologies is also a critical barrier in front of having the technical support needed for ZCBs. Another logical contributor to inadequate technical support is the absence of standardized operational and maintenance protocols from related parties (e.g., policymakers) that create the path toward adopting the technology for ZCBs [94]. Addressing inadequate technical support is imperative for ensuring the long-term functionality and success of ZCBs.

5.2. Inadequate Research and Practical Effort (Developed Index: 3.54)

The acquired developed index of inadequate research and practical effort is the second in rank order. A linguistic level that tends to be high due to a list of three technological barriers. The inadequate research and practical effort reflect a lack of empirical studies and pilot projects concerning the emerging technologies for the deployment and implementation of ZCBs. An illustrative case of this subdivision is the limited number of large-scale pilot projects demonstrating the practical integration of renewable energy systems within zero-carbon residential developments, particularly in regions characterized by unstable electricity grids. This lack of demonstrative initiatives can contribute to diminishing stakeholder confidence [95]. There are several factors that are directly responsible for inadequate research and practical effort. For instance, Siva et al. [93] identified the low prioritization of applied research within public and private research and development funding as a major barrier. Similarly, Olawumi and Chan [96] emphasized the limited collaboration between academic institutions and industry partners in advancing practical pilot projects. Furthermore, Myint et al. [97] noted that the short-term focus prevalent among construction stakeholders often discourages investment in experimental initiatives. Thus, advancing research initiatives and strengthening practical implementations are vital for creating effective pathways to scale ZCB solutions.

5.3. Insufficient Knowledge and Infrastructure (Developed Index: 3.51)

The insufficient knowledge and infrastructure resulted in a developed index with a third level in terms of rank order. The linguistic level of this subdivision is inclined to be high but has a minimal difference compared to the first and second rank orders. Three technological barriers belong to this subdivision. The technological barriers related to this subdivision highlight the gaps in understanding, technical skills, and physical facilities required to successfully implement ZCB practices. In general, the shift toward sustainable construction is hindered by incomplete knowledge of design approaches for ZCBs and also insufficient infrastructure for the renewable carbon initiative. For instance, suburban areas often struggle to incorporate district energy systems because of gaps in expertise

and inadequate planning [98]. Too et al. [99] highlighted that the insufficient embedding of zero-carbon principles within academic curricula can lead to a gap in trained professionals. Inadequate practical frameworks that fail to align infrastructure advancements with the needs of zero-carbon initiatives can also contribute to curbing the technologies for ZCBs [100]. From another perspective, Weerasinghe et al. [101] indicated that the misconceptions surrounding zero-carbon technologies, such as being expensive or impractical, exist. These misconceptions can widely exacerbate the implementation barriers for ZCBs. Thus, improving education and policy integration in conjunction with public engagement about zero-carbon buildings is essential for overcoming knowledge and infrastructure barriers.

5.4. Poor Resources and Immaturity (Developed Index: 3.35)

The lowest rank across the developed indexes in terms of poor resources and immaturity, with the linguistic level inclined to be moderate. This subdivision comprises three technological barriers hindering the implementation of ZCBs. The subdivision of poor resources and immaturity refers to the insufficient financial, technological, and human resources as well as the early developmental stage of zero-carbon technologies and practices. The subdivision of poor resources and immaturity refers to the insufficient financial, technological, and human resources as well as the early developmental stage of zero-carbon technologies and practices. This stage of development causes reluctance among developers and investors, thereby slowing the extended adoption of such solutions. For example, high initial costs and limited economies of scale for carbon-neutral construction materials have delayed their use in large construction projects [102]. The limited access to green financing options by practitioners can cause a delay in adopting the technologies for implementing ZCBs [103]. Pan and Pan [104] highlighted that technological uncertainty regarding the long-term performance of innovative materials is also a crucial factor in adopting the technology for ZCBs. Also, a lack of skilled labor to deploy applies a common barrier to adopting immature green technologies, such as solar building retrofitting [105]. Therefore, it is important to give attention to the maturity and resourcing of green technologies, which is a vital strategy for mainstreaming ZCB practices.

