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A novel decision support framework for building refurbishment towards zero carbon emissions

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ABSTRACT

The refurbishment of existing buildings is vital to maximise carbon emissions reduction and alleviate the impacts of climate change. While various decision support frameworks for building refurbishment exist. There is a notable gap in the availability of comprehensive frameworks that combine diverse methods, tools, and systems to support decision-making aimed at reducing whole-of-life carbon emissions. This paper brings together the development and validation processes of a novel early-stage decision support framework for building refurbishment towards zero carbon emissions in New Zealand (RefurbZC). The development of the framework was based on the critical analysis and interpretation of the literature review, preliminary study, and case study of university buildings in New Zealand, which integrate international best practices adopted to the local context and lessons learnt from real-life case studies. The framework was validated and refined using a focus group workshop with New Zealand building experts involved in the refurbishment process. The new RefurbZC provides a better detailed guideline to use in the early stages of the refurbishment process, focusing on maximising whole-of-life carbon reduction. It helps to understand the refurbishment decision-making process, identify areas for integrating carbon-reduction initiatives, determine key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration in carbon-reduction building refurbishment. The presented framework contributes extensively to theoretical and practical knowledge of building refurbishment towards zero carbon emissions and offers a basis and foundation for future work in this research area.

1. Introduction

The impact of climate change has presented critical challenges over the last few decades [1]. Evidence has shown that global carbon emissions have continuously increased, from 22.5 billion tons in 1998 to 34.04 billion tons in 2018 [2]. The Paris agreement in 2016 sought to limit the temperature increase from 1.5 °C to 2 °C above pre-industrial levels by 2050 [3]. In response, countries and organisations worldwide are committing to achieve net-zero carbon emissions by 2050, with significant strategies and policies being

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implemented to meet these targets [4]. Responsible for one-third of global greenhouse gas (GHG) emissions, the contributions of the building and construction industry are critical for carbon emission reduction.

Refurbishing existing buildings offers a favourable opportunity to maximise carbon reduction, playing a key role towards a net-zero carbon future. This appears to be especially true in advanced economies such as the UK, Europe, Hong Kong and Australia where the existing building stock forms most of the built environment [5,6]. Numerous studies have demonstrated that refurbishing existing buildings offers significant carbon reduction benefits when compared to constructing new buildings. Both operational and embodied carbon emissions are favourably impacted, with evidence indicating that refurbishment can lead to a reduction in carbon emissions of approximately 50 % compared to new construction [7,8]. The importance of building refurbishment in reducing carbon emissions has been widely acknowledged. Therefore, the question is not whether to refurbish existing buildings but how to refurbish existing buildings to maximise carbon reduction. This research focuses on the refurbishment of buildings that can achieve the highest level of whole-of-life carbon reduction.

Decision-making is a major area of interest within the field of building refurbishment. Over the years, researchers have paid attention to the design and development of decision support tools, with a large and growing body of research focusing on developing multi-objective optimisation mechanisms to better support decision-making in selecting the best fit-for-purpose refurbishment options and alternatives [9–14]. For example, Dalla Mora et al. [12] provided tools and procedures to support decision making for cost-effective and carbon emissions optimisation, while Serrano-Jiménez et al. [14] developed a multi-criteria decision support method towards selecting feasible and sustainable housing renovation strategies. Even though these mechanisms have been tested through building refurbishment case studies, they are often limited to theoretical contexts that lack clear evidence of performance improvement in practice. Authors (e.g. Lu and Lai [15]; Aste et al. [16]; Too et al. [17]) call for research to move away from stimulation studies to develop detailed frameworks designed in collaboration with key stakeholders' perspectives (e.g. clients, designers, contractors, and the user group, etc.) as reliable references for evaluating the building performance. Whilst various practices, methods, approaches, and tools that support the decision-making process exist, there is a need for systematic approaches where available mechanisms are integrated to support the decision-making process.

Researchers have shown an increased interest in developing comprehensive frameworks that support the decision-making process in building refurbishment. The first serious discussion and analysis of refurbishment decision support framework regarding energy efficiency, management, and sustainability emerged during the 2000s. Mickaityte et al. [18] created the first conceptual sustainable refurbishment model for public buildings based on sustainable development principles, decision-making process considerations, and influencing factors. The proposed model was illustrated using a case study of building pollution mapping in Europe, which provided the pollution impact on human health to inform the selection of refurbishment measures. Although the study offers an insight into the decision-making process, there is a lack of practical demonstration of this matter within the case study.

In the same vein, Kolokotsa et al. [19] proposed a framework for building design and operational improvement by analysing various decision support methods for building energy management and sustainability in Europe. However, this framework fails to address the strategic planning as well as method and tool selection, which provide the necessary information and resource support for refurbishment activities. The significance of this strategy is later illustrated in the study of Ma et al. [20]. The authors developed a systematic approach for sustainable building refurbishment by reviewing current research and development in the field, together with relevant policies and standards in Australia. This approach has offered construction researchers and practitioners an adequate understanding of effectively implementing building refurbishment and promoting energy conversation and sustainability. Despite the advancements made in developing the framework, it remains at a conceptual stage.

Bhuiyan et al. [21] later generated a decision tree for social housing refurbishment from the literature to overcome the weakness of poor business cases in the UK. The model can help building professionals understand the refurbishment process and create business models that support sustainability by lowering energy use and improving thermal comfort. Similarly, Steskens et al. [22] developed a decision-making tool that assists architects and building professionals in designing an energy efficient building retrofit solution. The tool can be used for small refurbishment projects and allows consideration of various aspects of renovation without requiring excessive time. Nonetheless, these approaches focus on improving energy and operational carbon performance in the refurbishment process while the impacts of life cycle carbon emissions have been disregarded.

In contrast, Jensen and Maslesa [23] developed a tool called RENO-EVALUE to facilitate initial goal setting among primary stakeholders in early project phases and to support communication between non-professional users and building professionals. The tool is also applicable for comparing alternative project proposals and monitoring project progress and outcomes. While RENO-EVALUE serves as decision support during the early stages and can be used for evaluation throughout and after building refurbishment, it functions primarily as a valuation framework rather than one intended to support refurbishment implementation.

While many decision support frameworks for building refurbishment emphasise energy efficiency and overall sustainability, there remains a need for frameworks that specifically target whole-of-life carbon reduction. Much of the current framework found in the literature is conceptual or theoretical, with limited evidence of practical implementation within the construction industry, especially regarding the adoption and integration of key decision-support resources and tools throughout the refurbishment process. A significant gap exists in discussions about how stakeholders in building projects collaborate and bring together existing practices, methods, approaches, and tools during the decision-making process. This is particularly critical for successfully delivering refurbishment projects aimed at achieving lowest carbon emissions. More comprehensive integration is necessary to ensure that these frameworks can effectively support project teams in maximising carbon reduction in building refurbishment projects.

To bridge this identified gap, a research project was established to develop a novel decision-support framework for building refurbishment towards zero carbon emissions in New Zealand. The purpose of this paper is to outline the development and validation of the RefurbZC framework. First, key insights from our previously published research papers have laid the groundwork for the development of RefurbZC framework. Second, the developed framework was validated through a focus group workshop with building experts involved in the refurbishment process. After the validation process, the framework was revised and presented in its final form. The paper also discusses the theoretical and practical contribution of the RefurbZC framework as well as the limitations and recommendations for future research.

2. Materials and methods

The research design is structured in two principal phases: first, the development of the framework; and second, its validation. Fig. 1 provides an overview of the research methods utilised in these stages.

2.1. Framework development

The first objective of the paper is to present the development of a novel early-stage decision support framework for building refurbishment towards zero carbon emissions in New Zealand (RefurbZC). The framework was mainly developed and designed based on the authors' intensive qualitative research studies [24–28]. The previously published studies consists of (1) systematic and critical literature reviews to identify a structure and critical components for the refurbishment decision-making process in the international context, (2) a preliminary study using semi-structured interviews with building experts regarding reducing carbon emissions in building refurbishment in New Zealand, and (3) an in-depth investigation into the decision-making process of three real-life building refurbishment case studies considering whole-of-life carbon reduction provided practical implications, relevant whole-of-life carbon aspects and areas of improvement in the refurbishment decision-making process in the New Zealand context.

In addition, another literature review was conducted to determine the most suitable model to categorise RefurbZC's main components and characteristics discovered from the literature review and empirical data. The lean philosophy, which originated from the Toyota Car Manufacturing Company as an innovative approach to increase efficiency, effectiveness, and productivity in construction projects, was adopted to develop the new RefurbZC. This approach was selected due to its popularity in design and engineering practices, particularly in implementing integrated project design and delivery solutions for construction projects [28]. It takes advantage of the technological solutions becoming available (e.g. Building Information Modeling (BIM)) and ensures that improvements in construction projects are considered as a holistic combination of people, processes, tools and technology, recognising the intrinsic requirement for all three of these aspects to be addressed in parallel [29].

