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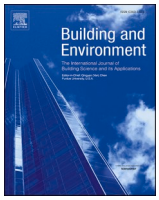

Decision making in reducing carbon emissions for building refurbishment: Case studies of university buildings in New Zealand

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ABSTRACT

The refurbishment of existing buildings offers the greatest opportunity to maximise carbon reduction within the built environment. Although the conceptual framework of the refurbishment process incorporating various methods, tools, and systems to support decision making in reducing whole-of-life carbon emissions exists in the literature, empirical research reporting on how and why the decisions are made in current industry practice is lacking. This paper aims to address this knowledge gap by investigating the decision-making process of building refurbishment considering whole-of-life carbon reduction using three real-life case studies that incorporate decarbonisation decisions. The important findings emerged from an interactive analysis between theoretical propositions and cross-case synthesis. The study sheds a new insight into (1) the effective adoption of building rating systems, (2) the required whole-of-life carbon reduction targets, (3) the importance of establishing a dedicated financial budget for carbon-reduction refurbishment solutions, (4) the need for adaptable refurbishment designs and long-term strategies, (5) holistic design reports, (6) the promotion of early contractor involvement (ECI) approach, (7) government funding and incentives, and (8) the availability of supply chains and data. The originality of the paper is providing a new understanding of the decision-making practices and challenges faced in the refurbishment process, in which lessons learnt for improving the implementation of building refurbishment towards zero carbon are recommended. The research expands theoretical knowledge and practical experience in whole-of-life carbon analysis and performance estimation for building refurbishment. The insights gained from this study offer practitioners and researchers a streamlined interdisciplinary guide to better deliver refurbishment projects towards zero carbon.

1. Introduction

As climate change poses a devastating global risk, reducing carbon emissions is imperative to alleviating extreme climate change impacts [1]. The construction sector contributes significant harm to the environment. It accounts for more than 40% of global energy use and one-third of worldwide greenhouse gas (GHG) emissions [2]. The design and construction of buildings has been identified as a crucial area to reduce carbon emissions [3]. In New Zealand, buildings are directly and indirectly responsible for up to 20% of New Zealand's GHG emissions [4]. Radical improvements in building design and construction are therefore required to help reduce environmental impacts, supporting the mitigation of climate change, achieving a low-carbon economy, and uplifting the quality of people's lives [5].

Refurbishment projects generate only half the embodied carbon emissions of new builds, thus representing a promising area to support climate change mitigation goals [6]. In New Zealand, existing buildings are forecasted to account for an estimated 65% of the total climate impact of the detached-house sector between 2018 and 2050, while new buildings make up the remaining 34% [7]. While the carbon emissions related to the development of the building stock can be reduced by imposing strict carbon-reduction requirements for new buildings, attaining these goals for existing buildings remains a challenging task. Therefore, it is crucial to ensure that existing buildings are refurbished properly to reduce whole-of-life carbon emissions.

A complex and challenging decision-making process is necessary when pursuing the limiting of carbon emissions during building refurbishment projects. In a refurbishment process, numerous decisions are

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made throughout the different phases, from the initial decisions on why and when to refurbish, the design of refurbishment scenarios and strategies, the optimal selection among design alternatives, to decisions made during the process of construction, operation, usage, and finally, demolition and reuse. More importantly, most critical decisions are made in the pre-design and design phase [8,9]. It is argued that the decision-making process is an art, fine-tuned over a long period through experience and learning from trial and error. Nowadays, decision-making is even more complicated due to the availability of "more alternatives to choose from", the "large cost of making errors", "more uncertainties", and "the need for quick decisions" [10]. Accordingly, making decisions incorporating zero-carbon targets for building refurbishment can be difficult as it is a multi-objective problem influenced by various constraints and limitations (i.e. project target, budget, building techniques) [11]. Likewise, government policies and social factors such as user comfort can also impact decision-making in the refurbishment process [12–14]. The involvement of multiple stakeholders adds further complexity [15,16]. Managing clients' requirements and stakeholders' values with the need to focus on zero-carbon strategies can be problematic [17]. To successfully deliver building refurbishment towards zero carbon, there is a need to better support and encourage decision-makers to make effective decarbonisation decisions throughout the refurbishment process.

In recent years, decision making in reducing carbon emissions for building refurbishment has been a significant research area of interest. Due to a large volume of literature in the research area, it is important to uncover knowledge structures and gaps to help inform the conceptual framework of the refurbishment decision-making process. In doing so, both up-to-date systematic and critical reviews of the literature in the research field have been performed. A systematic review was undertaken to examine the state-of-the-art research on zero carbon refurbishment due to its organised, transparent, and reproducible way to synthesise research findings and discover future studies. Simultaneously, a critical literature review was undertaken to assess, critique, and synthesise the literature on decision support for building refurbishment in a way that facilitates a new conceptual framework for the decision-making process of building refurbishment considering whole-of-life carbon reduction. Both reviews considered the bibliometric search strategy using the keywords: "zero carbon" OR "net zero carbon" OR "zero emission" OR "zero energy" OR "nearly zero energy" AND "refurbishment" OR "retrofit" OR "renovation" via Scopus to determine the relevant literature. To narrow the scope of the review, a set of selection criteria were considered, including (1) English journal articles published at the final stage in recent years, (2) relevant subjects in the construction research field, (3) papers published in top-ranking journals in the construction field ranked by Scimago Journal and Country Rank (e.g. Building and Environment, Energy and Building, etc.), publishing the largest number of papers in the research context. As a result, the systematic review considered the final selection of 147 up-to-date research articles, which were analysed using mixed-method data analysis, including quantitative (science mapping) and qualitative (thematic) analysis [18]. The critical review considered the final selection of 15 state-of-the-art decision support mechanisms to reduce carbon emissions in building refurbishment [14]. More details on systematic and critical reviews of the literature in the research field are found in Refs. [14,18]. Findings from the literature reviews revealed that there has been an increasing amount of literature on developing decision-support mechanisms to aid in identifying the optimal refurbishment solutions at the design phase of the refurbishment process [19–24]. It is suggested that a holistic multi-objective decision-support mechanism considering whole-of-life carbon, economic factors, co-benefits, and other impacts is necessary for building refurbishment towards zero carbon. In contrast, fewer studies have investigated the decision-making process for building refurbishment in any systematic way [11,25–27]. However, these studies have focused on the decision-making processes for energy management and sustainability leaving behind the focus on a particular area, such as whole-of-life carbon reduction, in much detail. Furthermore, there has been little discussion about the decision-making process for building refurbishment in practice that considers the impacts of whole-of-life carbon emissions and integrating necessary decision-support resources and tools. Most prior studies that focus on decarbonisation decision making in building refurbishment are limited to the theoretical context and lack clear evidence of application in current industry practice. In addition, various simple-to-complex decision support methods, tools and systems can be found in the literature but empirical research reporting on how these methods, tools and systems are actually adopted to support decision making in the practical refurbishment process is lacking. Key stakeholders' perspectives (e.g. clients, consultants, contractors, and the user group) and the documentation of real-life refurbishment projects are considered as reliable references for investigating decarbonisation decisions and the performance of building refurbishment. It is also important to identify existing challenges to reducing whole-of-life carbon emissions in the refurbishment decision-making process and potential opportunities for improvement. Lessons learnt and suggestions for improvement that extend the theoretical and practical knowledge and bridge the gap between theory and practice, might offer a basis and foundation for future work in this research area.

This paper aims to address the knowledge gap by examining the practical decision making in reducing carbon emissions for building refurbishment in New Zealand. It focuses on the major refurbishment, which, among other things, involves a significant improvement in energy and carbon performance [28]. The scope of work focuses on the early stages of the refurbishment process, including the pre-design and design phases. The term "refurbishment" is employed consistently throughout the study which comprises a modification and improvement to an existing building to bring it to an acceptable condition according to ISO 21931: 2010, EN 15978: 2011 and BREEAM: 2014. The boundaries for calculating life cycle carbon emissions of building refurbishment include the production of new components, transport of new elements, and construction as part of the refurbishment process, as well as waste management and end-of-life of the substituted and remaining existing building components according to EN 15978: 2011 and EN 15804: 2012 [29].

Drawing on the literature, we identified the critical components of the refurbishment decision-making process. After that, we explored this process in practice using a case study approach. We then discussed unexpected outcomes, tensions, and lessons learnt towards the implementation of building refurbishment towards zero carbon by integrating theoretical and empirical findings.