6. An Innovative Strategic Roadmap to Reduce the Technological Index

The primary objective for developing this strategic roadmap was to offer an innovative representation of information based on the literature [55]. Therefore, an innovative strategic roadmap for reducing the technological index was created to meet the increasing demand for a faster shift toward ZCBs [97,105–107]. The strategic roadmap is based on the insights of selected previous studies. In this regard, prior studies in different areas of construction management have commonly adopted this approach to develop literature-based strategic roadmaps. For example, Raza and Zhong [108] developed a sustainable strategic roadmap for 3D printing in the construction industry. Olugboyega et al. [109] developed a conceptual model based on previous studies to evaluate the success of building information modeling in construction projects. Similarly, Wang et al. [110] used a list of recent studies to develop a framework for adopting building information modeling to facilitate disputes in the construction industry. Horry et al. [111] created a roadmap to aid the delivery of sustainable development goals in the architectural, engineering, and construction sectors. Recently, Karacigan et al. [112] explored strategies from previous studies to design a strategic roadmap to accelerate the adoption of blockchain technology in the construction sector. Therefore, the previous studies can be considered an innovative solution for developing strategic roadmaps. Table 7 introduces the strategic roadmap.

Although technology continues to advance, there is still a significant gap between innovation and its broad, effective application [129]. This strategic roadmap aims to systematically address the subdivisions of technological barriers that curb the implementation of ZCBs. The roadmap provides a clear framework by mapping actionable strategies across four subdivisions and prioritizing them based on their developed index and negative impact on hindering the implementation of ZCBs. This roadmap is more than an innovative plan; it is a novel framework that creates the track to substantial reductions in CO₂ emissions throughout the building life cycle. At its foundation, this roadmap calls for a major shift in how ZCBs are implemented. It highlights the need to adopt innovative technologies, which can span from the initial planning phases to the stages of operation, management, and maintenance. For instance, it incorporates established actionable strategies like digital twin technologies, performance-based contracts, and updated regulatory measures to ensure that technological complexity becomes an asset rather than a barrier.

Table 7. An innovative strategic roadmap to reduce the technological index.

Subdivisions	Priority	Roadmap Strategies	Actionable Example	Source
Inadequate technical support	High	Provide free digital twin and BIM platforms to lower entry barriers for ZCB design and operation	An open-access cloud Digital Twin and BIM-XR platform	1
		Host client-focused workshops and online courses to enhance understanding of ZCB technologies	Transforming built-environment education and training for nearly ZCBs	2
		Offer incentives to reduce maintenance costs and establish performance-based service contracts	Performance-based contract	3
		Allocate targeted research and development grants for emerging ZCB technologies	Re-COGNITION project	4
Insufficient knowledge and infrastructure	High	Require updated building regulations to incorporate renewable energy systems	Energy Performance of Buildings Directive 2024	5
		Provide tax incentives and low-interest financing for on-site renewable installations	The United States investment tax credit for solar energy	6
		Allocate resources to develop smart-grid capabilities and digital platforms for energy management	SmartNet project	7
		Support joint public–private pilot programs that showcase renewable solutions across different climate zones	Net-Zero Energy Residential Test Facility	8
Poor resources and immaturity	Moderate	Promote virtual power purchase agreements and off-site renewable sourcing to bypass on-site space constraints	Virtual power purchase agreements	9
		Sponsor pilot and demonstration projects of emerging ZCB technologies across diverse building types	An Italian pilot project for zero-energy buildings	10
		Develop standardized, modular renewable energy kits for easy plug-and-play deployment.	Solar photovoltaic technology	11
		Simplify complexity with vetted component libraries and integrated design platforms	BIM object libraries	12
Inadequate research and practical effort	High	Launch Living Labs and technology-transfer offices to speed up turning research into real-world solutions	KTH Live-In Lab	13
		Create clear retrofit guidelines and modular upgrade kits tailored to existing building conditions	EnerPHit Standard	14
		Use BIM pre-validation and digital-twin analysis to find and fix operational and maintenance issues	BIM and Digital Twin Integration	15
		Build alliances among academia, industry, and policymakers to exchange continuous practical feedback	RINNO Retrofitting Manager platform	16

Sources: 1 = [113]; 2 = [114]; 3 = [115]; 4 = [116]; 5 = [117]; 6 = [118]; 7 = [119]; 8 = [120]; 9 = [121]; 10 = [122]; 11 = [123]; 12 = [124]; 13 = [125]; 14 = [126]; 15 = [127]; 16 = [128].

The proposed innovative strategic roadmap can be applied in countries that struggle to integrate technology to foster the implementation of ZCB in difficult weather conditions, for example, countries that have a hot summer and a cold winter, such as China [56]. Therefore, Figure 3 depicts the workflow for applying an innovative strategic roadmap to reduce the

technological index and advance the implementation of ZCBs in the construction sector. The methodology of the innovative strategic roadmap comprises four sequential stages, each designed to ensure a structured and methodologically rigorous application within building projects. Stage 1 involves identifying the index of a subdivision and determining its priority (i.e., high or moderate), thereby ensuring that the most critical index is addressed first. Stage 2 entails selecting a suitable strategy from a range of literature-based options, with the opportunity to request further clarification prior to advancement. Stage 3 provides a practical illustration of the chosen strategy to strengthen understanding and applicability. Stage 4 then commences the implementation of the strategy, following the actionable framework established in Stage 3. Figure 3 provides the workflow for an innovative strategic roadmap with an example for the application, as illustrated in Figure 3a,b.