The original lean-based sociotechnical systems model has three primary subsystems: 1) process, 2) people, and 3) tools and technology [30]. Collaboration is an important element of lean thinking in construction, facilitating the integration of different actors' competences and efforts in joint problem-solving [28,31]. However, collaboration attributes such as good communication, which are central to establishing a cohesive partnering team [32,33], have not yet been incorporated in lean-based sociotechnical systems model. In this research, the lean-based sociotechnical systems model was extended by including the collaboration and integration subsystem in the development of the RefurbZC framework.

2.2. Framework validation

The second objective of this paper is to validate the developed framework in terms of its appropriateness, potential implementation, and areas of improvement. To achieve this aim, a focus group workshop was conducted with building experts involved in the refurbishment process to explore their expert knowledge and industry experience, critical reflections, and recommendations to ensure that the developed framework is applicable and generalisable to the industry practice. The workshop was chosen as the most appropriate

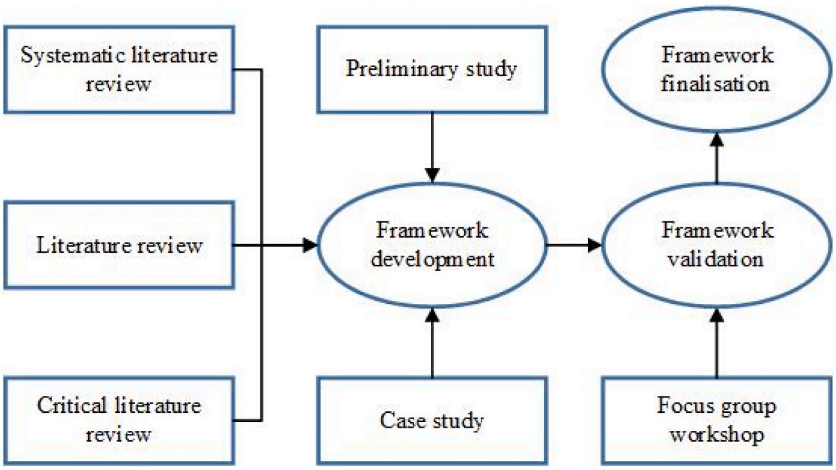

Fig. 1. Research design.

approach for this study due to the opportunity to guide product, program, service development and examine its effectiveness [34–36]. In particular, the focus group is useful to pilot-test the prototypes to fine-tune ideas, concepts or plans before implementing [36]. It is not only identifying the drawbacks of prototypes but, more importantly, understanding why these deficiencies exist, providing richer explanations of how to improve specific components compared to the quantitative validation approach [35,37].

The workshop was prepared, organised, and moderated based on the recommendations provided by Ref. [36]. In the planning stage, a focus group protocol including the purpose, background information, types of information needed, types of participants to be invited, questionnaires, the workshop structure and activities, number of groups to be conducted, plan of action, deliverables, timeline, and budget was developed. The protocol was then peer-reviewed and refined by academic researchers experienced with focus group discussions and familiar with the issue being studied.

The following stage purposively recruited participants based on their professional background, pertinent knowledge and reputation in the New Zealand's construction sector. The participant selection criteria included (1) those who have worked within the New Zealand's construction sector for at least five years, (2) those who have knowledge and expertise in sustainable design, construction, project delivery or related skills, (3) those with experience of carbon-reduction initiatives for building refurbishment projects. A professional networking platform, LinkedIn, was used to identify potential participants responsible for sustainability issues and/or those who experienced and/or led sustainable/green building projects within government agencies and construction firms. Participants received an invitation via email and were then asked to carefully read the project information, sign the written participant consent form following standard ethics protocols and confirm their attendance at the workshop. A panel of 11 experts representing various building stakeholders involved in the building refurbishment projects, including building clients/developers, projects managers, engineers, architects, sustainability and carbon consultants, cost advisors, contractors, and facilities managers, agreed to take part in the focus group discussions. The experts have been working for government agencies and construction/property companies of various sizes in New Zealand, specialising in sustainable construction and carbon reduction. One week before the workshop, an information sheet was sent to all participants setting out pre-workshop and workshop agendas, research background, and an introduction to the developed framework. Participants were asked to read the information carefully, go through each step of the framework and think about the questions discussed during the workshop. In the implementation stage, the workshop was held virtually via Microsoft Teams on September 22nd, 2022. The online workshop method was chosen because it greatly expands the pool of potential participants and adds considerable flexibility to the process of scheduling the time and date [38]. Busy professionals and those located across the country, who might otherwise be unavailable for a face-to-face meeting, can often be reached through information technologies. In addition, there were also potential researcher benefits such as cost and time-savings due to the automatic and accurate capture of the discussion data [38,39]. Not to mention COVID-19 impacts and restrictions, the use of virtual groups created a healthy and safe environment where participants can contribute at their leisure and individual location [40]. Table 1 shows the participants demographics.

The workshop started with the moderator providing a brief presentation about the framework and its development. Next, participants were asked to introduce their interests and experience in the topic. Moving into the main parts of the workshop, two group discussions took place in the breakout rooms. The first discussion was for critically analysing, providing feedback and suggestions for improvement of the framework (e.g. what should be improved, changed, added, re-worded or clarified in the framework). The second discussion focused on the potential implementation of the framework. Participants were randomly allocated into three small focus groups for each debate, with each group having a unique colour code. An electronic Microsoft form indicating the instruction and questions was shared with each group for recording the answers. After that, all participants returned to the common meeting room to share the group discussion results. The moderator then stimulated discussion between the participants by encouraging them to express their critical views and exchange opinions. The workshop was wrapped up with an online survey and a meeting Poll where participants reflected on their viewpoints and individually provided feedback on the framework.

The virtual workshop was video-recorded with permission from participants. Data were also recorded from electronic forms, surveys, hand-written notes, and memory. Transcriptions and notes were logged and coded in line with the developed framework for thematic analysis to yield qualitative results -[41,42]. A qualitative data analysis software – NVivo – was adopted to support a five-stage process of transcribing and preparing data, data organisation, data familiarisation, themes creation and assigning of codes, and data sorting to identify main themes in each category from the data obtained [43,44].

Table 1
Focus-group participants' profiles.

Expert #	Position	Type of organisation
1	Lead Climate Mitigation Advisor	Local Government
2	Facilities Manager	State sector
3	Strategic Project Planner	State sector
4	Project Director	Project Management
5	Project Manager	Contractor
6	Sustainability Engineer	Engineering Consulting
7	Sustainability Consultant	Environmental Consulting
8	Carbon Navigator	Engineering Consulting
9	Architect – Carbon Analyst	Architecture and Design
10	Architect – Sustainability	Architecture and Design
11	Architect	Architecture and Design

3. Findings

This section reports the findings from the development and validation of the RefurbZC framework based on the data reported in the previously published studies [24–27,45] and empirical data from the focus group workshop. Incorporating the findings from authors' previous work on literature review, preliminary study and case study as well as the extended lean-based sociotechnical systems model, the initial form of the framework was designed, which was then tested during the focus group workshop. The detailed description of