2. The refurbishment decision process

It is often difficult to distinguish the refurbishment process clearly from that of new buildings. The refurbishment process is assumed to be similar to the new building process, including pre-design, design, construction, and operation phases [8]. However, Jensen et al. [30] identified seven different characteristics between a refurbishment and a new build. The main difference is that a preliminary investigation of the existing building is the basis for developing design solutions, whereas a new building has the building site as a foundation. Existing building design, condition, performance, and users are key considerations. Pre-evaluation and post-evaluation of refurbished buildings are necessary to measure the improvement of building conditions, energy performance, carbon and cost savings, and user satisfaction. The early-stage refurbishment decision-making process traditionally incorporates the following main phases (1) building condition assessment, (2) goal setting, (3) generation of refurbishment alternatives, (4) performance estimation and evaluation [8,9,11]. Recent evidence suggests that outlining refurbishment strategies is a critical step that should be considered before generating refurbishment solutions [14,24,28]. Thus, the early-stage decision-making process of building refurbishment

proposed in this study is shown in Fig. 1.

Setting goals, objectives, and criteria is often the starting point of the refurbishment process since all subsequent phases are adapted to these strategic and significant aspects. Selecting the right goal helps building stakeholders address existing problems and seek the best refurbishment solutions [9,14]. The goal and objectives can be based on the client's requirements, values from involved stakeholders, building rating systems (e.g. BREEAM, LEED, Green Star, etc.) and life cycle carbon budgets for individual buildings to define the carbon performance goal [7,31]. However, the building condition assessment can be done before the goal setting to reveal the actual state of the building, and thus its refurbishment requirements, the site's advantages and disadvantages, and the appropriate refurbishment solutions [8]. Therefore, these two steps could be undertaken iteratively to ensure the achievable goal is set considering the existing building condition problems. The procedure can continue with formulating refurbishment strategies, which represent different levels of refurbishment, from a few actions to a major refurbishment, and provide proposals for refurbishment solutions such as upgrading building fabrics, installing efficient equipment, and installing microgeneration [11,20,24]. The next step is a generation of refurbishment alternatives, where a multi-criteria analysis of the refurbishment components is performed, and the best possible options are selected [11,32]. Then, the performance of these possible options can be estimated using simple economics and energy calculations, or rough estimates, energy simulation tools (e.g. EnergyPlus, IES, etc.), life cycle assessment (LCA) tools (e.g. LCAquick, eTool, OneClick LCA, etc.), and life cycle costing (LCC) methods or other complex and comprehensive decision support systems that incorporate multi-objective optimisation factors [8,29,31]. However, there has been limited investigation of how these methods, tools, and systems are applied to support building stakeholders making carbon-related decisions for building refurbishment in practice [18]. This is an important area for further work. After estimating performance, refurbishment alternatives can be evaluated quantitatively and qualitatively based on the project goals and objectives set earlier. Evaluation can be done continuously and iteratively throughout the design process, for example, evaluation of simulation results and calculations at the end of each design stage [8,9]. Then, the optimal refurbishment alternatives are selected before proceeding to the following stages of the project (e.g. detailed project design, construction, operation).

3. Research design

3.1. Research approach

This research investigated the pragmatic early-stage refurbishment process to identify what carbon-reduction decisions were made and how building stakeholders delivered building refurbishment towards zero carbon in New Zealand. This investigation adopted an exploratory case study approach, which was found appropriate for gaining first-hand experience with current refurbishment approaches and understanding the practical context of the decision-making process. The case study strategy is a reliable means of capturing rich information in complex situations such as construction projects. It generates insights into the phenomenon being studied and allows the investigator to retain the holistic and meaningful characteristics of real-life events [33–35]. Fig. 2 shows an overview of the research process.

3.2. Case study selection

An important step in developing case studies is defining the cases which will be studied [36,37]. This research selected multiple case studies to reflect the major refurbishment towards net zero-carbon targets by 2050. The criteria for case selection included refurbishment projects that: (1) targeted a high level of sustainability/zero carbon certification or equivalent goals; (2) sought to integrate sustainable/low-carbon practices or products; (3) provided sufficient access to data, reports, and stakeholders; (4) were a similar building type; (4) were launched by different organisations within the past five years. Consequently, three university buildings were selected for the study. These recently refurbished buildings showcased examples of low-carbon designs and technologies.

Case study 1 was explored as a pilot study in enhanced detail and with additional data. A pilot case allows the investigator to observe different phenomena from many different angles or try different approaches on a trial basis [34]. Case 1 was a refurbished educational building - a part of a sustainable redevelopment project. The project consisted of a new atrium that connected a new building with the existing library, lecture theatres, and the refurbished building. The project aligned with the organisation's green building standards and vision of moving towards net-zero GHG emissions consistent with national and international commitments.

Case study 2 was a library building transformation, showing the organisation's commitment to reducing GHG emissions and achieving carbon neutrality by 2030. The existing library conjoined two-story buildings. The project targeted carboNZero Building Operations accreditation that included a range of environmental measures to improve building performance and reduce carbon footprint.

Case study 3 – an educational building located at a university campus was a part of an adaptive reuse project towards a net-zero carbon future in New Zealand. The redevelopment project encompassed refurbishing two sections, North and East buildings, and constructing a new atrium that connected two parts of the existing building. The project was awarded six Green Star for design by New Zealand Green Building Council (NZGBC), achieving 93 out of 100 points – the highest Green Star points given to any New Zealand building. Table 1 summarises the main characteristics of three selected case studies.

3.3. Data collection

The use of various sources of evidence enhances credibility and the richness of data due to the data triangulation opportunities in case study designs [34,38,39]. Accordingly, multiple evidence sources were used to improve the overall quality of the research and accurately render the refurbishment decision process. The primary data sources were interviews with stakeholders involved in the case studies, project documentation (e.g. sustainable strategy reports, sustainability plans, site investigation reports, building performance reports, energy efficiency reviews, sustainable design briefs, building condition assessment reports, drawings, design specifications, study reports), and direct observation (e.g. site visits). One of the most important sources of case study evidence is interviews, which were employed to gain insights into the

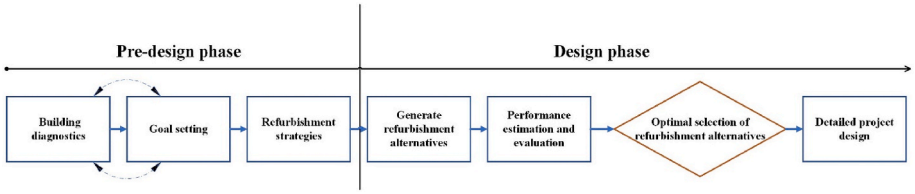


Fig. 1. The early-stage decision-making process of building refurbishment.

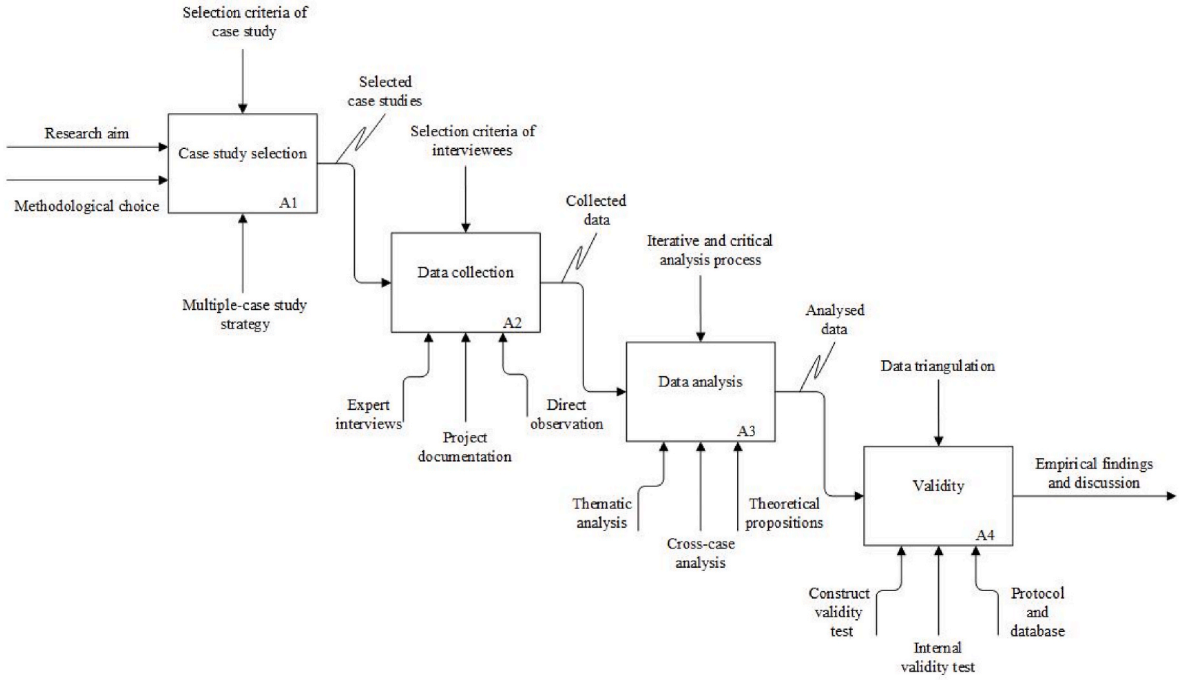


Fig. 2. Research process.