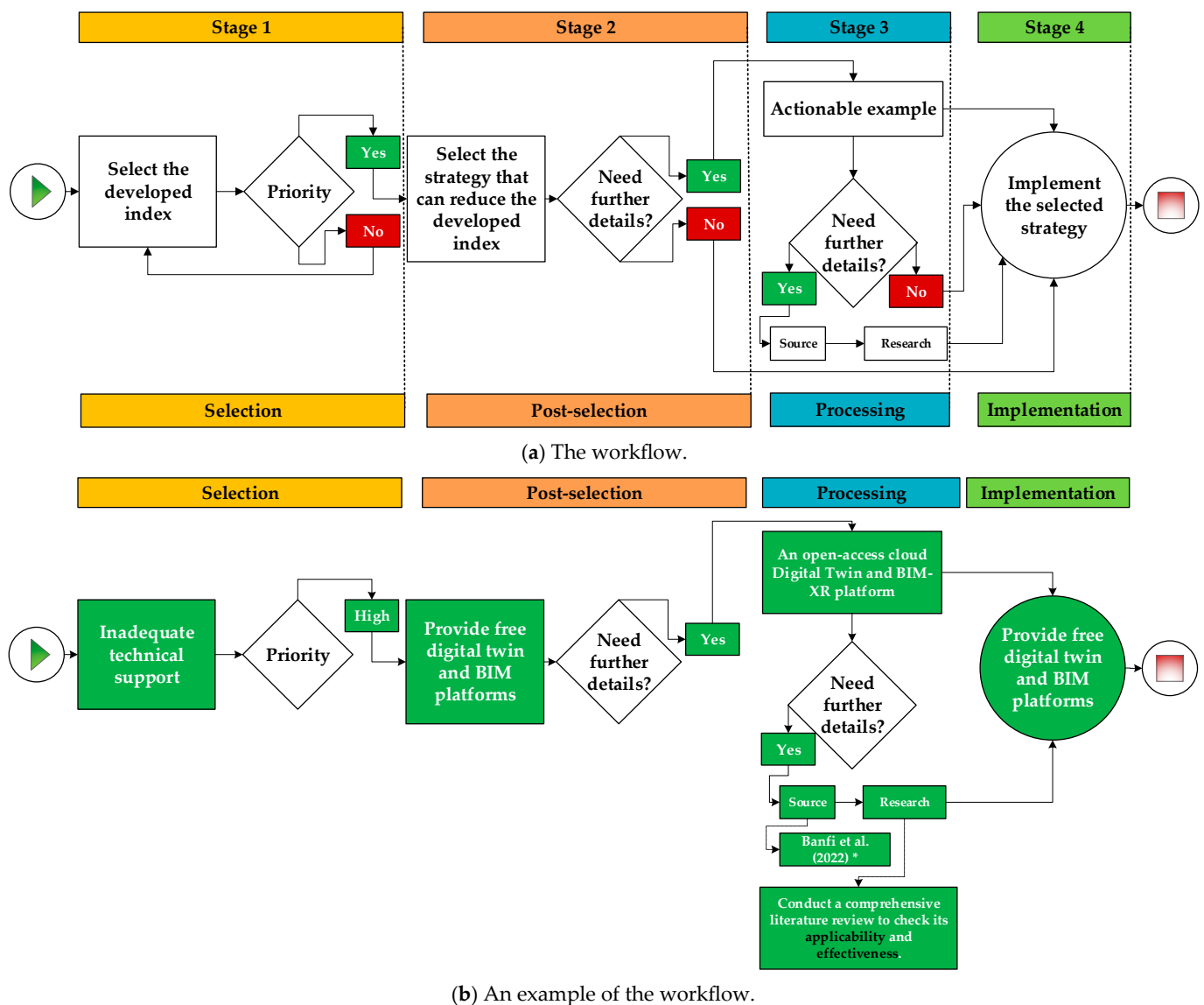


Figure 3. The workflow of applying the innovative strategic roadmap. Note: * = [113].