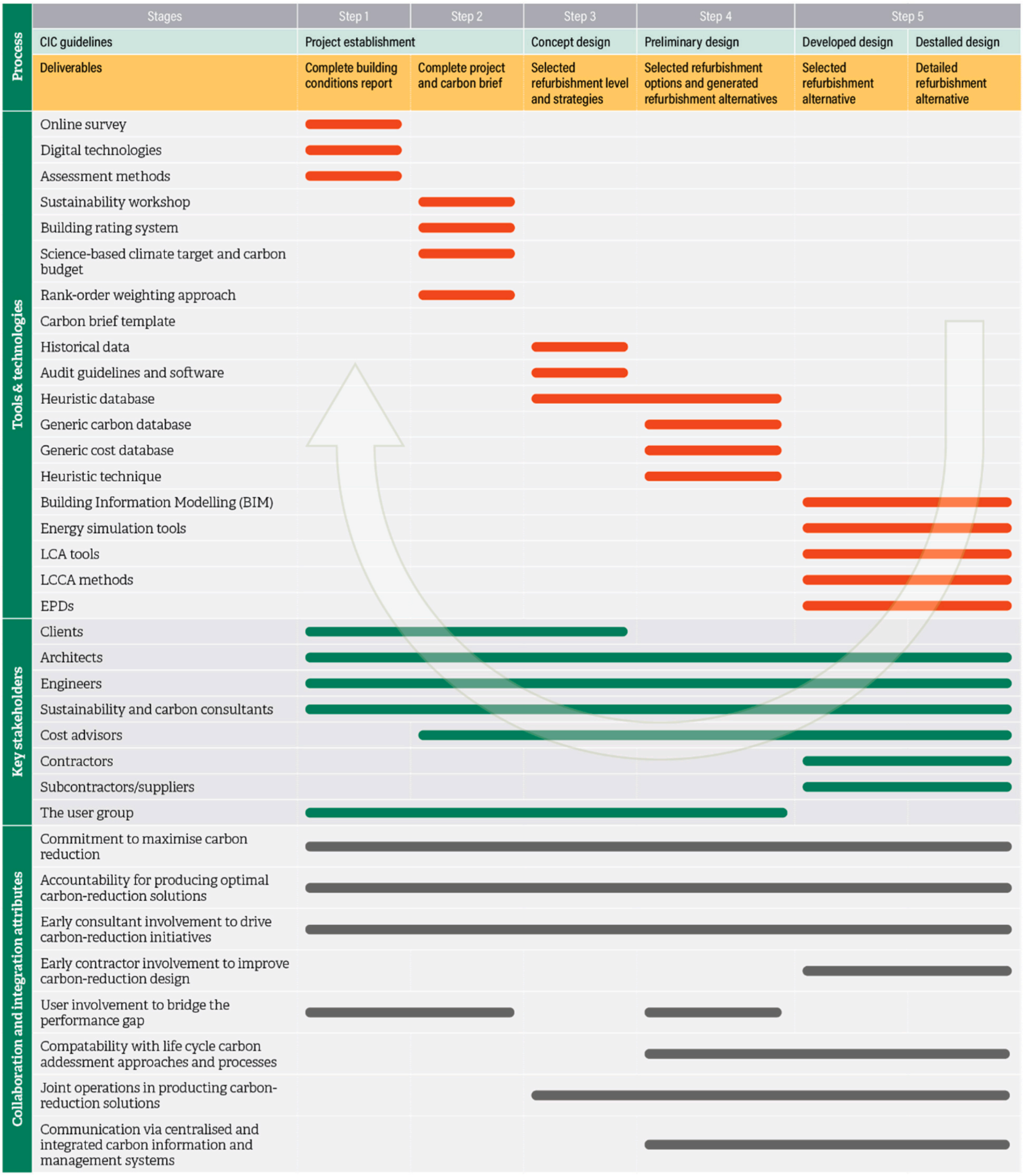

Fig. 2. The high level of five-step decision support framework.

improvement suggestions and actions taken to improve the RefurbZC framework that catered for the experts' validation input and evaluation can be found in the supplementary material (Appendix A). The following sections describe (1) the RefurbZC framework in its final form together with the discussion around the appropriateness of the specific elements of the RefurbZC, and (2) the RefurbZC framework potential application and implementation in practice.

3.1. RefurbZC framework

Overall, the high-level framework of the RefurbZC includes four components: people, process, tools and technology, collaboration and integration attributes, as demonstrated in Fig. 2. The arrow presents the circular link between steps, demonstrating the continuous evaluation, reflection, and improvement throughout the process. The refurbishment decision-making process comprises five steps: (1) Building Condition Assessment; (2) Goal Setting; (3) Refurbishment Strategies; (4) Generation of Refurbishment Alternatives; (5) Performance Estimation and Evaluation. These steps align with design phases in NZCIC guidelines – New Zealand Building and Construction Industry Council to indicate a formal relationship between the steps of the framework and the actual project timeline. The lower level of the framework also includes four components: people, process, tools and technology, collaboration and integration

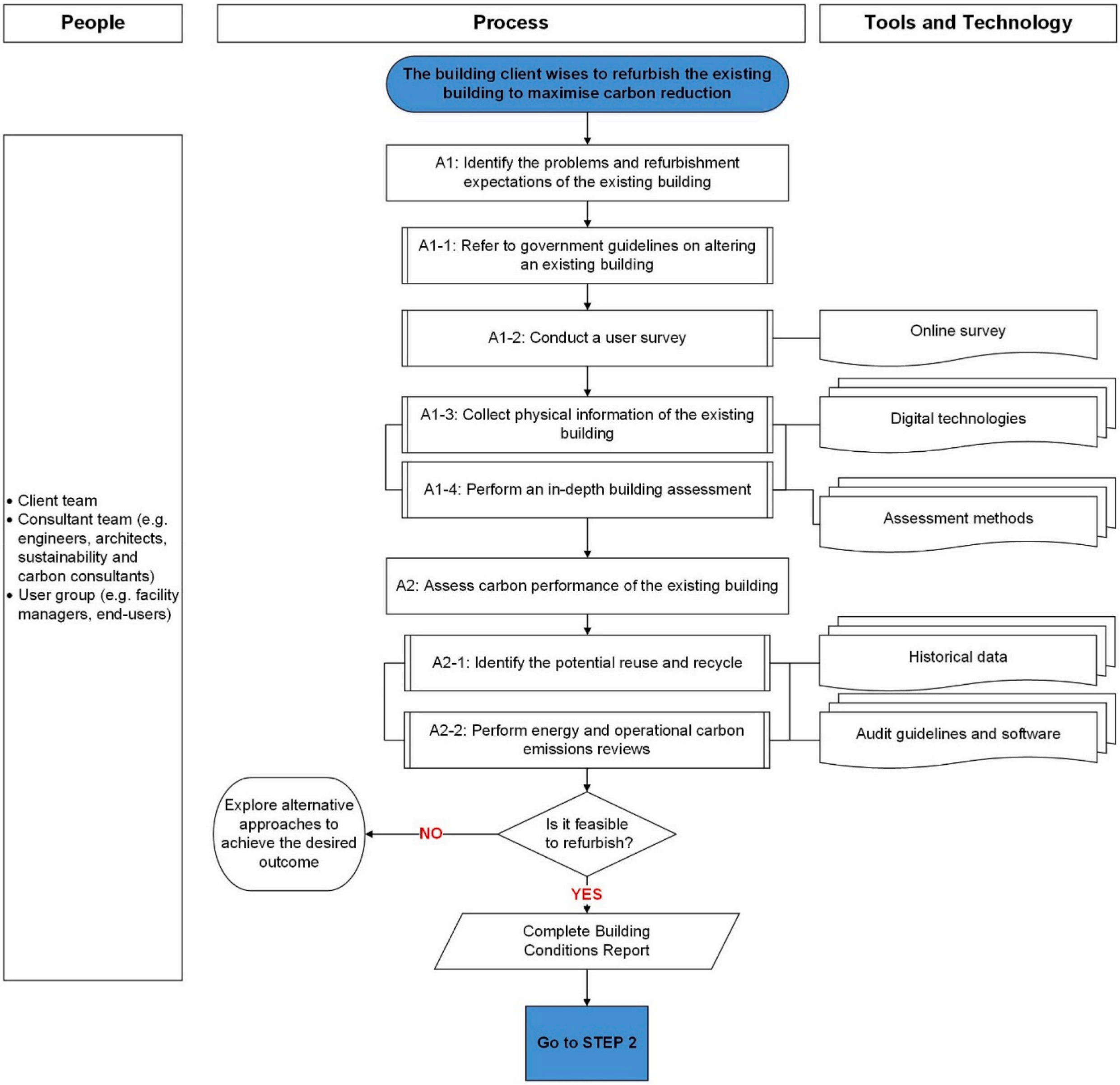

Fig. 3. Low level of decision support framework - Step 1.

attributes that provides the comprehensive decision-making processes, decision points, additional guidance and lists of the information needed to inform decisions at each step. Flow chart symbols and meaning can be found in the supplementary material (Appendix B). The following sub-sections outline the lower level of the framework in detail.

