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Design for reuse in prefabricated timber buildings: Simultaneous evaluation of criteria and alternatives and TOPSIS analyses

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ABSTRACT

Determining the most viable and feasible reusing option for prefabricated timber buildings has proven to be a vital challenge yet to be addressed to transform the construction sector. While the industry acknowledges the value of circularity, a lack of efficient strategies impedes its adoption. This paper redefines the Design for Reuse (DfR) concept by applying it to timber construction and further identifies and evaluates reuse options and key barriers hindering the effective reuse of materials. The study assesses various timber reuse options for prefabricated timber buildings after their end-of-use using the Simultaneous Evaluation of Criteria and Alternatives (SECA) method. This paper presents a novel methodological framework by integrating SECA with The Order Preference by Similarity to the Ideal Solution (TOPSIS) method, drawing on expert insights from the Australian construction industry. The findings indicate adaptive reuse as the most viable option, and the key criteria include technical challenges related to disassembly, market demand, and the level of stakeholder endorsement. Eight key timber reuse barriers are identified in the results to provide an evidence-based understanding of industry practitioner' challenges. The contribution lies in systematically assessing reuse options for prefabricated timber materials and offering policymakers a foundation for establishing deconstruction practices that promote sustainable construction. Theoretically, this study extends current knowledge of circular economy (CE) practices in timber construction by introducing a validated decision-making framework that accounts for both quantitative and qualitative factors. The empirical findings on reuse options for prefabricated timber buildings will help industry professionals make strategic decisions that promote CE principles.

Abbreviations

AHP	Analytic hierarchy process
C&D	Construction and demolition
C&DW	Construction and demolition waste
CE	Circular economy
CLT	Cross-laminated timber
DfR	Design for reuse
DLT	Dowel-laminated timber
EOU	End of use

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(*continued*)

AHP	Analytic hierarchy process
kt	Kilotons
MCDM	Multi-criteria decision-making
Mt	Million tons
NLT	Nail-laminated timber
SECA	Simultaneous evaluation of criteria and alternatives
TOPSIS	Technique for order preference by similarity to ideal solution

1. Introduction

According to the Australian National Waste Report [1], the total amount of timber waste generated between 2020 and 2021 was 2.4 million tons (Mt). Out of this amount, 646 kilotons (kt) originated from construction and demolition waste (C&DW), making it the second-largest generator of timber waste. The amount of timber waste generated by the construction and demolition (C&D) sector increased by 34 kt compared to the 2016–17 period [2]. The C&D-based timber waste accounts for 35 % of all landfill timber waste in Australia [3]. In 2016–17, Australia reused and recycled approximately 42 % (9.98 kt) of its total timber waste, which primarily originated from construction, demolition, and renovations [4]. This amount remains below the ambitious target of achieving an 80 % recovery rate across all waste streams by 2030 in Australia. Timber requires less processing than other materials, such as concrete, enabling more efficient reuse [5]. The widespread use of timber as a building material contributes to increasing volumes of C&D waste [6], making sustainable reuse essential for fostering economic opportunities and addressing the environmental challenges posed by construction waste [7].

According to the Australian Greenhouse Office, reusing materials can result in a 95 % reduction in embodied energy [8]. Deforestation is a significant concern in Australia; 172 thousand hectares of natural forest were lost in 2023, resulting in an estimated 60.5 Mt of CO2 emissions [9]. In 2022–2023, embodied carbon from the building construction industry accounted for 10 % of Australia's total carbon emissions, equivalent to 21 Mt, making it the largest source of embodied carbon [10].

A CE approach to reusing timber for construction offers significant sustainability benefits, including reducing the need for new timber materials [11], lowering deforestation rates [12], lowering the embodied carbon footprint of buildings, conserving natural resources, and reducing landfill waste [4]. Furthermore, prefabricated construction adheres to an integral principle of CE, namely, selecting component materials to enable the component to be used over and over again [13]. The ease of assembly and disassembly of timber components allows them to be reused in various construction projects, resulting in reduced waste and greenhouse gas emissions [14,15].