Table 1
Summary of the main characteristic of three case studies.

Characteristics	Case study 1	Case study 2	Case study 3
Type of client	State sector (Tertiary Education)	State sector (Tertiary Education)	State sector (Tertiary Education)
Main use	Teaching facilities, office spaces, learning spaces	Learning spaces	Teaching facilities, office spaces, learning spaces
Project size	approx. 10,000 sqm	approx. 10,000 sqm	approx. 24,500 sqm
Project timeline	2018–2024	2020–2023	2019–2024
Status	Under construction	Under construction	Under construction
Total project budget	NA	$60.5 m	NA
Original erection	1980s	Built in 1968 and extended in 1985	1970s
Existing conditions	Unoccupancy with poor and unsustainable conditions	Under operation with poor condition	Under operation with poor thermal and performance comfort
Certification	NA	carboNZero Building Operations (Targeted)	6 Star - Green Star
Main refurbishment considerations	Exterior wall and roof insulation, double-glazed windows, LED lighting, BMS system, centralised heat pump and chiller plant, off-site PV system	Low-e solar control double glazing, insulated walls and roof, external solar shading, operable windows, mixed-mode ventilation	Super-insulated and airtight curtain wall system, low-energy mechanical ventilation system, high-performance solar glazing, PV system, LED lighting

refurbishment process and carbon-reduction decisions. Interviewees from different building stakeholders' backgrounds, roles, and positions, who were involved in the decision-making process of the cases studied, were chosen to gather in-depth and supplementary information, reflect participants' relativist perspectives and attain an overall picture of the case [37,40]. They were also able to provide a shorthand history of the case study and helped identify other relevant sources of evidence [34].

The subject matter experts were selected using purposeful sampling techniques [41–43], as it allowed the selection of individuals with vast knowledge on reducing carbon emissions for building refurbishment to offer meaningful and insightful details. The selection of participants varied on a case-by-case basis depending on the key actors involved in the refurbishment process, including but not limited to clients, project managers, consultants, cost advisors, facilities managers, contractors, etc. First, permission to investigate three case studies was obtained from the project clients. Based on the project clients' references, additional key actors involved in the refurbishment decision-making process were identified, making up to twenty-five key actors in total. Once key actors and their profiles were identified, they were assessed based on the following requirement criteria: (1) have attained a tertiary education level, (2) have worked within the New Zealand building and construction industry for at least five years, and (3) have expertise in sustainable design, construction, project delivery or related skills.

There was an attempt to select multiple case studies, which were pioneering showcases to reflect the major refurbishment towards net zero-carbon targets by 2050. Therefore, all identified participants came from industry-leading organisations in the field. All had expertise in sustainable building refurbishment since they had been involved in successfully delivering building refurbishment projects that incorporated sustainability and carbon reduction objectives. Some of them were in top positions in their various companies and organisations, actively involved in sustainable design, construction, and project delivery. Eventually, invitations were sent to all identified participants of three case studies who met the selection criteria. With project clients' permission and reference, most selected participants agreed to contribute to the research, apart from two invitees, due to their work commitments and other priorities.

Twenty-three semi-structured interviews were conducted, which allowed probing views and opinions and encouraged extensive answers [37]. During the interview, stakeholders were asked to describe the refurbishment process and explain what, how, and why carbon-reduction decisions were made. The interviews included questions about: (1) participant information, (2) project brief, the refurbishment process and stakeholders involved, and (3) the

decision-making process and carbon-reduction decisions. Additional questions were discussed to identify further problems and unexpected subjects related to the refurbishment. Most of the interviews were held virtually via Microsoft Teams between July 2021 and January 2022 due to COVID-19 impacts and restrictions in New Zealand. The use of virtual groups created a healthy and safe environment where participants can contribute at their leisure and individual places [44]. The interviews lasted between 30 and 60 min and were digitally recorded subject to the participant's permission and transcribed for data analysis. Table 2 below shows interviewees' demographics in three case studies.

3.4. Data analysis

In an exploratory case study, qualitative data analysis involves iterative observation, analysis, and reflection [45]. The data obtained from interviews and observations was compared to the written evidence gathered from project documentation, triangulating information. Follow-up emails were sent, and phone calls were made to the participants to clarify inconsistencies and missing data. The qualitative software package NVivo 12 was used to organise information and code, analyse data, identify themes, and for interpretation. Following authors' suggestions in Refs. [34,46,47], a general qualitative strategy for analysing data was applied first, using theoretical propositions from literature review, descriptive frameworks, and rival explanations to understand the preliminary data and provide an explanatory view for each case. Then, a cross-case synthesis was used as a specific analytical technique. Major themes were identified for each case before analysing the similarities, differences, and associations across cases. After that, patterns were determined using replication logic within and among cases before confronting the existing theoretical propositions in an iterative process. The discussion resulted from an interactive analysis between the literature and the cases studied.

3.5. Validity

Three design tests were conducted to confirm the validity and reliability of the findings following authors' recommendation in Refs. [34,37,48]. The first test was to ensure construct validity, including using multiple sources of evidence and data triangulation. In addition, mistakes and errors were avoided by thoroughly checking transcripts and codes. The data and initial analysis results were returned to the interviewees to validate and revise. The findings were peer-reviewed by communicating and discussing the analytical results with key informants. Second, implementing pattern matching, explanation building and addressing rival explanations during the data analysis assisted in strengthening internal validity. Third, a case study protocol and

Table 2
Interview participants' profiles.

Case	Participants	Positions	Type of organisation	Years of experience in the construction industry	Years of experience in building refurbishment	Education degree and/or accreditation
Case 1	C1-CR1	Client Representative	Tertiary education	≥40	≥30	BEng, CMEngNZ, IntPE(NZ), APEC Engineer, FFMANZ
	C1-E1	Mechanical Engineer - Lead	Engineering & Consulting	≥10	≥10	BEng, MEngNZ
	C1-E2	Structural Engineer	Engineering & Consulting	≥10	≥10	BEng, MEng, MEngNZ
	C1-A1	Principal Architect - Zero carbon specialist	Architecture & Design	≥30	≥15	BArch, NZRAB Registered Architect, NZIA Member
	C1-A2	Architect - Lead	Architecture & Design	≥20	≥10	BArch, NZRAB Registered Architect, NZIA Member
	C1-A3	Architect - Carbon analyst	Architecture & Design	≥5	≥5	BArch, MArchProf, NZIA Member
	C1-CT1	Quantity Surveyor	Main Contractor	≥10	≥5	BConst, NZIQS Registered QS, GSAPs
	C1-CT2	Construction Project Manager	Main Contractor	≥10	≥5	BConst, NZCB Member
	C1-QS1	Cost Manager	Cost Management	≥15	≥15	BConst, NZIQS Registered QS
Case 2	C2-CR1	Client Representative - Project Manager	Tertiary education	≥20	≥10	BSc, Prince2 Practioner
	C2-QS1	Quantity Surveyor	Multinational Engineering Consulting	≥15	≥10	BConst, PhD, NZIQS Registered QS
	C2-A1	Architect - Lead	Architecture & Design	≥10	≥10	BArch, March, RIBA Registered Architect, GSAPs
	C2-SC1	Sustainability Manager	Engineering & Consulting	≥20	≥20	BBSc, CEng, MCIBSE, GSAPs, NZGBC Accredited Energy Modeller
	C2-E1	Principal Engineer	Engineering & Consulting	≥20	≥20	BEng, CMEngNZ, CIBSE Member
Case 3	C3-CR1	Client Representative - Lead	Tertiary education	≥30	≥20	BSc, DipBldgCons(RICS), MBA, CBS, FRICS
	C3-CR2	Client Representative - Building Services Engineer	Tertiary education	≥10	≥10	BEng, MSc, MIPENZ, CPEng, MCIBSE, MIET, IntPE(NZ)
	C3-E1	Technical Director - Lead	Engineering & Consulting	≥20	≥15	BEng, MEng, CPEng
	C3-E2	Building Services Engineer	Engineering & Consulting	≥10	≥10	BEng, CMEngNZ
	C3-SC1	Sustainable Buildings Specialist	Engineering & Consulting	≥15	≥15	BEng, CEng, CMEngNZ, GSAPs, WELL AP, MCIBSE, LEED AP BD + C
	C3-PM1	Project Manager	Project Management	≥15	≥10	BAS, BArch, NZRAB Registered Architect, NZIA Member, Prince2 Practioner
	C3-A1	Principal Architect	Architecture & Design	≥25	≥15	BArch, NZRAB Registered Architect, NZIA Member
	C3-QS1	Quantity Surveyor	Cost Management	≥15	≥15	BConst, NZIQS Registered QS
	C3-CT1	Construction Project Manager	Main Contractor	≥20	≥10	BEng, MSc

database were created to improve the reliability. A case study protocol consisted of the overview of the case study, data collection procedures, research objectives and questions, and a tentative outline for the case study report. The case study database represented all sources of evidence using the computer-aid qualitative data analysis software NVivo12, word-processing tools (e.g. Word and Excel files), and cloud storage.