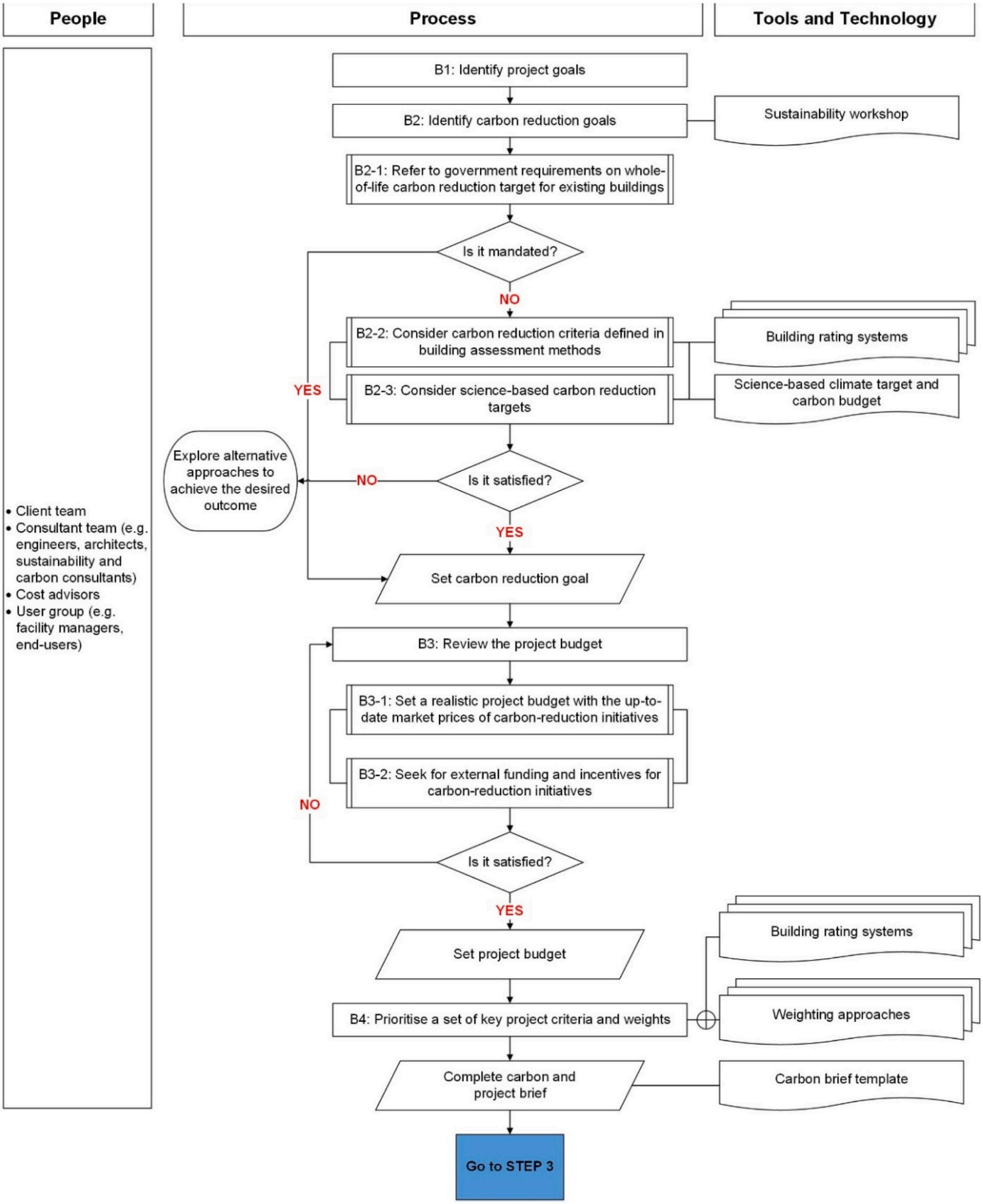

Fig. 4. Low level of decision support framework - Step 2.

3.1.1. Step 1: building condition assessment

The decision-making process begins with a building client wanting to refurbish an existing building to maximise carbon reduction (see Fig. 3). According to all focus-group experts, it is essential to establish a clear carbon-reduction aspiration at the outset of the process. Beginning with this goal provides focus for targeted improvements in the existing building and ensures that carbon reduction remains central throughout the refurbishment.

Step 1 (A) of the framework was come up with the building condition assessment. Evidence from literature review confirmed that this stage evaluates the state of building components and services, identifies operational issues, and determines the suitability of refurbishment [20,46]. Findings from this assessment inform the level and type of refurbishment needed. As recommended in the previous studies, both the client team and user group are encouraged to be involved in this step, with consultants brought in for a more thorough evaluation.

Step 1 begins with activity A1, identifying issues and refurbishment needs in the existing building. First, relevant government guidelines must be reviewed to ensure compliance, such as following the MBIE's EPB methodology for earthquake-prone buildings in New Zealand [47] if applicable, as suggested by workshop participants. Findings from the literature (e.g. [48]) and case studies revealed that a user survey (A1-2) should be included to pinpoint operational and functional issues in the building. Focus group findings also underscored the value of user surveys in shaping assessment scope, refining project objectives, and targeting issues from the user perspective. This was a practice not yet widespread in New Zealand's construction sector. As participant (#1, #2, #4, #10) noted, "the users could highlight areas of the building they like or dislike, which better informs assessments". If new occupants were involved, facilities managers should be consulted to clarify expectations. Incorporating the user feedback could help to develop effective refurbishment strategies.

After the user survey, essential physical data about the existing building such as location, type, area, orientation, occupancy, year built, and construction details should be collected (A1-3). According to the results from case studies, the client and consultant team could conduct a walk-through assessment using a checklist to systematically record the condition and issues of building elements (A1-4), ranking them for upgrade needs. Visual documentation, including photos and video, was recommended. Technologies like 3D or laser scanning could further enhance site inspections and, when integrated with BIM, improve information accuracy and management.

Finding from case studies suggested using structural and material tests to assess existing buildings, as these evaluations directly impact project goals, especially carbon reduction targets. Further supporting this idea, workshop participants #3, #5 and #8 indicated that achieving significant embodied carbon reduction may be difficult for earthquake-prone buildings that require extensive new materials. In addition, participants #5 and #7 highlighted that testing existing structures and materials is crucial for determining reuse potential, which informs how much material can be retained for carbon reduction.

The next activity (A2) involves assessing the building's carbon performance. For embodied carbon emissions, the team could review the reuse and recycling potential of existing building elements and materials. To improve energy efficiency and reduce operational carbon emissions, the client and consultants could assess historical energy use data and perform energy and carbon audits using guidelines such as ASHRAE, AS/NZS 3598.1:2014 [49], and the Ministry for the Environment's "Measuring Emissions: Detailed Guide 2020", as reported in case studies.

Conducting energy and operational carbon audits was recommended in the literature [20], as their results provide a valuable baseline for assessing improvements after refurbishment. However, the case study results identified that the actual implementation was limited in practice. Some focus-group experts believed that this is often due to building design and services changes in major refurbishments or adaptive reuse projects, which could make pre-refurbishment energy data less relevant. Audit accuracy may also depend on the availability of well-managed energy data, which was currently lacking in New Zealand. Therefore, these audits should only be carried out when budget, intended use, and data availability allow.

At the end of this step, the decision on whether to refurbish the existing building could be revised. If it is not feasible to refurbish the existing building, alternative approaches (e.g. change the use with minimum intervention, adaptation with a minor change, demolition, and redevelopment) should be explored to achieve the desired outcome. The project team is also expected to complete the Building Conditions Report, which includes a list of to-be-improved areas, as determined in the case studies and focus group.

3.1.2. Step 2: goal setting

Step 2 (B) of the framework was designed for establishing project goals and criteria (see Fig. 4). In reviewing the literature, this is an important point of the refurbishment process since the decision made in the following steps are adapted to these strategic and significant aspects [46]. According to case studies, the client team could set and prioritise these goals, with support from consultants and cost advisors as needed. The user group could also contribute valuable perspectives at this stage.

The departure point of Step 2 is activity B1, where the client team sets the refurbishment project goal in line with organisational strategies, drivers, and values. Case studies results highlighted that maximising carbon reduction in refurbishment projects to support the organisation achieving net-zero carbon target is an aspiration. In activity B2, the case studies and workshop participants recommended holding a sustainability workshop to set a whole-of-life carbon reduction goal. The sustainability champion could start the conversation on setting whole-of-life carbon reduction as a desirable project outcome. Workshop participants also noted that buy-in from client decision makers is crucial for making carbon reduction a mandated project goal.

Activity B2 is structured as a hierarchy, as experts suggested during validation. The primary mandated approach (B2-1) follows the New Zealand government's "Building for Climate Change" programme, setting legal minimums for operational efficiency and embodied carbon [50]. Alternative options include using building rating systems (B2-2) or adopting science-based whole-of-life carbon reduction targets (B2-3). Consultants may assist clients in pre-assessing which criteria or targets to apply.

Building rating systems could help structure early decision-making, set goals, and highlight design implications, with approved methods found in Ref. [51]. Using these systems from the start integrates carbon-related design considerations throughout the process. However, some rating systems may be inflexible, labour-intensive at early stages, and may not fully reflect project values, as mentioned in case studies. There could be a tendency with the building rating systems to put a capital cost value on points and targeting points based on their cost rather than the value that criteria offered. Therefore, benefits should be clearly identified and aligned with project criteria during design, rather than relying solely on rating systems to guide decisions.

Given that some building rating systems may not prioritise whole-of-life carbon reduction, it is important to also consider New Zealand's science-based carbon budget [52]. Using both approaches can guide life-cycle carbon analysis and help optimise refurbishment design. While applying these methods can be time-consuming and data-intensive, integrating rating systems with carbon budgets supports both sustainability and maximum carbon reduction goals. Climate targets and carbon budgets currently applied only to new buildings. The development of carbon budgets for individual existing buildings or the entire building stock is recommended for future work, which could further inform benchmarks and strategies for refurbishment projects.

After identifying the carbon reduction goal in B2, the question is whether the determined carbon goal is satisfied. If no, alternative approaches are explored to achieve the desired outcome. Otherwise, the outcome of this activity is to set a carbon reduction goal following one of the three mentioned options.