Using reclaimed materials from buildings after their end-of-use (EOU) is referred to as reuse in this study. By extending the lifecycle of timber-material products, reuse strategies can minimize the demand for virgin timber, thereby alleviating pressure on forests and contributing to the preservation of biodiversity [16]. The possible reuse options for prefabricated timber buildings after their EOU are refabrication [17], biocycle [18,19], elemental retrofit [20], transform [21], and adaptive reuse [22]. Refabrication involves disassembling the building into components and then reassembling or remanufacturing a new building with the same functions [17]. Biocycle refers to the process of disassembling the building into components and parts, chipping up the components and parts into sawdust, and then putting them into garden beds, particle boards [18], or producing biomass energy [19]. Elemental retrofit involves the disassembly of the building followed by use of the elements and parts in renovations or retrofits of existing buildings [20]. Disassembling the building and repurposing the components and parts into other pieces of fit-outs and furniture e.g., shelves, partitions, boards, walls, and benches is the transform reuse option [21]. Finally, adaptive reuse entails new uses of the building with minimal changes in design and function, for example, partially enclosed buildings [22]. These options are the most common reuse options for prefabricated timber buildings and their viability is evaluated in this study.

Using reprocessed and reused materials has been limited by a variety of factors. Negative attitudes about the quality and price [23] of reusable materials limit their adoption as alternatives to virgin materials [6]. Additionally, construction professionals often disregard client preferences of reused materials, further impeding demand increase [24]. The limited supply of reused materials then reinforces low demand [25]. Furthermore, the lack of comprehensive regulatory frameworks and standards for reusable materials creates additional barriers for their adoption [26]. According to Niu et al. [6], several factors prevent the industry acceptance of reprocessed structural timber: legislative hurdles, cost feasibility, and concerns about quality. On top of this, there are concerns about contamination and structural integrity, as noted by Brol et al. [27]. The factors and barriers impeding the adoption of reprocessed structural timber fall under economic, social, environmental, technical, and legal criteria, all of which are essential to the selection of a viable timber reuse option. The most viable reuse option is defined as one that is determined based on these criteria to be sustainable, practical, preferred, and feasible.

Selecting the most viable timber reuse option for prefabricated buildings can be challenging due to the sheer range of available alternatives and the variety of criteria involved. This study addresses this complexity by employing multi-criteria decision-making (MCDM) analysis. MCDM evaluates various criteria and alternatives to determine the most viable reuse options [28]. In MCDM, conflicting timber reuse alternatives are analyzed and compared through mathematical simulation. Utilizing MCDM in timber reuse decision-making reduces the impact and incidence of biases on decision-makers. For selecting the best reuse options from alternatives, MCDM analyses like the Analytic Hierarchy Process (AHP), TOPSIS, and SECA are frequently used.

The MCDM analysis has been applied in various studies in the construction sector to different contexts. For instance, Chen et al. [29] developed an assessment process based on the Fuzzy Delphi method and Analytical Network Process (ANP) to rank the adaptive reuse alternatives for a historic building in Taiwan. The researchers identified the most viable reuse alternative based on economic, social, environmental, architectural, and historical criteria. However, they assessed and ranked adaptive reuse alternatives focusing on the building's function – such as composite use, commercial use, community activities, and education and exhibition – without addressing the potential barriers to reuse. Another study conducted by Haroun et al. [30], developed a framework based on the AHP method to rank the adaptive reuse options of a heritage building in Egypt. The ranking was based on criteria of economic performance, environmental impact, social value, architectural value, and heritage value. Again, an MCDM analysis was used to find the best alternative for a heritage, building, and focused primarily on aspects of building function such as mixed uses, office building, museum, and hotel.

Keshavarz-Ghorabaee et al. [31] applied the Fuzzy SECA method in their research to introduce a new method for sustainable e-waste management scenarios evaluation based on social, environmental, economic, and social criteria. While this study evaluated various scenarios for sustainable e-waste management and addressed different levels of disassembly, along with the subsequent treatment of recyclable materials, the researchers overlooked the challenges associated with the reuse of timber buildings. In their study, Tighnavard Balasbaneh et al. [32] used an MCDM analysis to determine the most viable reuse material among plywood, timber, steel, and plastic. They undertook a life cycle assessment and economic analysis of these reusable formwork materials, and identified plastic formwork as an ideal alternative for sustainability purposes in terms of its reusability and serviceability. Milošević et al. [28] studied the potential for the sustainable and cost-effective reuse of industrial buildings in Serbia by using Fuzzy AHP, which allowed them to evaluate different physical and spatial performances of the buildings and their locational indicators. Although this study developed a framework using Fuzzy AHP for selecting industrial buildings for adaptive reuse by focusing primarily on locational and physical characteristics, it neglected to address the specific criteria and challenges associated with the reuse of buildings, as well as the potential reuse applications in the context of the CE model.