4. Empirical findings

4.1. Building condition assessment

4.1.1. Initial building condition assessment

In all cases, the client representatives conducted an initial building condition assessment to support the development of the business case. In case 1, the client team undertook systematic registration of the degradation state of the building components and services. A walk-through assessment addressing the physical condition was performed during a site visit, including evaluating building structure, building services (e.g. fire, lighting, HVAC, and hydraulic systems) and building envelope (e.g. leaky building inspection, thermal performance, etc.). Table 3 shows an example of an initial walk-in HVAC system assessment in case 1. The results indicated that the existing building had a suitable concrete structure with seismic strengthening, however most building services needed replacing as they were at the end of their lifespan, and the thermal envelope required upgrading. Similar to case 1, the initial building assessment in cases 2 and 3 revealed poor conditions and operational problems. Particularly in case 2, the seismic building report called for urgent earthquake strengthening work to meet the Building Code requirements. A pre-refurbishment survey was also carried out to better understand the current users' activities and expectations.

4.1.2. In-depth building condition assessment

After the initial building condition assessment, the consultant team (i.e. engineers, architects, sustainability and carbon consultants) in cases 2 and 3 were involved to assess the building performance and identify potential reuse of the existing building. For instance, in case 2, "*a key aspect of this project was moving from fossil fuelled heating to an electric supplied system, while staying within the limitations of the existing electrical supply infrastructure. High level estimates were carried out during early stages to evaluate what system options would be capable of staying within the existing capacities*", explained C2-E1. Although there was no specific energy audit done at this stage, the project team undertook several energy reviews for heating, lighting, and electricity usage. In case 3, the consultant team conducted a façade assessment study, confirming that the facades were thermally poor and weighty, causing seismic issues. Though the structural test proved that the structure could be reused despite several limitations, the building services were beyond the life expectancy. The high cost of ongoing maintenance, the replacement of services, and energy bills was expected if the refurbishment focused on upgrading the façade only. The inefficient building operation also led to higher energy use and operational carbon emissions. This is an important finding demonstrating the practical building condition assessment.

A major refurbishment level was chosen for all cases, which was necessary to achieve radical improvements in energy efficiency and operational carbon reduction. Notably, case 3 was intended to be partially refurbished following initial building condition assessment. The scope of work was to extend the building lifetime to around 15 years, then demolish and build a new building. However, the results of further building assessment mentioned above called for implementing the major refurbishment, which benefited both carbon and cost aspects in the long term. This empirical finding emphasises the importance of the consultant team participating in producing a comprehensive building condition assessment, which is a basis for selecting appropriate refurbishment levels and strategies as well as generating refurbishment solutions later in the process.

4.2. Goal setting

All cases had an overall refurbishment goal to achieve a better learning and working environment for learners, researchers, and staff, aligned with the organisations' sustainability and net-zero carbon strategies. Table 4 demonstrates each case study's specific carbon goals.

It was observed that building rating systems were suggested to be applied from the beginning stage. According to the client team in case 3, the Green Star rating system offered a structured way to incorporate sustainability criteria into the design process. Similarly, the refurbishment solutions in case 2 followed the specific operational carbon performance targets in carboNZero Building Operations certification. Using

Table 4
Specific carbon goals of case studies.

	Case 1	Case 2	Case 3
Building rating systems	In-house green building standards	carboNZero Building Operations certification – a specific carbon performance tool	Green Star – a holistic sustainability certification
Energy performance target	Energy Intensity Design and Performance Target after opening – 80 kWh/sqm/year (based on the client's experience with the annual energy consumption of other similar buildings within the portfolio)	As per carboNZero Building Operations certification	Targeted 6-star Green Star
Operational carbon reduction target	Based on energy performance target	As per carboNZero Building Operations certification	Targeted 6-star Green Star
Embodied carbon reduction target	No specific target Qualitative-based approach such as reusing existing materials, using low carbon materials, and minimising new added-in materials and demolition waste	No specific target	Targeted 6-star Green Star

Table 3
Example of an initial walk-in HVAC system assessment in case 1.

Areas	HVAC system				
	Ducted Preconditioned Outside Air	Ducted Return Air	Toilets AC and Exhaust	AC in Offices Teaching Spaces and Corridors	Full BMS Control
C1-Level 1	Y	Y	Y	Y	Y
C1-Level 2	Y	Y	Y	Y	Y
C1-Level 3	Y	Y	N	Y	Y
C1-Level 4	Y	Y	N	Y	Y

Note: Y: Yes – items to be replaced; N: No change.

rating systems also helped prioritise the main improvement of refurbished buildings, such as energy, carbon emissions, water, etc. A critical lesson learnt in case 1 was that using the Green Star rating system might embrace low-carbon design features when experiencing unforeseen construction delays such as the COVID-19 situation. "*We should have had a Green Star rating on it, then some of these sustainable things would be non-touchable because people wouldn't want to lose the points*", C1-CR1 admitted.

However, several limitations were found in the application of these rating systems in the current practice. Regarding Green Star, cases 1 and 2 took this certification into account but decided not to adopt it due to its high cost, precise requirements and inflexibility in selecting design options. "*Sometimes, to get the points, it causes you to go down a road that doesn't make sense for your building … instead of spending that X$ on consultants and all the work you have to do to get a Green Star rating, we'd rather spend it on physically making the building better*", C1-CR1 declared. As mentioned in case 2's design brief, there could be a tendency with the Green Star tool to put a capital cost value on points and target points based on their cost rather than the value that criteria offered. C3-PM1 echoed challenges when executing Green Star in case 3, explaining that some of the credits, such as waste management, were based on Australian standards and not applicable in New Zealand's context. Another limitation was that this assessment method provided no detail about embodied carbon reduction targets and calculation.

In terms of carboNZero Building Operations certification, the scope of work considered only operational carbon emissions. "*Some clients and designers think going for a project that's carboNZero certified means that they are delivering a building that uses no carbon. But that still uses loads of the embodied carbon, which is, sometimes, a larger portion than the operational carbon*", C2-A1 stated. The tool was going through the launching process and not officially ready for use at the time of the project. There was also an unclear requirement of undertaking LCA to calculate whole-of-life carbon emissions of the refurbishment. This challenged the consultant team in targeting and quantifying the life cycle carbon performance.

In summary, the application of these rating systems in the current practice is limited to setting embodied carbon reduction targets and providing detailed calculation method. Table 5 describes the lifecycle carbon targets considered in the current version of building rating systems applied to cases 2 and 3.

Table 5
A comparison of lifecycle carbon targets in building rating systems applied for cases 2 and 3.

	Green Star	carboNZero Building Operations certification
Operational carbon emissions	Awarded up to 20 points where operational carbon emissions figures were significantly lower than a standard building Awarded 10 points if predicted operational GHG emissions reductions were >100% in comparison to the reference model (standard building) for education projects	Targeting 4 Star NABERSNZ rating or higher for all office buildings OR 8 out of 20 points (base building) or 9 out of 23 points (whole building) in the 'Greenhouse Gas Emissions' Credit of Green Star Performance Demonstrating a carbon reduction plan for the building to phase out fossil fuel consumption on site by 2025 Offsetting the remaining operational carbon by purchasing carbon credits
Embodied carbon emissions	Awarded embodied carbon credits for the use of materials that were responsible sourced, transparency and lower embodied impact over their life No detail about embodied carbon reduction targets and calculation	No specific target

Due to the limitations of mentioned building rating systems, setting an embodied carbon budget as a necessary project deliverable was suggested by the participants in cases 2 and 3, though faced complications due to the lack of compulsory national targets and diversity of the building stock. From experience in case 2, C2-QS2 said, "*defining what reasonable targets should be … the target or a budget, how much carbon can we use on this project*?". The lack of compulsory carbon reduction targets in New Zealand led the consultant team to refer to various standards on embodied carbon reduction overseas to compare against the actual carbon performance in case 3. However, critics questioned the feasibility of setting an equal allocation of carbon reduction for the existing building stock. "*If you divided the target on square meters, you'd find that some buildings work and others don't. Some buildings can be delivered more than others. We should not try to be too prescriptive about any individual building but take a holistic view of the whole portfolio*", C3-CR1 argued. Importantly, the carbon budget for the refurbishment should be different from the figure for new buildings. As C2-SC1 believed, "*if lifecycle carbon is X kilograms per square meter. You're refurbishing a building, and it's easier to hit those targets than building a new building … But you can still do a refurbishment in a high carbon way. You could do heaps of shading and fins, and there's a lot of aluminum*".