As evidenced in case studies, activity B3 centres on setting the project budget in relation to carbon-reduction goals for the refurbishment. At this stage, involving a cost advisor is essential to understand both the overall costs and the potential carbon savings that may result from different carbon-reduction initiatives. The goal is to establish a realistic project budget that is informed by current market prices and reflects the true investment required for meaningful carbon reduction (B3-1). Simultaneously, the project team is

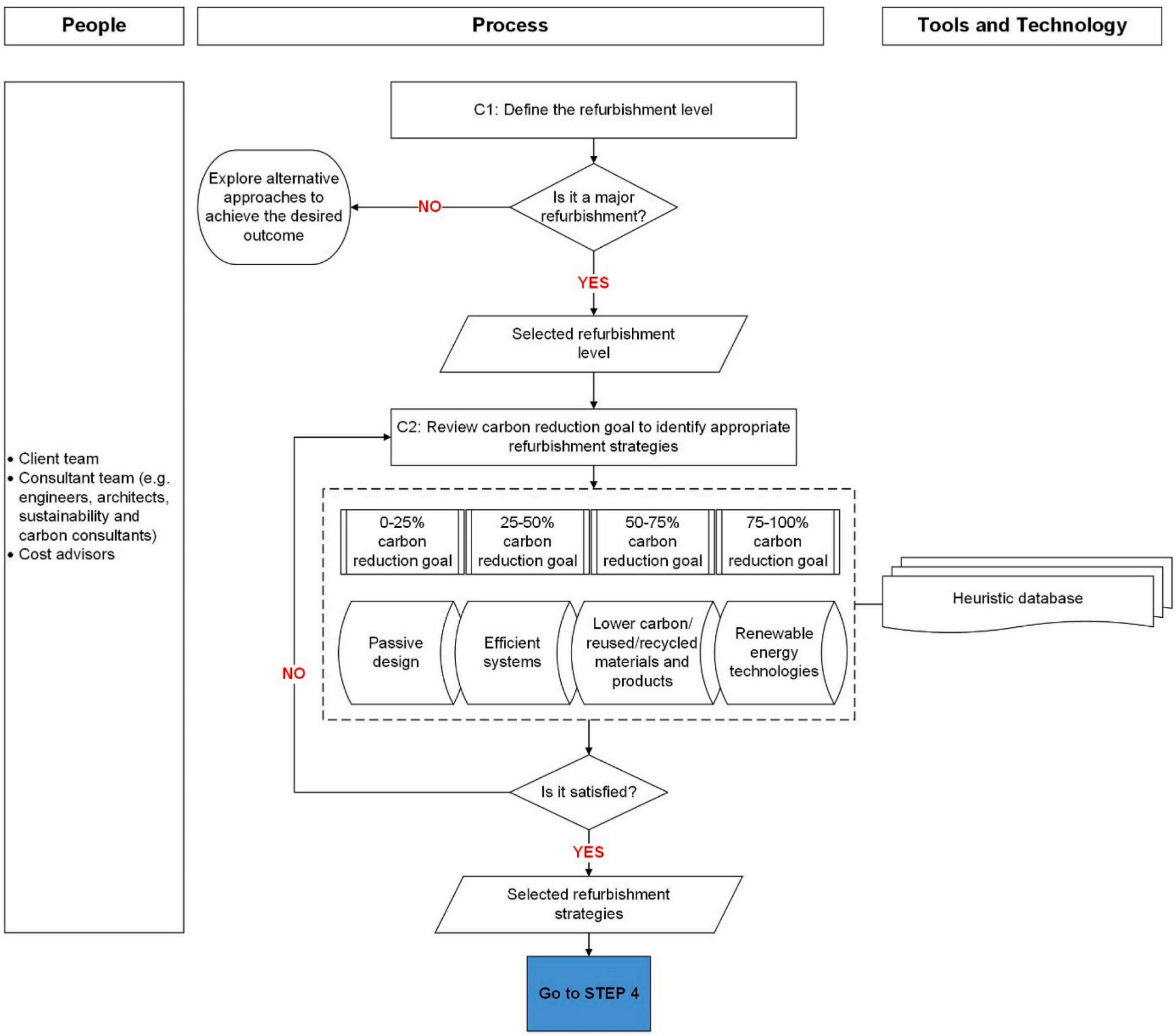

Fig. 5. Low level of decision support framework - Step 3.

encouraged to seek out external funding opportunities and government incentives that support carbon-reduction measures (B3-2).

A key debate highlighted by workshop experts was related to the budgeting approach for carbon-reduction solutions. While some suggested that a separate and specific budget could earmark for these solutions, most participants agreed that carbon-reduction costs should be integrated into the overall project budget from the outset. If the carbon-reduction option is treated as an add-on, it risks being deprioritised or "chopped" during design phases. By embedding these costs in the main budget, the project is more likely to maintain its commitment to carbon reduction throughout its development.

This difference in perspective often stems from the roles and priorities of various stakeholders. Clients may concern higher upfront costs, while consultants may see opportunities for carbon and cost savings through design innovation and creative solutions. As the project progresses to later stages, further assessment would identify options that balance carbon reduction with cost-effectiveness, allowing for trade-offs to be clearly evaluated. Therefore, it is crucial for clients to view carbon-reduction initiatives as core project objectives rather than optional extras. By setting aspirational carbon targets early and without imposing strict cost constraints, the project could remain focused on sustainability outcomes.

Ultimately, activity B3 concludes with a set project budget. Even if budget limitations exist, the team is encouraged to continue refining solutions, ensuring the project remains aligned with both carbon reduction and broader sustainability goals as it moves forward.

Next, the client should prioritise key project criteria and their relative importance (e.g. carbon, cost, energy, water, etc.) based on the established goals and budget (B4). User input could help identify key co-benefit criteria, such as indoor air quality [33]. These criteria and weights could be used later to assess the refurbishment solutions and performance. While simple weighting approaches (e.g. rank-order weighting) were identified in case study practices, there were many complex weighting approaches (e.g. the analytical hierarchy process (AHP) [53]) identified in the literature, depending on the decision-makers' preferences, project drivers and values [46]. Alternatively, the criteria and their weights in selected building rating systems could be followed. Regardless of the approach taken, trade-offs between key project criteria such as carbon emissions and cost are inevitable throughout the design process.

The outcome of Step 2 should be a complete carbon and project brief. The template and further guidance can be found in the New Zealand government guide to reducing carbon emissions in building and construction.

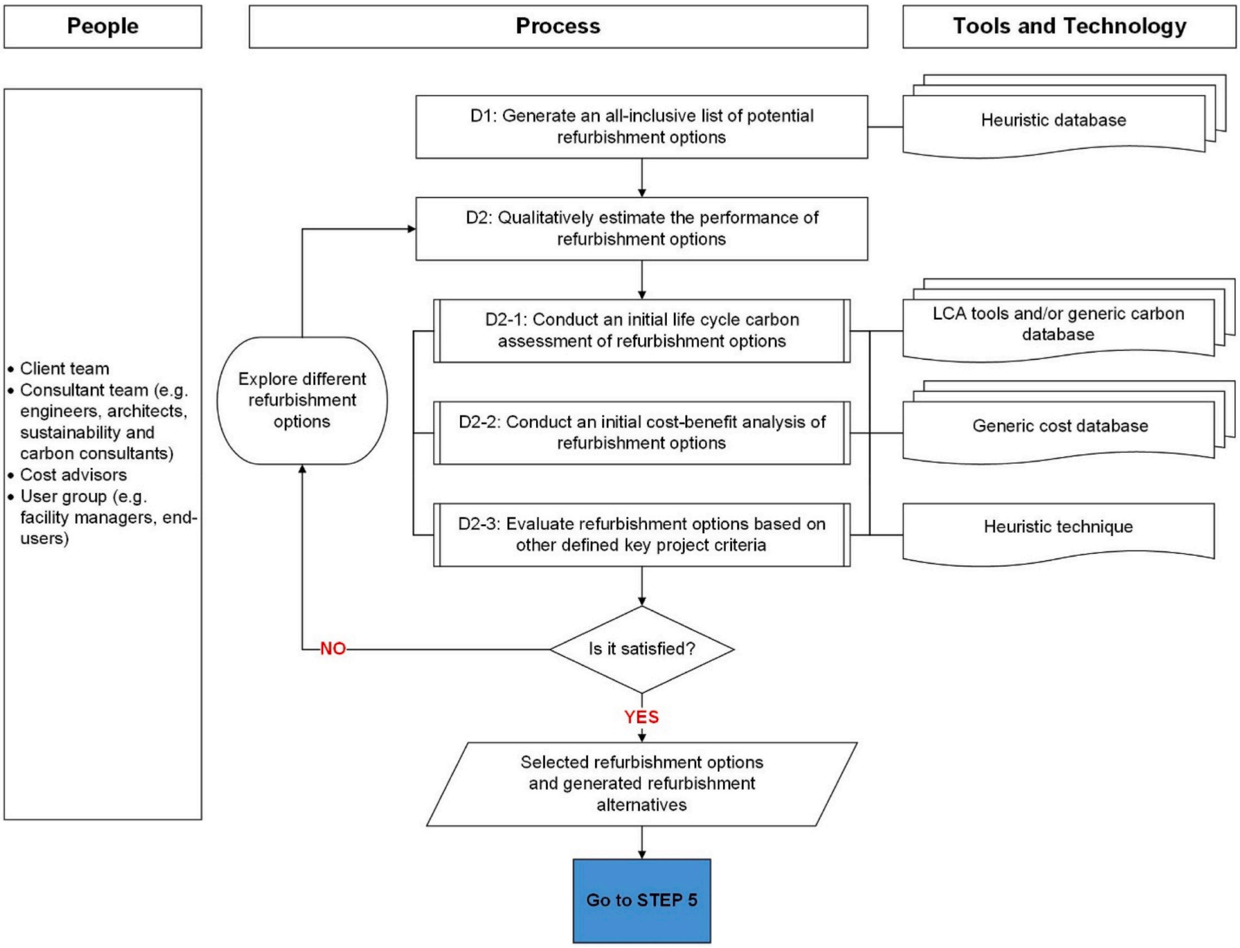

Fig. 6. Low level of decision support framework - Step 4.