In the context of timber construction, Meireles et al. [33] conducted an environmental life cycle assessment comparing an innovative prefabricated interior partition wall to a conventional system. They found that the innovative prefabricated interior partition wall demonstrated superior environmental performance over conventional interior partition walls. However, the researchers overlooked the decision-making processes and criteria for their reusing options. Cox-Rawlings et al. [34] developed a framework which considered a set of social, environmental, and economic criteria to assess different treatment options for wood waste streams, including business as usual, landfill, energy from waste, thermal treatment, and combined heat and power, all of which were based on an MCDM analysis. Given that there was no discernible value in upcycling or reusing wood, the researchers determined that energy from waste was the most viable option for treating wood. Their study focused solely on the treatment options for wood waste and did not explore the potential for reusing timber elements and components. In the context of CE, Balasbaneh and Sher [35] applied an MCDM analysis for identifying the best forms of mass timber construction, including dowel-laminated timber (DLT), nail-laminated timber (NLT), and cross-laminated timber (CLT) to evaluate CE potential in buildings. The findings revealed that DLT, CLT, and NLT were the top alternatives for addressing circularity, respectively. Their study lacked consideration of the strategies for extending the lifecycle of these timber materials through reuse, a solution which remains underexplored in the context of CE in construction.

In the studies above, MCDM analysis was used in construction for selecting adaptive reuse alternatives, and in timber construction contexts for selecting treatment options for timber waste as well as the most viable form of mass timber. However, none of these studies have examined different reuse options for timber buildings and reuse alternatives for prefabricated timber buildings. While other researchers have studied sustainability in the Australian construction industry (e.g. Refs. [36,37]), their focus has largely been on materials like concrete rather than timber. They have overlooked the complex nature of timber and its reuse in construction projects. Findings related to steel or concrete cannot be extended to timber as there are practical challenges specific to this material. Moreover, many studies neglected to address personal factors like industry perceptions, focusing instead on contextual issues such as quality and price. Hence, the use of reused timber must be studied systematically to capture all potential barriers limiting its uptake. The lack of empirical research on cascading structural timber has also been noted by scholars such as Niu et al. [6].

In summary, three significant gaps in the literature have been identified: first, the absence of studies examining the reuse alternatives for prefabricated timber buildings, particularly in the Australian context. Second, there is a tendency to generalize findings from studies on other materials, such as concrete and steel, without considering the challenges and opportunities associated specifically with the reuse of timber. The third gap pertains to the failure to consider both personal and contextual factors when evaluating timber reuse options, including industry perceptions.

Considering different aspects of timber reuse is essential to meeting feasibility requirements in timber building reuse. This study lays the groundwork for developing the application of MCDM analysis to assess timber reuse options for prefabricated timber buildings after their EOU. Additionally, this study identifies timber reuse barriers that impact the circularity of timber materials in construction. It evaluates a range of criteria, including social, legal, environmental, technical, and economic factors pertaining to timber reuse. The robustness of the findings in this study was ensured by validating SECA results using the TOPSIS method, a widely recognized form of MCDM analysis. This additional dimension of verification helps address any issues pertaining to the consistency and dependability of the SECA method. Other researchers reviewed existing frameworks but overlooked the need to target a comprehensive one which addresses all these issues. To fill the gap identified in current research, the main objectives of this study revolve around the identification of reuse barriers for timber materials and components of prefabricated timber buildings after their EOU, and the determination of the most viable reuse option among alternatives for these buildings.

2. Method

This study employed a quantitative method approach to address the research objectives. The chosen approach integrates data collection through an online survey with analytical methods to ensure reliable findings. The following subsections detail the survey methodology, evaluation criteria and alternatives, and analytical methods applied in this research.