Interestingly, the consultant team in case 3 suggested that there should be a specific financial budget for carbon-reduction solutions established in the goal setting to avoid unexpected costs and limiting the consideration of lower carbon options later in the process. "*We need to find a budget for carbon and sustainability.*" The budget should include the additional cost of reviewing carbon-reduction initiatives, energy modelling, life cycle assessment, and possible investment costs for low-carbon materials, products, and green technologies. Although these approaches supported making informed decisions on reducing carbon emissions, clients still faced challenges around their willingness to spend additional money on these services. "*They have values, but sometimes it is hard to demonstrate them to clients*", said C3-E2.

4.3. Refurbishment strategies

Identifying refurbishment strategies was crucial as it set out the plan of action to achieve an overall long-term aim of refurbishment projects. The refurbishment strategies that were considered in case studies are illustrated in Table 6 and Fig. 3.

The field study suggested a significant finding that passive design strategies were chosen as a primary refurbishment solution over system efficiencies and renewable energy generation. It was stated that the preference for passive design solutions resulted in the efficient use of building services systems, fewer construction materials, and cost savings. However, the consultant team in case 1 expressed challenges and

Table 6
Refurbishment strategies considered in case studies.

Case 1	Case 2	Case 3
Refurbishment proposals as follows: (1) Passive Design (2) System efficiencies (3) Environmentally friendly local-preferred materials and equipment (4) Reuse existing construction materials (5) Efficient waste management (6) Renewable energy generation	A top-down refurbishment strategy includes (see Fig. 3): (1) Extent of building (2) Passive and embodied design (3) System efficiencies (4) Renewable energy generation	A carbon reduction strategy includes: (1) Incorporate industry-leading "passive house" design principles (2) Adopt an "ultra-low energy" mechanical ventilation system (3) Use low-carbon and locally sourced materials (4) Reuse the existing structures (5) Minimise waste (6) Use renewable energy technologies

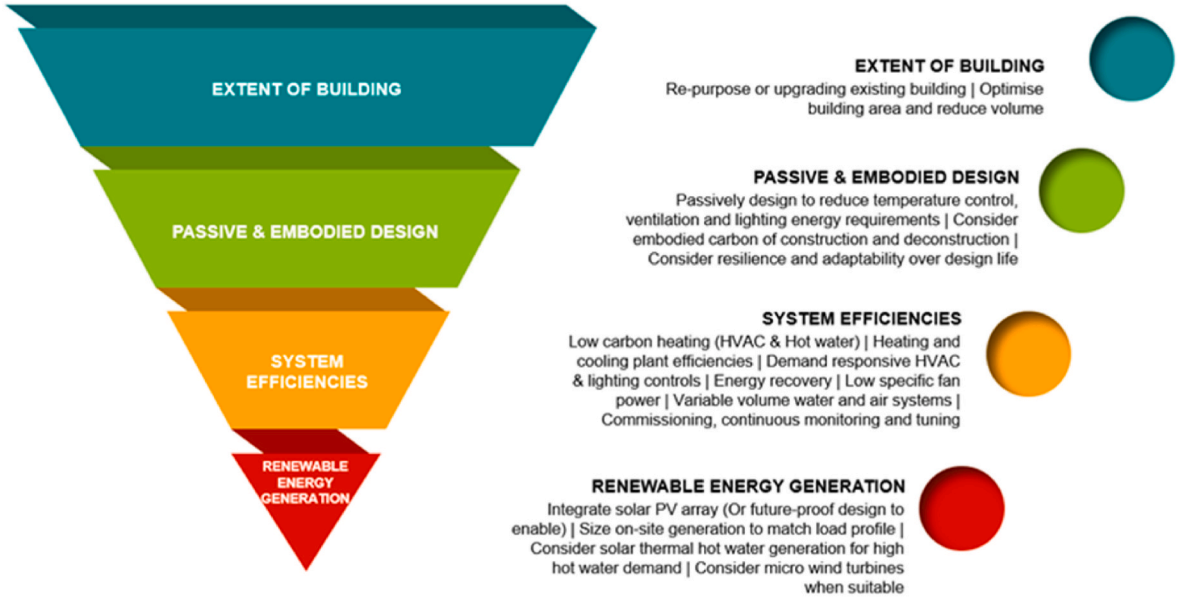


Fig. 3. Hierarchy of low carbon building design approach in case 2.

difficulties when prioritising passive design. It was thought that upgrading the insulation system using phase change materials to a higher standard might be unnecessary as it was not beneficial to the performance and were a cost premium. "*For elements like that, if you took half $X of phase change materials out and put in half $X of photovoltaic generation. Your overall carbon footprints can be significantly reduced*", said C1-E1. Fig. 4 illustrates examples of refurbishment strategies in case 2.

Renewable energy technology such as PV systems was selected in case 1 and case 3 as a long-term strategy for optimum energy production towards a net-zero carbon future. A large solar array was a part of the refurbished building, expected to deliver about 10% of the overall electricity usage in case 3. In contrast, an off-site PV system was not implemented during the refurbishment due to the budget constraint in case 1. Yet, the off-site infrastructure was prepared for future installation. However, the perception of "must-have" renewable technologies as a showcase of zero carbon initiatives was perceived in these cases. The consultant team acknowledged that a PV system was included to improve energy generation and public perception, notwithstanding the performance analysis showing the high carbon and cost payback period in the New Zealand context, where the electricity grid is relatively green. "*It seems that unless you stick solar panels on the roof, people can look and say: that's pretty cool, and you must be sustainable now*", C3-E1 claimed. Both wind turbine and PV system were considered in case 3's design brief. The consultant team convinced the client not to install the wind turbine based on the performance analysis and lessons learnt from case studies in other countries such as the UK. However, the PV system was still enforced to showcase sustainable design elements.

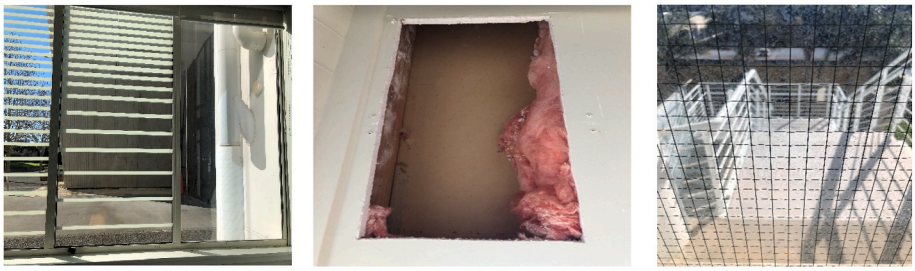
In all cases, strategies to reduce embodied carbon emissions from construction materials and products were employed. For example, existing building components and materials were recycled and reused. In particular, materials with high embodied carbon such as steel and aluminium were obtained locally in cases 1 and 3, as New Zealand was expected to produce approximately 80–90% of its electrical supply from renewables. Conversely, construction materials and products used in case 2 were primarily sourced from countries outside of New Zealand, such as China, Europe, and America.

4.4. Generation of refurbishment alternatives

4.4.1. Initial production of refurbishment alternatives

For case 1, the consultant team appraise the refurbishment strategies and alternatives identified in the client's high-level brief, which was established based on the results of building condition assessment. The brief encompassed refurbishment strategies and a comprehensive list of potential refurbishment options that required the consultant team's acceptance. A narrow range of possibilities had to be generated from the brief, limiting the consultant team to the creative and innovative design.

Cases 2 and 3 differed from case 1 in developing refurbishment alternatives. The refurbishment alternatives lay with the consultant team and were aligned with the client's objectives and requirements. In case 2, the consultant team supported the client consider potential refurbishment alternatives. An expansive list of Environmental Sustainability Design (ESD) opportunities was classified following the results of building condition assessment and refurbishment strategies. Each opportunity was identified as either a "must-have" or "nice-to-have" item and evaluated subject to value-added project cost and the alignment



a) Passive design (windows) b) Passive design (wall insulation) c) Reuse (reused stair)

Fig. 4. Examples of refurbishment strategies in case 2.

with the requirements of relevant building rating systems. This approach has not been widely recognised in the literature. Likewise, the consultant team in case 3 also identified various design opportunities such as energy-efficient façade and different types of building services, following the client's sustainability objectives.