3.1.3. Step 3: refurbishment strategies

Step 3 (C) was outlined to establish the refurbishment level and strategies to achieve an overall long-term objective of building refurbishment projects (see Fig. 5). It was suggested that the client team is responsible for selecting the refurbishment level and refurbishment strategies. The consultant team and cost advisors could provide advice to support this decision.

The first activity (C1) is to define the refurbishment level based on results from Steps 1 and 2. According to workshop experts, there wass inconsistent understanding in industry practice regarding "major refurbishment" and "partial refurbishment" due to varying definitions and scopes in New Zealand. To ensure transparency and consistency, the framework was designed to apply to major refurbishment projects, defined as significant modifications and improvements to an existing building to bring it to an acceptable condition according to ISO 21931:2022 [54], BS EN 15978:2011 [55] and BREEAM:2014 [56]. Refurbishment boundaries include the production and transport of new components, construction activities, as well as waste management and end-of-life of the substituted and remaining existing building components as defined in BS EN 15978:2011 [55] and BS EN 15804:2019 [57].

The decision on the refurbishment level should take the life-cycle cost and carbon emissions into account, as concurred by all workshop participants. This is because, in some cases, refurbishment focuses on upgrading certain building areas (e.g. upgrading building envelopes or building services), which may not resolve the problem of inefficient building operation in general. This could lead to a higher cost of ongoing maintenance and replacement and higher energy use and operational carbon emissions.

Once the refurbishment level is set, the next step is to review the carbon reduction goal and identify suitable refurbishment strategies. Based on the critical literature review, it was proposed that the carbon target could be broken down into levels (e.g. 0–25 %, 25–50 %, 50–75 %, 75–100 % of the carbon budget) to guide strategy selection, benchmarking and design optimisation. Strategies may include passive design, efficient systems, low-carbon products, recycled and reused materials, and renewable energy technologies [58, 59], chosen based on the building's conditions and heuristic database such as previous project designs. However, there is a need for flexibility and freedom in selecting appropriate refurbishment strategies as denoted in real-life case studies. This is because the consideration of the existing building condition and problems is the basis for developing refurbishment strategies. For example, passive design should be considered based on the physical conditions and capacities of the existing building. Renewable energy technologies could be regarded as long-term strategies for energy generation. However, performance assessment and feasibility studies are required to identify the trade-off between the advantages and disadvantages of these technologies. The evaluation of refurbishment strategies could be done by the consultant team to support the client make decisions. At the end of this step, the potential refurbishment strategies are selected.

3.1.4. Step 4: generation of refurbishment alternatives

Step 4 (D) was created to focus on generating different refurbishment options, design solutions like upgraded windows, installed PV systems, and added wall insulation, to address building issues (see Fig. 6). Refurbishment alternatives are combinations of these options that improve overall building performance. As signified in case studies, the consultant team typically develops these, with cost advisors providing input on cost-effectiveness and the client making final approvals. User groups may also contribute feedback on preferences and needs.

To begin with, the consultant team could generate an all-inclusive list of potential refurbishment options based on refurbishment strategies selected in step 3 (D1). As revealed in case studies, the intention is to include all possible refurbishment options in the decision-making at each design stage and encourage creativity and innovation in choosing refurbishment options. After that, the team could qualitatively estimate the performance of refurbishment options based on the key project criteria defined in step 1 (D2).

Sub-activities D2-1 and D2-2 were specifically designed to addressing the whole-of-life carbon reduction goal. The consultant team could conduct an initial life cycle assessment (LCA) of refurbishment options to identify lower-carbon opportunities (D2-1). Sustainability and carbon consultants are key actors in identifying potential carbon-saving solutions as shown in case studies. However, there might be a lack of information to conduct whole-of-life carbon assessment of refurbishment options according to workshop experts. Thus, initial carbon analysis should consider operational carbon emissions and upfront carbon emission (Module A1-A5 in building life cycle stages and modules BS EN 15978:2011 [55]). This could be done using available LCA tools and/or a generic carbon database. At the same time, an initial cost-benefit analysis could be conducted using a generic cost database to determine lower-cost and lower-carbon refurbishment options of the best practices (D2-2). The refurbishment options should be evaluated based on other defined key project criteria (D2-3).

The results from the workshop corroborated that having the proposed sustainability and carbon-reduction register as shown in the supplementary material (Appendix C) is necessary to support decision-making. Indeed, it could support to define the hierarchy of importance for each refurbishment option and their associated carbon impacts and benefits. The item could be ranked as a "must-have" or "nice-to-have". This embraces the critical refurbishment options contributing significantly to carbon reduction that could eventually be removed later due to cost constraints.

If the considered refurbishment options meet the requirements and expectations, the project team could select a narrow set of possible options and generate refurbishment alternatives as the outcome of Step 4. Otherwise, different refurbishment options could be explored, and the process is repeated from activity D2 until achieving the desired outcome.

3.1.5. Step 5: performance estimation and evaluation

Step 5 (E) was formulated to quantitatively assess refurbishment alternatives according to project criteria (see Fig. 7). The consultant team and cost advisors lead this process, with final approvals from the client. Input from contractors, subcontractors, and suppliers could also help identify the most suitable alternatives, as evidenced in case studies.

Step 5 begins by creating building design models using Building Information Modelling (BIM) (E1), establishing the existing building as the base case and comparing it to alternatives. BIM was recommended in the literature (e.g. [60]) and case studies to support whole-of-life carbon assessment using energy modelling and LCA in the following activities. After that, the performance of refurbishment alternatives can be quantitatively estimated (E2). This estimation includes (E2-1) evaluating building energy