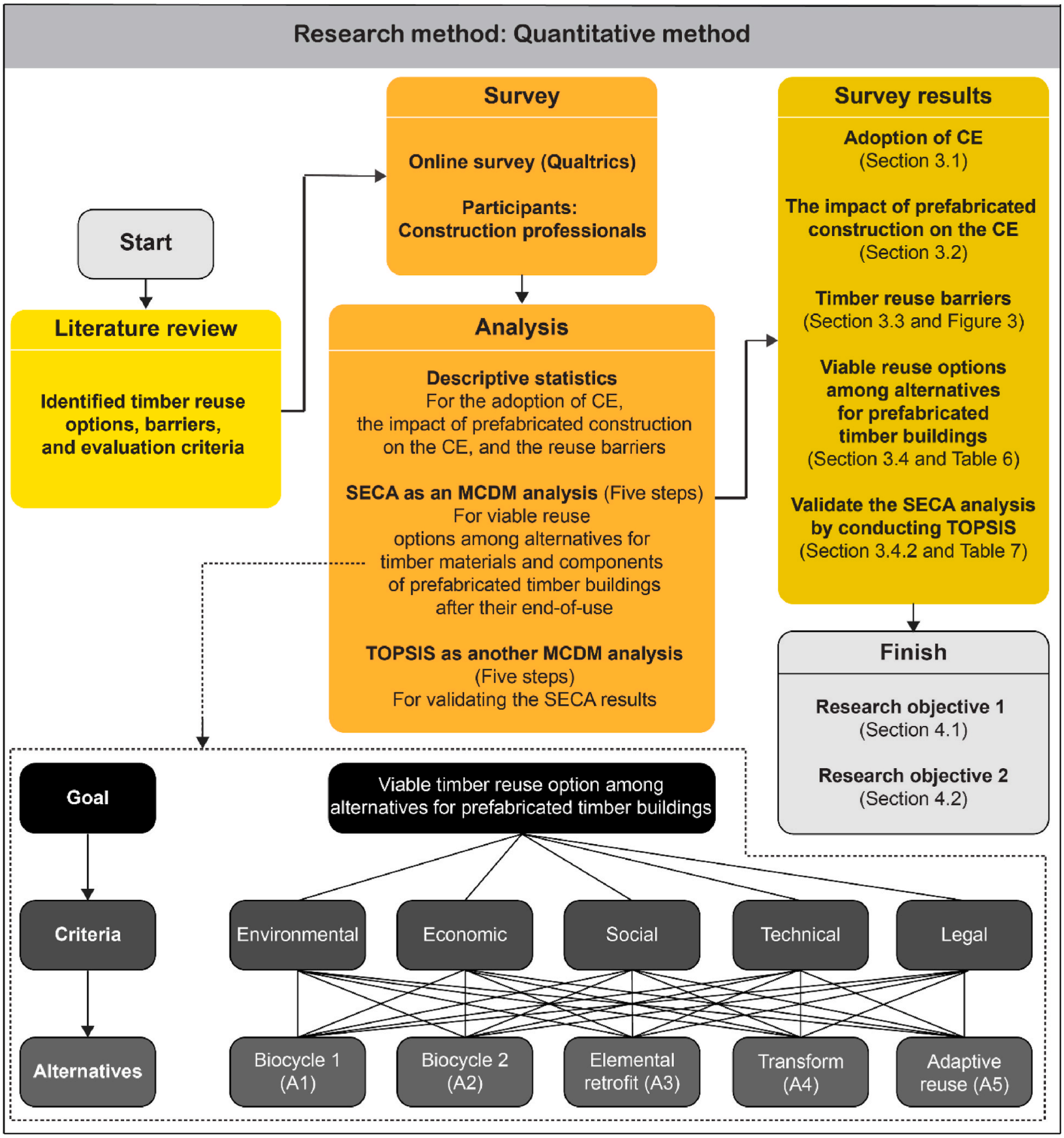
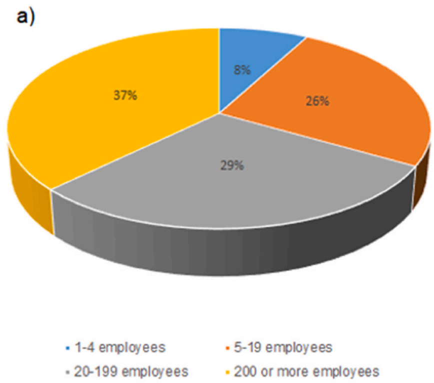


Fig. 1. Research flowchart including details of implementing an MCDM analysis for evaluating the reuse options for prefabricated timber buildings after their end-of-use employed for this study. Note: CE: Circular economy; MCDM: Multi-criteria decision-making; SECA: Simultaneous evaluation of criteria and alternatives; TOPSIS: Technique for order preference by similarity to ideal solution.