7. Implications

7.1. Theoretical Implications

The developed technological index offers a unique visualization for having an in-depth understanding of the current status of the barriers related to the technology that curbs the implementation of ZCBs. It offers the current body of knowledge an extension to give

further attention to integrating technology into the building construction sector. For example, researchers can use the developed technological index to accelerate the research effort toward adopting the technology in ZCBs. For instance, researchers can conduct a study by comparing the developed technological index with other countries via a cross-regional study. At the same time, an innovative strategic roadmap can advise researchers with informed directions on how to use the strategies with actionable examples. It will also enable the researcher to conduct further investigation into the strategies provided. Thus, this can expand the current knowledge to include the full implementation of ZCBs worldwide.

7.2. Practical Implications

The present study, through the final technological index, seeks to inform practitioners to foster their practical efforts toward using innovative technology to advance the implementation of ZCBs. The practitioners can use the list of identified technological barriers to avoid, in advance, the issues of integrating the related technologies for implementing ZCBs in future building projects. The developed technological index can also inform practitioners to create practical regulations for on-site and off-site building construction activities in order to support reducing the technological barriers to advance the implementation of ZCBs. An innovative strategic roadmap will help practitioners to overcome the current technological barriers. For example, providing unlimited access to Digital Twin and BIM platforms can reduce the entry barriers for ZCB during the design stage. This will help to put the innovative technologies for implementing ZCBs on the optimal path in the building construction industry.

7.3. Policy Implications

Beyond the practical implications, the current study has significant policy relevance to accelerating the adoption of technology in the building construction sector. The identified list of technological barriers provides a solid source of the current scenario that hinders the technology in the building construction sector. Therefore, this list works to notify policymakers on the recent technological barriers in order to foster the implementation of ZCBs by generating new national policies and regulations that align with the present and future scenarios. The developed index can also inform policymakers to understand how the present scenario of technological barriers is critical in order to implement the new policies and regulations. Meanwhile, the innovative strategic roadmap alongside its application procedures will support guiding policymakers to adopt technology in building construction in order to address the implementation of ZCBs.

7.4. Managerial Implications

The ranking of the developed technological index in each subdivision will prompt project managers to prioritize decisions based on what aligns most closely with their strategic plans toward extending the use of technologies to implement ZCBs. For example, adopting BIM addresses the barriers associated with inadequate technical support during the design stage. Therefore, adopting BIM will be a facilitator in having adequate technical support for the implementation of ZCBs. On the other hand, construction professionals can adopt an innovative strategic roadmap to prioritize the needed strategies to accelerate their decision-making toward full implementation of ZCBs. For instance, prioritize the strategies that belong to adequate technical support, such as offering workshops and online courses for construction workers to enhance their understanding of ZCB technologies.

8. Conclusions

The present study has addressed the objectives that strove to have the successful implementation of ZCBs. To end this, we (1) developed a technological index for imple-

menting ZCBs and (2) proposed an innovative strategic roadmap with actionable examples to advance the implementation. The review of previous studies enabled the identification of 17 technological barriers impeding the implementation of ZCBs. This list was then incorporated into an online survey administered to construction professionals. A total of 272 valid responses were collected and subjected to several analysis techniques. The study revealed that the developed technological index exerts a considerably high influence on constraining the adoption of the technology for the implementation of ZCBs. In response, the study proposed an innovative strategic roadmap designed to reduce the index and promote the adoption of technology to accelerate the implementation of ZCBs. In summary, the present study contributed to the current body of knowledge by offering a technological index and an innovative strategic roadmap that can be harnessed to advance the adoption of technology to foster the implementation of ZCBs.

Although the study was conducted by following rigorous methodology, a minor number of limitations were faced that should be explored in future studies. First, the acquired survey data is based on a single country (i.e., Nigeria), which may restrict the generalizability of the findings. However, future studies will be encouraged to repeat the research work in other regions and conduct a comparative analysis. This procedure will extend the current body of knowledge regarding the implementation of ZCBs across different regions. Second, the development of the innovative strategic roadmap relied on the authors' judgment, which introduces the possibility of bias. However, this approach is consistent with recent studies related to construction management on strategic roadmap development (e.g., [111,112]). Future research is therefore encouraged to validate the proposed roadmap in practice with experienced construction professionals to strengthen its reliability.

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Abbreviations

The following abbreviations are used in this manuscript:

ZCBs	Zero-Carbon Buildings
ZCB	Zero-Carbon Building
OECD	Organization for Economic Co-operation and Development
BIM	Building Information Modeling
LCA	Life-Cycle Assessment
CO ₂	Carbon Dioxide
FSE	Fuzzy Synthetic Evaluation
UNEP	United Nations Environment Programme
UK	United Kingdom

MENA	Middle East and North Africa
PCA	Principal Component Analysis
KMO	Kaiser–Meyer–Olkin

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