4.4.2. Qualitative assessment of refurbishment alternatives

After the initial evaluation, a qualitative approach was used to narrow down the refurbishment options in all cases. With respect to carbon reduction, the consultant team in all cases assessed design implications using experience, heuristics, qualitative estimation of carbon performance, consulting and partnering with other project team members such as client representatives and cost advisors. The engineers conducted the qualitative measure of building design performance while the architects considered the architectural design aspects. In all cases, a narrowing set of refurbishment solutions and scenarios was selected by the end of this stage.

There were important recommendations for future work observed in cases 1 and 3. A lesson learnt from case 1 was that an initial carbon analysis could be performed at this early stage using LCA tools, which provide generic carbon impacts of different building elements, to recognise carbon-intensive elements and their trade-offs between operational and embodied carbon emissions. Replacing the glazing was an example. As explained by C1-A1, using the double-glazed façade increased embodied carbon emissions while there was little payback in terms of thermal comfort and operational carbon performance in some typical building locations. From experience on case 3, the consultant team suggested that an initial carbon analysis should be performed early to identify refurbishment alternatives, which they then discussed with project partners before selecting the key options carried through the design process. External carbon specialists were contracted to provide independent peer reviews on the embodied carbon impacts of potential design opportunities. "*We did have some discussions early on in the project because obviously, you don't need a comprehensive LCA to quantify the embodied or operational carbon that is essentially going to be spent on a construction project*", said C3-SC1.

4.5. Performance estimation and evaluation

After qualitative assessment of refurbishment alternatives, the carbon performance of the narrowing set of refurbishment solutions and scenarios were quantitatively estimated and evaluated by undertaking energy performance assessment, life cycle carbon assessment, cost benefit analysis as well as adopting an early contractor involvement approach. Table 7 demonstrates a comparison in the use of assessment methods and approaches in case studies.

4.5.1. Energy performance assessment

Energy simulation was conducted to assess building performance and operational carbon impacts. The engineers, in all cases, conducted a quantitative analysis using building energy modelling to evaluate refurbishment solutions and scenarios regarding their energy and operational carbon performance. In addition, thermal comfort analysis and daylighting analysis were also performed to quantify the refurbishment solutions' comfort and well-being benefits. Energy consumption was calculated using thermal load and energy modelling software, IES Virtual Environment, to produce an optimal design. Based on the energy model, annual operational carbon emissions were calculated using the following emissions factors according to the Ministry for the Environment "Measuring emissions: A guide for organisations – 2019 detailed guide". Taking case 2 as another example, five refurbishment scenarios were modelled based on the set of refurbishment options – these options were divided into two general categories: façade and HVAC system upgrades. The comparison of annual operational carbon emissions between scenarios is illustrated in Fig. 5.

Table 7
A comparison in the use of assessment methods and approaches in case studies.

	Energy performance assessment	Life cycle carbon assessment	Early contractor involvement (ECI) approach	Cost benefit analysis
Case 1	Use building energy modelling tool to evaluate the operational energy and carbon of refurbishment solutions and scenarios	Use LCA tool to quantify the life cycle carbon emissions of the whole refurbished building at the end of the design phase as a retrospective analysis to extrapolate learning for future work	Use ECI approach to evaluate the quality and buildability of low-carbon design and technologies. Mitigate construction waste that went to landfill. Identify the potential for construction materials reuse and recycling	Use cost benefit analysis to identity the most cost-effective refurbishment alternatives
Case 2	Same as case 1	Not applicable	Not applicable	Same as case 1
Case 3	Same as case 1	Use LCA tool to quantify the life cycle carbon emissions of selected refurbishment alternatives to further improve the design in detail	As same as case 1 Support the selection of construction products and materials (e.g. providing embodied carbon emissions information)	Same as case 1

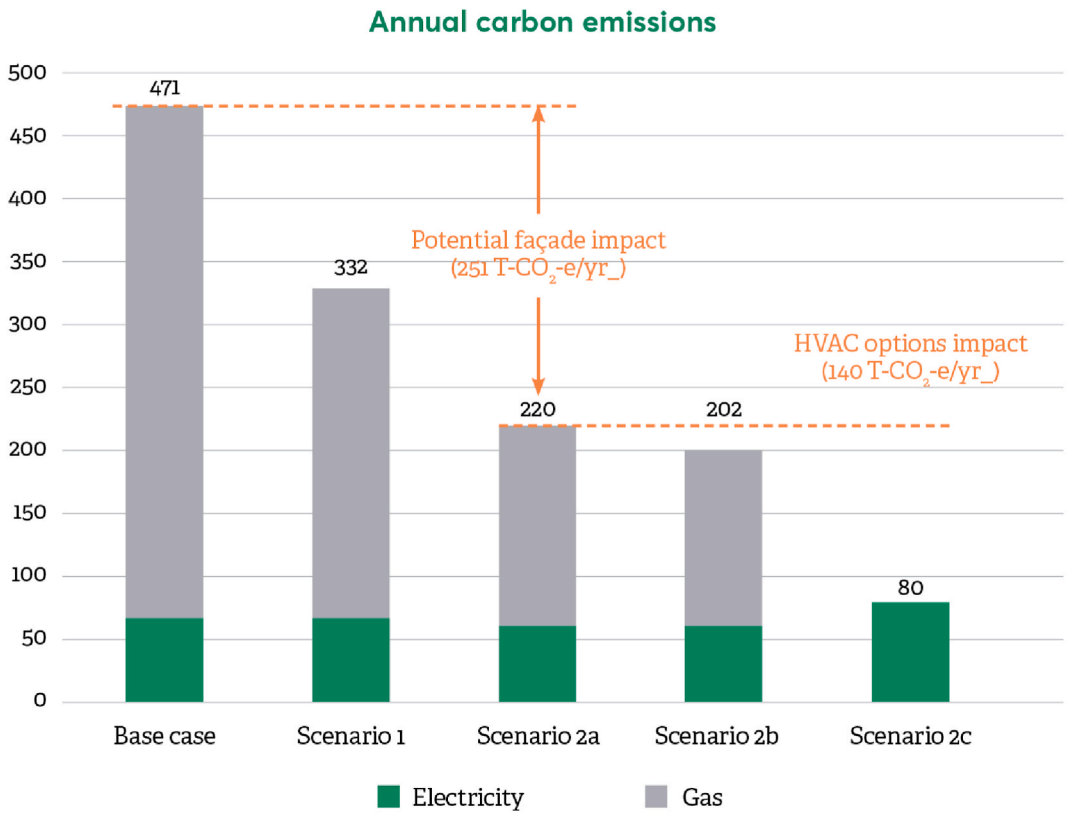
4.5.2. Cost benefit analysis

The cost benefits of several refurbishment options were also compared in all cases, considering several indicators such as capital cost, annual savings, payback period, Net Present Value (NPV), and Internal Rate of Return (IRR). In particular, the LCC of building services was reviewed to determine the most cost-effective options. For example, C3-SC1 explained the case 3 situation, "*We ran design options out on a 30-year whole-of-life cost model. We looked at the upfront capital costs and the various replacement costs during the life of this equipment. The central plant, for example, might only last 15 to 20 years before it needs to be replaced. Those costs were tabulated into a net present value (NPV) for each system. That was then used to identify the least costly option from a whole of life perspective*".

4.5.3. Life cycle carbon assessment

A comprehensive LCA using eTool was adopted in cases 1 and 3 to assess the carbon performance from a cradle-to-cradle perspective. eTool is one of the LCA tools for building and infrastructure projects. The original tool was launched in 2012. eTool LCI processes are from the following sources: Australasian and other regional Life Cycle Inventory (LCI) data such as North America, Europe, UK, New Zealand and Global, IMPACT EN15804 data, and cost factors from industry quotes cross referenced against construction cost handbooks. Its reports are compliant with international standards such as EN 15978 and ISO 14044.