2.1. Survey methodology

A survey was designed which aligned with the research objectives and conducted to evaluate the proposed alternatives from a broad range of participants, ensuring a comprehensive understanding of industry perspectives on the research objectives, and to ensure that the findings can be validated. Fig. 1 shows the research flowchart, including the criteria and evaluated timber reuse alternatives, which were conducted in a process involving a literature review to identify timber reuse options, barriers, and evaluation criteria.

Key role	No.
Project manager	25
Civil engineer	19
Architect	13
Technology officer/AI engineer	8
Site engineer	7
Contract manager	6
Technical manager	6
Structural engineer	5
Consultant in CE	3
Building service engineer	2
Construction manager	2
Estimator	2
Director	2
Joiner	2
Sum	102



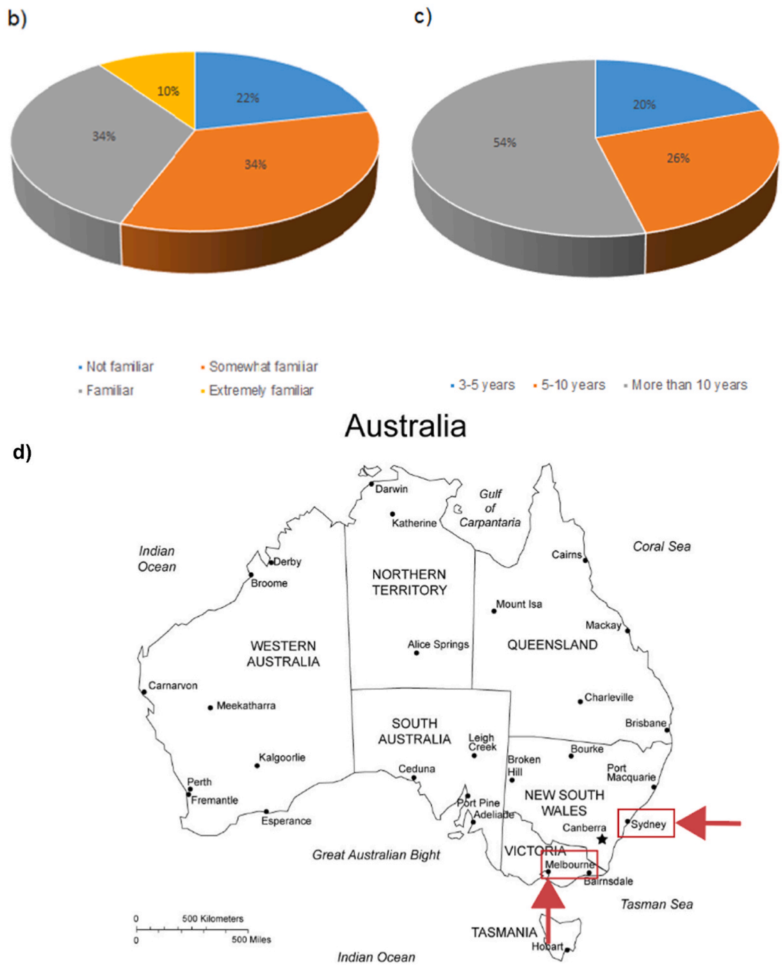


Fig. 2. Survey participants' background information; a) Company size, b) Familiarity with the CE, c) Years of experience, and d) Map of the study area.