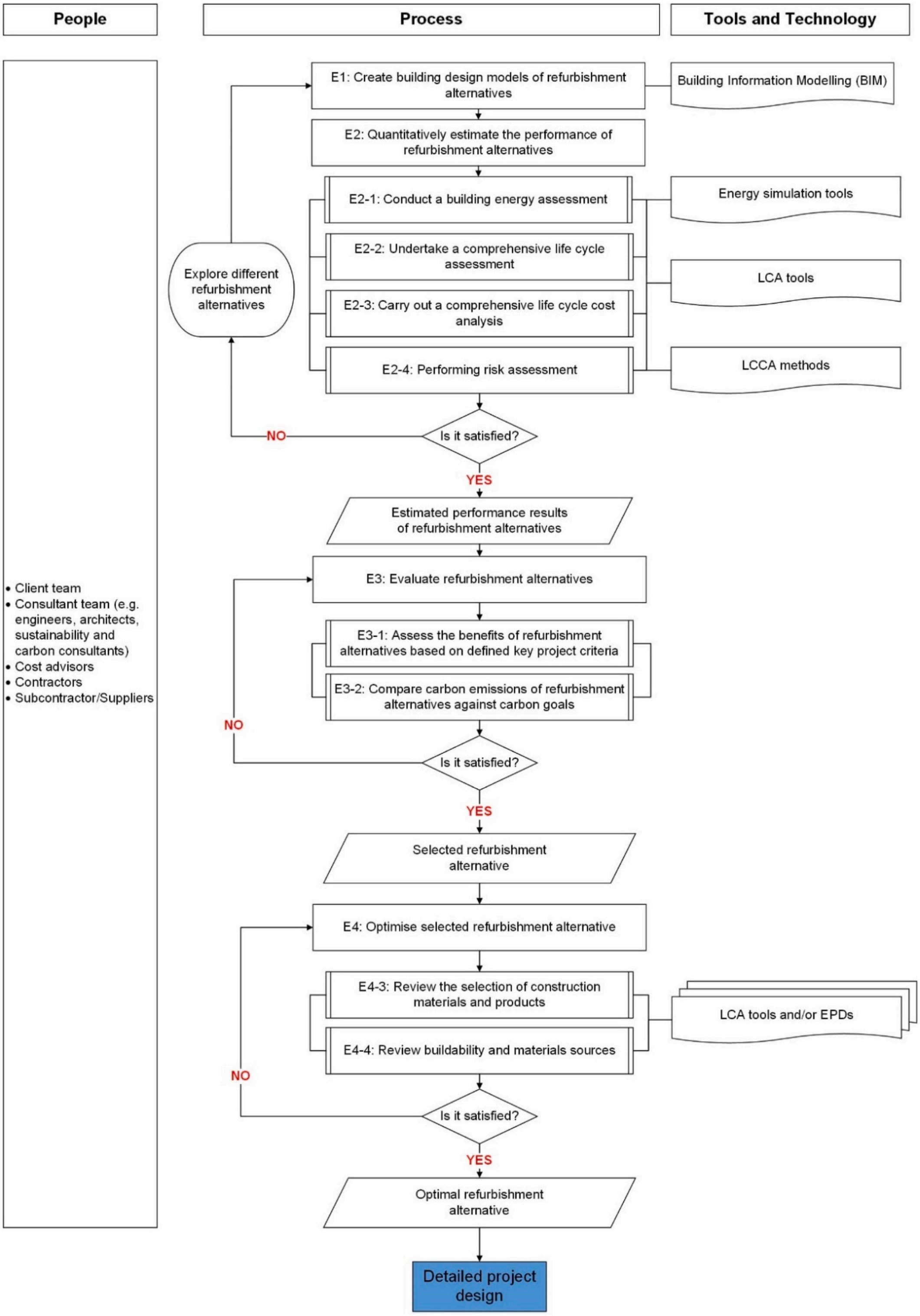

Fig. 7. Low level of decision support framework - Step 5.

performance, (E2-2) undertaking a comprehensive LCA to quantify whole-of-life carbon emissions, (E2-3) carrying out a comprehensive life-cycle cost analysis.

As suggested by focus-group participants, a risk assessment for refurbishment alternatives should be also included in step 5 (E2-4). Building refurbishment is subject to many factors, such as savings estimation, energy use measurements, weather forecasts, energy consumption patterns, system performance degradations, etc. Furthermore, there are uncertainties in undertaking LCA, such as insufficient carbon data. Therefore, risk assessment is essential to provide decision-makers with sufficient confidence to determine the best refurbishment solutions. The consultant team could work together to undertake energy modelling, LCA analysis and verifying carbon assessment results. Cost advisors are responsible for carrying out a cost-benefit analysis that considers several indicators such as capital cost, annual savings, payback period, Net Present Value (NPV), and Internal Rate of Return (IRR) to prioritise cost-effective options as mentioned in case studies.

The decision point is to review the selection of refurbishment alternatives based on quantitative performance estimation results. Alternatively, different refurbishment alternatives are explored, and the process is repeated until achieving the desired outcome.

Activity E3 involves iteratively evaluating refurbishment alternatives by assessing their performance and quantified carbon emissions against project goals. An example of evaluating refurbishment alternatives regarding economic and carbon performance indicators could be found in the supplementary (Appendix D). The result is the selection of the most suitable refurbishment option. After that, the selected refurbishment alternative should be optimised (E4). This could be done by reviewing the selection of construction materials and products based on LCA tools and product-specific data (e.g. Environmental Product Declaration (EPD)) (E3-3). The buildability and potential source of materials should also be reviewed (E3-4). While the consultant team work collaboratively to optimise the refurbishment alternative. Findings from case studies revealed that the contractors, subcontractors and suppliers should be engaged to review buildability and waste management plans and provide detailed carbon data, potential sources, and performance requirements of construction materials and products.

As endorsed by workshop experts the estimation, evaluation, and optimisation process of refurbishment alternatives should be iterative. At the end of Step 5, the optimal alternative is chosen, followed by detailed project design and continuation into the construction and operation phases.

3.2. RefurbZC application and implementation

The findings from the framework validation have confirmed that the RefurbZC provides a consistent and comprehensive decision-making process that can be applied to every refurbishment project incorporating carbon reduction initiatives. It was thought that RefurbZC can encourage the uptake of building refurbishment, in which the carbon reduction goal is prioritised. With social cooperation being demanded, decision-makers and their advisors tend to look for a holistic process to follow.

As recognised by all experts, there are various ways that the RefurbZC could benefit users such as building clients, developers, project managers, architects, engineers, cost advisors, sustainability and carbon consultants, contractors, subcontractors, suppliers, and the user group (e.g. facilities managers and end-users). For example, all participants agreed that the framework offers valuable information supporting decision-making in the procurement and design of refurbishment projects by providing detailed guidance on what should be done regarding carbon reduction initiatives. According to over half of the experts, the framework could be adopted as a conversation starter with decision-makers which encourages carbon-reduction decisions to be made early in the refurbishment process.

Another RefurbZC application could be a baseline and reference to ensure inclusive information and evidence provided by relevant stakeholders have been considered to make informed decisions, as indicated by most of the participants (80 %). The framework was also acknowledged as a mechanism to support the post-occupancy evaluation in the operation stage. For example, the performance gaps related to energy use and high maintenance costs could be identified by understanding why particular decisions were made at the earlier stages.

The survey distributed to all experts at the end of the workshop echoed their viewpoints on the potential implementation of the RefurbZC in the industry practice. The survey respondents were asked to rate the level of agreement with statements from 1 “strongly disagree” to 5 “strongly agree”. The results obtained from the survey are shown in Table 2, with most respondents (above 90 %) being either “agree” or “strongly agree”.

In addition, the Poll asked the respondents to indicate their likelihood of applying the framework in their future work. The Likert scale was used to weigh the response of the Poll respondents by setting the “definitely” as 5, the “probably” as 4, the “possibly” as 3, the “probably not” as 2 and the “definitely not” as 1 (see Table 3). The Poll results revealed positive feedback on the potential adoption of the RefurbZC in future refurbishment projects, as shown in Fig. 8. These were promising results, indicating the positive application and

Table 2
Survey results regarding RefurbZC potential implementation and benefits.

RefurbZC potential implementation and benefits	Mean
The framework could possibly help you understand the refurbishment decision-making process and requirements for reducing carbon emissions in certain activities	4.5
The framework could possibly help you identify areas for addressing carbon-related issues in the early stages of the refurbishment process	4.25
The framework possibly provides relevant information that supports your decision-making in reducing carbon emissions of building refurbishment	4
The framework could possibly help promote stakeholder collaboration in identifying carbon-reduction solutions for building refurbishment	4.25

implementation of the RefurbZC framework within the New Zealand construction industry.

4. Discussion

This paper set out to describe the development of a novel early-stage decision support framework for building refurbishment towards zero carbon emissions in New Zealand (RefurbZC). The development of RefurbZC addresses the need for a comprehensive approach to measuring whole-of-life carbon reduction for building refurbishment. Traditionally, the primary objective of building refurbishment is either bringing existing buildings up to current building codes and standards or improving building performance in terms of energy efficiency. For this reason, previous decision support frameworks have paid attention to improving operational carbon performance [21,20,61], leaving whole-of-life carbon performance as a significant unaddressed issue. While evolving from previous decision support frameworks, RefurbZC offers a better standardised process guideline to address the whole-of-life carbon performance of building refurbishment. The results further support the idea of building refurbishment associated with substantial embodied carbon emissions, mainly due to the use of energy-intensive construction materials [62][63]. Measures to promote energy efficiency refurbishment may not reduce overall carbon impacts [64,65]. Therefore, the development of RefurbZC framework has added to the rapidly expanding field of building refurbishment towards zero carbon emissions.

Unlike prior decision support mechanisms reviewed in the literature, the RefurbZC expands knowledge by providing an advanced step-by-step process for assessing decarbonisation decisions at different stages of building refurbishment. Compared to previous frameworks that only focus on either processes or tools and technology, the RefurbZC has bought a new understanding of applying lean philosophy by integrating the collaboration and integration attributes to the lean-based sociotechnical systems model that originally includes people, processes, tools, and technology [30]. This aspect significantly supports decision-making from a holistic point of view. Although the final decision is made by building clients, the RefurbZC was designed to ensure that various perspectives, sources of information and interests are represented. The study findings recommend that decisions should be made based on input provided by building stakeholders, including but not limited to project managers, engineers, architects, sustainability and carbon consultants, cost advisors, contractors, subcontractors, suppliers, facilities managers, and end-users.

To provide holistic carbon-reduction solutions for building refurbishment, the RefurbZC promotes the collaboration between key stakeholders and their interconnection with available decision-support resources and tools. It illustrates the influence and interconnectedness between the key actors and factors. The study results have highlighted a key consideration during the initial stages of refurbishment projects, which is the deliberate discussion among project teams regarding zero-carbon aspirations and commitments. These conversations should encompass the selection criteria for identifying effective refurbishment solutions, as well as a thorough examination of the meaning, benefits, and drawbacks of each option with respect to whole-of-life carbon emissions. It is equally important to assess how these criteria are prioritised relative to other factors such as capital cost value. This approach reflects the principles of Value-Focus Thinking [66], emphasising the preferred values of the decision-makers involved, and the creation of relevant refurbishment solutions based on these values [10,67]. The study has raised important points about shifting the discussion from individual variables to synergies across the decision-making process and enabling knowledge development and sharing between all parties and long-term relationships beyond a refurbishment project.