In case 1, the architects commissioned an external carbon specialist to quantify the life cycle carbon emissions of the refurbished building at the end of the design phase. However, the results did not contribute to the design improvement because this was a retrospective analysis to extrapolate learning for future work. While in case 3, the consultant



Scenario	Description
Basecase	**Existing library** – Existing façade, naturally ventilated primeter spaces, conditioned interior, existing boiler and chiller. High infiltration.
1	**Fully air conditioned** – full air conditioning, gas boiler, existing envelope, sealed windows, HRV
2a	**Upgraded façade** – upgraded envelope, mixed mode ventilation, existing boiler, HRV
2b	**Upgraded façade** – upgraded envelope, mixed mode ventilation, new condensing boiler, HRV
2c	**Upgraded façade** – upgraded envelope, mixed mode ventilation, new heatpump HVAC, HRV

Fig. 5. Annual operational carbon emissions of case 2.

team conducted LCA to estimate the carbon impacts of selected refurbishment alternatives, which were then reviewed and certified by the external carbon specialist. *"We used the LCA to validate our approach in the later design stage rather than identify different variations and options that we knew from a qualitative perspective was the right thing to do. This was providing that quantitative analysis to* support *that"*, C3-SC1 argued. The result from LCA was a baseline to improve the design in detail, such as comparing operational carbon emissions of different building services and considering embodied carbon emissions of construction materials and products through New Zealand's specific Environmental Product Declarations (EPD) database and some benchmarks based on relevant research provided by the Building Research Association of New Zealand (BRANZ). This original finding emphasises the necessity of using LCA tools in the early stages of the decision-making process to identify carbon hotspots and improvement opportunities.

4.5.4. Early contractor involvement (ECI)

The early contractor involvement (ECI) approach was employed in the design phase to evaluate selected refurbishment options in both case 1 and case 3. It was used to gain early advice and participation from subcontractors and suppliers in the buildability and optimisation of designs. In case 1, the subcontractors produced four trial windows with various double-glazed specifications to examine the quality and buildability. This activity helped ensure the feasibility of refurbishment solutions from a supply chain perspectiveas low-carbon design and technologies were innovative in New Zealand's construction supply chain. In case 3, the suppliers supported selecting construction products and materials by providing embodied carbon emissions information. The ECI approach also assisted in mitigating construction waste that went to landfill and identifying the potential for construction material reuse and recycling.

As the design continued to be improved, evaluation of refurbishment alternatives was carried out continuously and iteratively throughout the design process. Particularly for cases 2 and 3, selected refurbishment alternatives were assessed based on the design requirements of building rating systems. Energy performance assessment, life cycle carbon assessment, and other analyses such as thermal comfort and daylighting were constantly reviewed and demonstrated in design reports at the end of each design stage. It was important to note that embedding sustainability and carbon impacts with the design reports could drive the design decision and overcome the financial tensions of selecting low-carbon design characteristics. *"Our design reports, especially in the early phases, we're making a comparison of options. We will comment and indicate what's sustainable and the impact on sustainability from the operation and, in some*

cases, embodied carbon. It's a holistic approach to avoid criticism when people think that's not a value management item and delete to save some money", claimed C1-E1.

4.6. Other factors affecting decarbonisation decision-making

4.6.1. Funding and incentives

Another important finding was that all cases received the government's financial support, encouraging the decarbonisation decisions. Both cases 1 and 2 sought government incentives to facilitate the implementation of the low-carbon design. The projects received finance assistance from EECA's state sector decarbonisation fund to reduce carbon emissions. The government investment helped replace natural gas boilers and chillers for space heating and cooling with low emission alternatives and install efficient lighting in case 1. Whereas the grant empowered case 2 to adopt a high-performing façade as part of the refurbishment solutions, contributing to further operational carbon reduction. "*We've received a* grant *of $2 million that enables us to bridge the gap between the different things that would achieve a net-zero carbon*", said C2-CR1. An energy efficiency report, including energy modelling and performance analysis, was produced to justify carbon-reduction decisions.

On the other hand, case 3 secured the "shovel-ready" government funding to stimulate the construction and environmental industries and economy, public or regional benefit, and create jobs in response to COVID-19. The large-sized refurbishment provided an essential boost for the local building and construction sector through a locally based and sourced construction supply chain. The fund permitted the project to incorporate industry-leading practices and carbon-reduction refurbishment options.

4.6.2. Supply chain and data availability

Supply chain availability was acknowledged in the research findings as a tension that inhibited the decision on low-carbon designs and technologies, as mentioned in case 3. There were few alternatives to low-carbon products within New Zealand's construction supply chain, such as curtain walling and PV systems. The traditional façade manufactured in New Zealand was carbon-intensive aluminium and glass compared to state-of-the-art CLT panels produced overseas. According to C3-QS1, only two different PV systems were available in New Zealand, also sourced from other countries. With New Zealand's electricity grid being green, installing these PV systems in New Zealand might lead to a much longer carbon payback than in Australia.

Concerns were also expressed about the carbon data availability for the New Zealand building and construction sector, especially data related to construction products and materials. While some of New Zealand's construction manufacturers have provided EPD's products such as cement and insulation, many gaps existed in other areas. Furthermore, as part of the LCA analysis, C3-SC1 claimed an inadequate benchmark for large commercial buildings. *"We had to build a reference building to compare ourselves against, and part of that process was coming up with a counterfactual"*. Many assumptions were made during the LCA process, which affected the carbon calculated and quantified results.

5. Discussion

This paper examines the practical early-stage refurbishment process that incorporates decisions on maximising carbon reduction. This process is considered to be a way of developing and implementing building refurbishment towards zero carbon. We investigated *what*, *how* and *why* carbon-related decisions are made in three case studies. In doing so, we acknowledge that the refurbishment decision process in the practical context is in line with theoretical frameworks. However, the empirical analysis uncovers unexpected outcomes, tensions and lessons learnt that emerge in the three processes studied. This section discusses these aspects based on the literature and a cross-case analysis among three case studies.

The first important finding is in line with the previous studies [8,11], confirming that building rating systems can be used early as a structured methodology to incorporate carbon performance criteria into the refurbishment process. These rating systems support the decision-making process by providing direction for setting goals, prioritising objectives and specific areas of improvement, and their potential design implications. The decision to use these rating systems in the early stage rather than assessing the finished building encourages the project team to incorporate the carbon-reduction design consideration throughout the process. However, our findings emphasise that using these rating systems might create inflexibility in the selection of refurbishment design solutions. These systems are also time-consuming to include in the early stages of the refurbishment process and are limited to recognising project values (e.g. cost benefits, co-benefits for users). Thus, there should be a more effective way to apply these rating systems in building refurbishment. The study suggests that the refurbishment solutions' actual critical benefits should be identified separately to align with the project's specific targets. These benefits can then be considered alongside the design requirements of rating systems, rather than using these rating systems as a framework to inform refurbishment design approaches.

The study also identifies another limitation of applying building rating systems to determine the carbon reduction goal for building refurbishment in practice. Most of the rating systems fail to prioritise whole-of-life carbon reduction targets and the current assessment approach to whole-of-life carbon reduction is mainly qualitative (e.g. using low-carbon materials). This finding highlights a need for setting whole-of-life carbon reduction goals, especially specific embodied carbon reduction targets and calculation methods for the refurbishment of existing buildings. The observation is in line with our earlier findings in the literature review [14] and other authors [7,49], which call for the use of scientific climate change targets and a carbon budget to define the life cycle carbon performance goal. Although there are carbon budgets for new buildings, our study suggests that a bespoke carbon budget for existing buildings is needed. This is due to the scope of LCA assessment of refurbished buildings differing from that of new buildings [6,29]. Furthermore, using the carbon budget for new buildings [7] as a reference may encourage refurbishing existing buildings in a high carbon way. For example, a major refurbishment considers retaining the existing building structure, resulting in a large amount of carbon savings. But it still uses carbon-intensive construction materials such as steel, aluminum, phase change materials, refrigerants, and carpets, etc. for other building components such as windows, façades, services and equipment, and internal finishes. Although the total carbon emissions of a refurbished building may be lower than that of a new building and within the carbon budget of a new building, it may prevent the practice of identifying lower carbon refurbishment options in each building element category to achieve overall maximum carbon reduction. Moreover, it is important to note that the carbon budget should be allocated based on the potential carbon reduction of each refurbished building as well as the level of refurbishment ranging from partial to major refurbishment. A carbon budget should be allocated for an existing building portfolio instead of individual existing buildings. From there, building owners could evaluate and establish feasible targets for every single building. These observations have not been adequately recognised in literature. In addition to the carbon budget, the findings suggest a specific financial budget as an allowance for carbon-reduction refurbishment solutions to avoid unexpected costs in reviewing carbon-reduction initiatives, energy modelling, LCA, and upfront investment costs for low-carbon construction materials and products, and green technologies, subsequently limiting the consideration of lower-carbon options later in the process. However, it could create potential bias, especially from the client's perspectives, decarbonisation solutions are associated with higher cost, leading to the reluctancy in making decarbonisation decisions.