Based on these findings, an online survey was designed to obtain quantitative data. The survey aimed to explore CE adoption in the Australian construction industry and assess the impact of prefabricated construction on circular practices. It also sought to identify barriers to the reuse of timber materials and elements and determine the most viable reuse options for these materials, providing a structured basis for the four sections presented in the results. The survey results were then analyzed through descriptive statistics, SECA, and TOPSIS, with each method applied as follows: descriptive statistics for the adoption of CE, the impact of prefabricated construction on the CE, and the reuse barriers, SECA method to evaluate five reuse alternatives for prefabricated timber buildings based on environmental, legal, technical, economic, and social criteria, and TOPSIS method was applied to validate the SECA results. Each stage of the MCDM analysis is discussed separately in Sections 2.2, 2.3, and 2.4. The protocol for the study was reviewed and approved by the University Research Ethics Committee.

To recruit the participants, criterion-based and chain strategies [38] were applied to facilitate selection of the most viable participants and to ensure the value of data collected. Participants were selected based on their current employment in construction companies in Australia. Identifying the participants for the survey was done through LinkedIn and by browsing the websites of relevant construction companies in Australia. Additionally, the participants could introduce new contacts by using the chain sampling method. Efforts were made to include individuals with prior experience in timber construction within Australia to ensure the relevance and applicability of their expertise to the study objectives. The combination of LinkedIn-based outreach and snowball sampling was used to access a diverse and representative pool of construction professionals. LinkedIn allowed us to directly identify professionals with relevant expertise, while the chain sampling method facilitates connections with traditionally qualified participants who met the inclusion criteria. This process was established to ensure that the respondents had sufficient expertise and knowledge to provide valuable insights into building construction in Australia.

Using snowball sampling, 102 construction professionals from a range of construction companies in Australia were recruited for the survey group. For the MCDM analysis, only the data from experts who fully completed the relevant section of the survey were used. This ensured the reliability and validity of the data used in the decision-making framework. Fig. 2 shows demographic information about survey participants. Most of the participants were familiar with the CE concept, had more than 10 years of experience in the industry, and were employed in medium to large construction companies in Australia. In this figure, the geographical focus of this research is illustrated. Sydney and Melbourne, Australia were the primary cities where the survey participants were located.

The survey included multiple-choice answers, closed-ended questions, and multiple-choice rating scales related to the research objectives. It consisted of five main sections, each carefully designed based on relevant literature and aimed at gathering comprehensive insights into participants' experience with CE and timber reuse.

- **Background information:** 5 questions designed to gather background information from the participants including their roles, years of experience in the industry, company size, familiarity with CE principles, and service offerings. These questions were informed by similar studies assessing industry expertise (e.g. Ref. [39]).
- **Companies' CE strategies:** 4 questions asked participants to indicate the level of adoption of CE in their companies. The structure of these questions was based on CE adoption frameworks found in the literature (e.g. Ref. [40]).
- **CE and prefabrication construction:** 2 questions addressed the impact of using the prefabrication method of construction on CE practices. The design of these questions was informed by studies that explore the relationship between CE and prefabrication in construction (e.g. Ref. [41]).

Table 1
Evaluation criteria for assessing timber reuse alternatives.

Major criteria	Sub-criteria	Ref
Environmental	(C1) The amount of waste generation of the proposed reuse alternatives	[31,42]
	(C2) Efficient resource consumption of the proposed reuse alternatives	[42,43]
	(C3) The amount of greenhouse gas emissions of the proposed reuse alternatives	[43,44]
Economic	(C4) The cost of labor for each of the proposed reuse alternatives	[45,46]
	(C5) The cost of processing for each of the proposed reuse alternatives	[31,45]
	(C6) The amount of cost associated with the design stage of the proposed reuse alternatives	[45,46]
	(C7) The cost of transportation for each of the proposed reuse alternatives	[45,46]
Social	(C8) The degree of stakeholders' acceptance of the proposed reuse alternatives	[31,43]
	(C9) The degree of contributions to local development of each proposed reuse alternatives	[43,46]
	(C10) Positive cultural perceptions of each proposed reuse alternatives	[46,47]
	(C11) The market demand for each proposed reuse alternatives	[43,48]
	(C12) Local community engagement of each proposed reuse alternatives	[43,49]
	(C13) Absence of potential safety and health risks associated with each proposed reuse alternatives	[43,50]
Technical	(C14) Technical challenges associated with the disassembling process of each proposed reuse alternative	[42,45]
	(C15) Concerns related to the design and compatibility of each proposed reuse alternative	[45,51]
	(C16) The simplicity of operation of each proposed reused alternative	[31,45]
	(C17) The availability of local infrastructure and equipment for each proposed alternatives	[45,52]
	(C18) The requirements for specialized personnel for each proposed reused alternative	[31,45]
	(C19) Ensure that the final reused product of each proposed reuse alternative meets high-quality standards	[11,23]
Legal	(C20) Compliance of each proposed reuse alternative with relevant laws and regulatory requirements	[11,53]