The development of RefurbZC considers the strengths and limitations of various academic decision support tools and frameworks as well as addresses key challenges identified by industry experts. This ensures that the developed framework facilitates performance improvement in practice where it is important to identify existing challenges to reducing whole-of-life carbon emissions in the refurbishment process and potential opportunities for improvement. Accordingly, the RefurbZC provides a structured framework that includes the suitable adoption of different tools, methods, and mechanisms to encourage concerted actions by industry actors towards maximising whole-of-life carbon reduction in the refurbishment process. It clarifies when, why and how these tools, methods and mechanisms should be used to assess whole-of-life carbon aspects along the refurbishment process to achieve the desired outcome and reduce performance gap issues. The framework also guides users on the various evaluation criteria to be considered at each step of the decision-making process. Taken together, the RefurbZC is a theoretical and practical construct that extends the theoretical knowledge and bridges the gap between theory and practice, offering a basis and foundation for future work in this research area.

The research findings suggest that decision-making on carbon-reduction initiatives in practice for building refurbishment is a complex process involving the analysis of multiple interactions between various existing and new building components. The process of identifying the most optimal decarbonisation refurbishment alternatives comprises the reconciliation of project objectives, budget, available refurbishment design and technologies, carbon assessment approaches and expertise. There has been attempts to develop various decision support tools to address this multiple-objective trade-offs [68–70]. However, this study argues that approaches proposed in literature often demand building professionals' capacity and capability to undertake integrated simulation-based decision

Table 3
Likelihood of applying the RefurbZC framework in future work.

Response	Likert weight	Percentage
Definitely	5	18.18 %
Probably	4	36.36 %
Possibly	3	45.45 %
Probably not	2	0.00 %
Definitely not	1	0.00 %

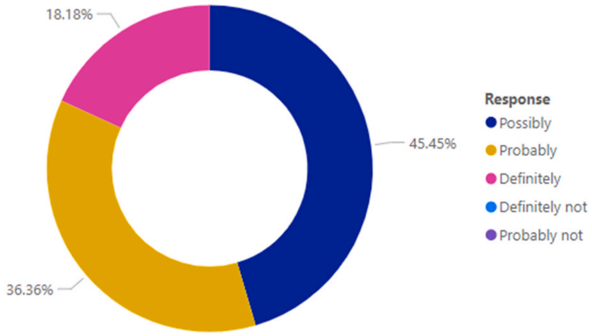

Fig. 8. Results on the potential adoption of the RefurbZC in future refurbishment projects.

support tools, which may not be feasible in practice. Take the New Zealand case as an example. The lack of carbon data and literacy throughout the New Zealand construction industry leads to ambiguous and inconsistent whole-of-life carbon assessment. Adopting complex decision support systems incorporating multi-objective optimisation factors to generate the most fit-for-purpose refurbishment alternative is challenging for industry practitioners. Not to mention, the constraints associated with additional consultancy costs for adopting complex systems for whole-of-life carbon assessment are significant barriers to stimulating decision-making in implementing carbon-reduction initiatives. These challenges appear to be global issues for the construction industry. Since there has been no step-by-step method with detailed guidelines to better deliver building refurbishment towards zero carbon emissions, the RefurbZC provides industry practitioners with robust information, expectations, and desired outcomes at well-defined decision points.

The RefurbZC seeks to enable the best practice that is reasonably ambitious compared to the current industry practice. Since the framework is addressing different stakeholder groups, it has been developed to be easy to understand and simple to use. Alongside with step-by-step decision flowcharts, narrative that outlines what, why and how actions should be taken to reduce carbon emissions in building refurbishment is included in every step. Primary users of RefurbZC might be clients, developers, project managers, facilities managers, who want to better understand the refurbishment decision-making process, identify areas for integrating carbon-reduction initiatives as well as human resources and mechanisms required to achieve carbon-reduction initiatives. Architects, consultants, cost advisors, and contractors might use RefurbZC as a reference for strategy illustrations, carbon and cost assessment, and comparisons of different carbon-reduction proposals. One of the advantages of RefurbZC is that it can be used as a communication tool between stakeholders to manage the different expectations and values as well as to show to which degree the carbon-reduction objectives have been met. The RefurbZC provides all relevant information such as people, process, tools and technology, collaboration and integration attributes that should be considered logically, robustly, and consistently to better make decarbonisation decisions.

However, in practice, the findings indicate that the inclusion of every aspect demonstrated in the RefurbZC may vary from one refurbishment project to another, depending on the project requirements, client's resources and expectations. For example, sometimes, using LCA tools to assess carbon performance of refurbishment options is not seriously considered because assumptions made about outcomes or preferences are so strong that refurbishment options are selected without in-depth analysis. The carbon literacy and expertise as well as budget for life-cycle carbon assessment of refurbished buildings may also be limited. In other cases, the refurbishment options are determined by thorough consideration of all information and evidence. Even though, the implementation of the RefurbZC differentiates from a case-by-case basis, it still offers a comprehensive guide based on best practices for reducing carbon emissions in the refurbishment process, where the impact of the decision can be critically evaluated, and the decisions made with in-depth analysis may necessarily be the most appropriate ones in terms of carbon reduction.

Taking cognisance of critical discussion and recommendation highlighted in this research, it is noted that the following key aspects should be considered when adopting the RefurbZC in any refurbishment project. First, the carbon-reduction goals and suitable refurbishment proposals can be tailored and embedded in different refurbishment strategies with a certain number of actions, which can be altered depending on each case. Second, the adoption of climate target and carbon budget, carbon benchmarking, carbon accounting and scope of work (i.e. LCA boundaries for building refurbishment [71]), carbon databases, as well as building rating systems, energy modelling and LCA tools, should be well-defined for robust whole-of-life carbon assessment and benchmarking. Third, knowledge development and sharing in carbon literacy is necessary for successfully delivering building refurbishment towards zero carbon emissions since the process of assessing carbon emissions requires both heuristic knowledge and practical experience in carbon performance estimation. Carbon-reduction initiatives must be addressed throughout the refurbishment decision-making process, and the process will be made only if all involved stakeholders are engaged and understand theory and practice. Finally, organisational and project team commitments towards delivering carbon-reduction goals for refurbishment projects are crucial for generating a trust-based collaborative environment for achieving targeted carbon performance and overall project outcomes. Establishing partnering relationships among the project participants will assist in cooperatively mitigating carbon impacts across the value chain.

5. Conclusion

This paper presents the development and validation of the state-of-the-art decision support framework (RefurbZC), contributing to the existing body of theoretical and practical knowledge on building refurbishment towards zero carbon emissions. The framework was devised through a rigorous analysis and interpretation of literature review, preliminary study and case study. It integrates international best practices adapted to the local context and incorporates lessons learned from real-life case studies. The potential application and implementation of the RefurbZC framework in practice has been confirmed by industry experts through an explicit validation process.

The study findings demonstrate the framework unpacking the activities and decarbonisation decisions to be made in the refurbishment process as a step-by-step decision flowchart. The results show that the framework supports the involved building stakeholders to better understand the refurbishment decision-making process and requirements for reducing carbon emissions in certain activities, identify areas for addressing carbon issues in the early stages of the refurbishment process, determine relevant information and key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration in carbon-reduction building refurbishment.

However, the decision support framework has several limitations. First, the developed framework utilised case studies exclusively from university buildings. It is important to note that the decision-making processes and unique features of university buildings may not fully represent those of other building types, such as privately-owned buildings. Therefore, future research should be undertaken to apply the framework to other types of buildings, thereby broadening its applicability and validity. Second, the RefurbZC provides all relevant information such as people, process, tools and technology, collaboration and integration attributes that should be considered logically, robustly, and consistently to better make decarbonisation decisions for building refurbishment. However, in practice, the inclusion of every aspect demonstrated in the RefurbZC may be vary from one refurbishment project to another, depending on the project requirements, client's resources and expectation. Even though, the implementation of the RefurbZC differentiates from a case-by-case basis, it offers a comprehensive guide based on best practices and its flexibility to be customised in specific case for reducing carbon emissions in the refurbishment process, where the impact of the decision can be critically evaluated, and the decisions made with in-depth analysis may necessarily be the most appropriate ones in terms of carbon reduction.

To further enhance the robustness of this study, it is recommended that the tool be validated through practical application on one or more real-world case studies. By implementing the tool with actual building projects, its effectiveness and impact can be more thoroughly demonstrated. This step is recognised as an important direction for future research.

CRediT authorship contribution statement

Thao T.P. Bui: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Suzanne Wilkinson:** Writing – review & editing, Validation, Supervision. **Niluka Domingo:** Writing – review & editing, Validation, Supervision. **Casimir MacGregor:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.114282.

Data availability

The data that support the findings of this study are available on request from the corresponding author, T.T.P.B. The data are not publicly available due to restrictions, e.g. containing information that could compromise the privacy of research participants.

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