Another significant issue that emerges from empirical findings is using a reference building as a benchmark to assess the life cycle carbon performance of refurbished buildings. The choice of a reference building determines, to some extent, the life cycle carbon performance of the selected building design. For example, building is x% better than the reference building, which is usually a standard building that meets the minimum requirements of the Building Code in New Zealand. For refurbished buildings, it may not be comparable to benchmark against a new standard building. Therefore, the real test should be how the refurbished building performs against its carbon budget or the aim to achieve near or zero carbon emissions. For example, Asdrubali et al. [50] compared the carbon performance of an optimal refurbishment against two refurbishments for achieving the NZEB standard. This approach can support the project team to conduct a comparative life cycle carbon reduction analysis for the optimisation of the building refurbishment design.

There are similarities between the empirical findings of building condition assessment in this study and those described in the literature. In a building refurbishment, building condition assessment is often used to benchmark building energy use, recognise the degradation state of building components and services, identify system operational problems, and find appropriate refurbishment solutions [9,11]. At this stage, a pre-refurbishment survey is also recommended to better understand the current users' activities and expectations [8]. However, the results of the present study underline a requirement for an in-depth building condition assessment to help: (1) establish the refurbishment level (e.g. partial or major refurbishment); (2) acknowledge life cycle carbon and cost benefits; and (3) set out appropriate long-term refurbishment strategies (e.g. site preparation for future installation of renewable technologies). In terms of refurbishment strategies, the findings somewhat support the idea of a hierarchical approach towards zero-carbon refurbishment, which prioritises refurbishment strategies in the following order: (1) retrofit fabrics, (2) more efficient equipment, (3) micro generation [20]. Nevertheless, we propose that there needs to be a flexible approach to implementing passive design, efficient building services and renewable technologies that are appropriate to the physical condition of the existing building and project budget. Performance assessment and feasibility studies are required to understand trade-offs and the advantages and disadvantages of renewable technologies before making a decision that prioritises overcoming public perception. Other important strategies found in this study include prioritising local materials, using low-carbon materials, maximising reused and recycled materials of existing buildings, which should be considered to reduce embodied carbon emissions.

Many decision support systems are available in the literature for the generation of refurbishment alternatives, performance estimation and multi-objective optimisation in the design phase [18,51,52]. However, these do not appear to be used in real-life case studies. A possible explanation is that the existing decision support systems might not be commonly employed in the construction market. Using complex simulations and generic algorithms to support the decision-makers in selecting the best refurbishment solutions could sideline the strength of real-world experience-based knowledge and team collaboration in the process. Incorporating the existing knowledge and industry practices, the findings from this study suggest a better approach to the generation of refurbishment alternatives and performance estimation and evaluation. First, a wide range of potential refurbishment options should be considered following project goals, objectives, and client requirements in the generation of refurbishment alternatives. The intention is to include all possible refurbishment options in the decision-making at each stage of the design and encourage creativity and innovation in choosing refurbishment options. Then, refurbishment options can be selected using experience, heuristics, lessons learnt from global case studies, qualitative estimation of carbon performance, and consulting or partnering with other project team members [53]. In New Zealand, several simple LCA tools (e.g. LCAPlay), complex LCA tools (e.g. LCAquick, eTool) and carbon database tools (e.g. CO_2NSTRUCT) which provide generic carbon impacts of different building elements, are suggested to be used for initial life cycle carbon assessment. After that, methods including comprehensive computer-aided energy simulations, LCA and financial analysis are used to quantitatively examine carbon performance and continually improve the design. A carbon payback analysis to identify trade-off carbon benefits between embodied and operational carbon emissions should also be considered, which is in line with Asdrubali et al. [50]'s recommendation.

The present results are significant in offering new perspectives on supporting building refurbishment towards zero carbon. Holistic design reports that show the decision on carbon reduction solutions aligned with project values should be presented to overcome the financial restrictions. The ECI approach allows the project team to understand the requirements of implementing innovative low-carbon designs and technologies, and gain insight into embodied carbon emissions of construction materials and products early. Government funding and incentives are essential, enabling the maximum carbon reduction for refurbishment projects. The grant assists the building client to achieve the required operational carbon performance targets by implementing cost-effective refurbishment measures and reducing the financial payback period. Contrary to expectations, there is still abundant room for further progress in improving the supply chain and data availability that affect the selection of low-carbon products and the carbon calculated and quantified results.

The study reports on the decision-making process of three major building refurbishments where the decision to refurbish existing buildings has apparently been taken by the time the more detailed work is done. This can be explained by the fact that the decision to refurbish versus demolish and build a new building was preferred due to several factors such as building vacancy, refurbishment prospects, time and cost savings and carbon reduction benefits. Demolishing and rebuilding could be time-consuming and expensive due to building locations and the limited timeframe of occupant relocations. Repurposing the useable existing building components, on the other hand, might reduce the length of construction by years, saving significant construction costs and minimising construction materials and construction waste. However, in practice it may be dependent on the specific project and such decisions would be considered at very different stages. Sometimes, the decision is made without an in-depth analysis due to strongly held pre-assumptions about project outcomes or preferences. In other cases, the decision is determined by thorough consideration of the evidence for and against. It is suggested that an opportunity for further work assessing the decision to refurbish or demolish should be undertaken and the impact of the decision should be critically evaluated. Decisions made without in-depth analysis may not necessarily be the most appropriate ones in terms of sustainability [54].

6. Conclusion

This study examines decision making in reducing carbon emissions in the early stage of refurbishment. The investigation has identified carbon-reduction decisions and critical factors supporting these decisions in the refurbishment process of three case studies. First, the field data revealed that using building rating systems is inflexible in the selection of refurbishment design solutions, time-consuming to include in the early stages of the refurbishment process and limited to recognising project values (e.g. cost benefits, co-benefits for users). Therefore, the study proposes an effective use of building rating systems, which should integrate carbon performance criteria, the client's requirements, and stakeholder's values to recognise the actual benefits of refurbishment solutions. Second, the findings report on the lack of determining the carbon reduction goal for building refurbishment in practice. These targets are required to be established for whole-of-life carbon assessment, benchmarking, and the optimisation of the refurbishment design. Thus, the study suggests that setting whole-of-life carbon reduction

targets for refurbished buildings is imperative. Third, the findings highlight the implication of the specific financial budget for carbon-reduction initiatives, which encourages the consideration of lower-carbon refurbishment options. However, further investigation is required to identify the extent that this specific financial budget for carbon-reduction initiatives could potentially stimulate decarbonisation decisions from different perspectives. Fourth, the empirical findings have shown several limitations in practical building condition assessment. The need for implementing flexible, appropriate, and long-term refurbishment designs and strategies that are appropriate to the physical condition of an existing building and project budget is therefore emphasised. Fifth, incorporating the findings from existing knowledge and industry practices, the study suggests a better approach to the generation of refurbishment alternatives and performance estimation and evaluation with a new insight into the use of decision support mechanisms in the refurbishment process, which strengthens the idea that real-case experience-based knowledge and team collaboration should be considered. Finally, the results highlight the significance of several aspects in delivering refurbishment projects towards zero carbon, including holistic design reports, ECI approach, government funding and incentives, and supply chain and data availability. These aspects are significant in better delivering building refurbishment towards zero carbon.

This work contributes to existing knowledge of the decision-making process of building refurbishment towards zero carbon by investigating three refurbishment projects in practice that adopt similar and different approaches to reducing carbon emissions. The novelty of this research is providing the practical knowledge of the decision-making process with existing challenges in making decarbonisation decisions and adopting decision support mechanisms, and suggestions for improvement that expand the theoretical knowledge and bridge the gap between theory and practice. The findings will be of interest to practitioners and researchers who wish to expand their knowledge and experience in life cycle carbon assessment and performance estimation for refurbishment projects. The decision-making process revealed in this study can be a benchmark for comparable projects and studies. In exploring the current decision-making practices, the findings of this study have several important lessons to better deliver building refurbishment towards zero carbon for future practice.

The generalisability of these results is subject to certain limitations. The most important limitation lies in the fact that the paper is reliant on interviews and the views of participants provide the foundation of the conclusions. Such interviews can be misleading in terms of how decisions were actually made, with an element of post hoc justification. Notwithstanding, reflection and lessons learnt are still valuable for continuous improvement in decision-making for future refurbishment projects. It is unfortunate that the study has not been able to include the decision to refurbish or demolish existing buildings in detail. This is an important issue for future research. The research also focuses mainly on major refurbishments for university buildings in New Zealand, in particular projects which received funding from the government. Future research should include other types of buildings and levels of refurbishment (e.g. a partial refurbishment) in different locations and context. In addition, the study is limited by the lack of information on external validity. Further work needs to be done to validate the research results in the broader construction sector.

CRediT authorship contribution statement

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

Declaration of competing interest

The authors declare that there is no conflict of interest.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110557.

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