- **Reuse of timber:** 5 questions that explored participants' experience with reusing timber building structural elements and their perception of the possible barriers to reusing prefabricated timber elements and components. The questions were developed based on identified barriers in the literature.
- **Rating of timber reuse alternatives:** Respondents were then asked to rate different possible timber reuse alternatives for prefabricated timber buildings, based on the provided criteria/factors. The participants needed to rank the degree of factors for each reuse option based on the 5-point Likert scale; 1 (Very Low), 2 (Low), 3 (Moderate), 4 (High), and 5 (Very High). The reuse alternatives and criteria were derived from previous research.

2.2. Determination of alternatives and criteria

Based on the literature discussed in Section 1 where existing reuse options for prefabricated timber buildings are analyzed, the possible reuse alternatives for prefabricated timber buildings are biocycle, elemental retrofit, transform, and adaptive reuse, in place of the refabrication option. In this study, the most viable reuse option will chosen from a range of five alternatives: 1) biocycling to produce garden beds or particle boards, 2) biocycling to produce biomass energy, 3) elemental retrofit to use disassembled elements and parts in renovations or retrofits of existing buildings, 4) the transformation approach which involves repurposing the disassembled components and parts into other pieces of fit-outs and furniture, 5) adaptive reuse which includes new uses of the building with minimal changes in design and function. An MCDM analysis for evaluating the reuse options of prefabricated timber buildings after their EOU was conducted with.

Table 1, which shows the criteria and sub-criteria used for evaluating alternatives.

Primary and quantitative data were used for analysis using the survey method. Quantitative data were gathered from the combination of closed-ended and Likert-scale questions. Data security and anonymity were ensured through the survey platform. The results from the questionnaire were analyzed utilizing descriptive statistics. The IBM SPSS Statistics software was used to analyze questionnaire results (compute percentages and frequencies). An MCDM analysis known as SECA was used to select the most viable reuse option among alternatives for timber materials and components of prefabricated timber buildings. When multiple criteria or factors need to be considered, MCDM has proven to be an optimal decision-support tool, particularly in studies seeking to solve building material reuse-related problems. For instance, Vinodh et al. [54] identified the best plastic recycling method by using an integrated Fuzzy AHP and TOPSIS.

Based on the relative importance or priority of the criteria, the MCDM analysis evaluates the alternatives (5 reuse alternatives in place of refabrication option) against 20 criteria (factors) to obtain an overall ranking for each alternative. The SECA method was chosen over alternatives MCDM analysis methods like AHP, for several key reasons, the most notable one being that SECA enables simultaneous weighting of criteria and ranking of alternatives, and relies heavily on criteria developed from expert opinions. Unlike AHP, SECA is well-suited for contexts where criteria and alternatives must be considered together, and decisions must be made with minimal biases and inconsistencies to ensure more balanced proportions of subjective evaluations and objective data [55].

With the SECA method, a framework was developed around the varying importance of criteria while complex weight assignments and extensive pairwise comparisons often associated with other MCDM methods were avoided. The reliability of the SECA method has been proven in various MCDM contexts, including industrial management [56], environmental management [55], and manufacturing [57]. This study employs SECA to offer a balanced and thorough assessment of different reuse alternatives in order to highlight its effectiveness in this particular context.

The results obtained through the SECA method are validated using TOPSIS, a widely recognized decision-making method for ranking alternatives based on their closeness to an ideal solution. TOPSIS has been extensively used in decision-making analyses, as demonstrated in prior studies [58]. It was selected for this study to validate SECA results by comparing its rankings of reuse options for prefabricated timber buildings with an independent, widely used method. TOPSIS calculates the relative closeness of each alternative to an ideal solution and uses these calculations to produce rankings that are systematically compared to those of SECA. Studies such as Behzadian et al. [59] have demonstrated the effectiveness of TOPSIS for validating other MCDM results for decision-making processes in design and engineering domains by confirming consistency and alignment between methods. Velasquez and Hester [60] emphasized the robustness of TOPSIS for providing rankings in decision-making analyses, while Pinzon Amorocho and Hartmann [61] applied it to validate the ranking of criteria in building renovations. Additionally, Greco et al. [62] emphasized the use of TOPSIS for evaluating weighted criteria and rankings, further underlining its suitability for this study.

The choice of TOPSIS reflects its methodological complementarity with SECA, allowing for an effective comparison of criteria weights and alternative rankings. Although alternative validation methods could provide additional insights, TOPSIS was deemed sufficient for this study due to its ability to provide clear and interpretable comparisons within the practical constraints of the research. By leveraging the reliability and robustness of TOPSIS, this study ensures that the SECA results are validated comprehensively, providing a solid foundation for the findings.

2.3. The SECA method

The SECA method relies on maximizing the total performance of alternatives by reducing the divergence of criterion weights from a reference point, taking into account both the variation within individual criteria and the variation across different criteria [55,56]. The SECA method is described below.

Step One forming the criteria matrix for decisions about timber options.

An analysis of the performance of m alternatives against n criteria for choosing various timber options is conducted in this step, leading to a decision matrix.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

The i th alternative's performance value on j th criterion is represented by x_{ij} and $x_{ij} > 0$.

Step Two normalizing the criteria matrix.

In order to develop the corresponding normalized decision matrix, the entries of the original decision matrix are normalized, ensuring that the criteria are comparable on a common scale [63]. There are two types of equations that can be employed depending on the criterion.

$$n_{ij} = \frac{x_{ij}}{\max\limits_{i} x_{ij}} \ \textit{if } j \ \epsilon \text{ beneficial criteria} \tag{2}$$

$$n_{ij} = \frac{\min\limits_{i} x_{ij}}{x_{ij}} \ \textit{if } j \ \epsilon \text{ non} - \text{beneficial criteria} \tag{3}$$

In the decision matrix, n_{ij} represents the normalized value of each element.

Step Three calculating standard deviations and conflict levels.

Each criterion's vector $V_j = [n_{ij}]_{m\times 1}$ is now determined. By estimating within-criteria and between-criteria variations utilizing the elements of the normalized decision matrix, standard deviations (σ_j) and correlations (r_{jl}) between vectors of criteria are calculated, respectively. Then, the degree of conflict (π_j) need to be calculated to represent the level of inconsistency among criteria. Therefore, the π_j between criterion j and other criteria can be calculated as follows:

$$\pi_j = \sum_{l=1}^{n} (1 - r_{jl}) \tag{4}$$

The standard deviation (σ_j) indicates data spread and is used to measure the degree of contrast in interactions among the alternatives. By contrast, the correlation (r_{jl}) index determines the degree of disagreement between two criteria based on linear relationships, and plays a critical role in estimating the conflict between two criteria.

Step Four weighting criteria based on the reference point.

Weights are normalized (σ_j and π_j) to provide within-criteria and between-criteria reference points.

$$\sigma_j^N = \frac{\sigma_j}{\sum_{l=1}^{n} \sigma_l} \tag{5}$$

$$\pi_j^N = \frac{\pi_j}{\sum_{l=1}^{n} \pi_l} \tag{6}$$

In this equation, π_j^N and σ_j^N are the normalized values of π_j and σ_j, respectively.

Step Five multi-objective nonlinear programming model.

As shown below, a multi-objective non-linear model can be derived to evaluate criteria and alternatives simultaneously. Equation (7) applies the weighted sum method to maximize the total performance of alternatives. In order to minimize the divergence of each criterion's weight from its reference point, the sum of squared deviations from the reference points is used. Equations (8) and (9), respectively, are used to calculate deviations within and between criteria. The model constraints determine the criterion weight limits. According to Equation (10), criterion weights add up to 1. Each criterion's weight bounds are shown in Equations (11) and (12) below.

$$\text{Max } S_i = \sum_{j=1}^{m} W_j X_{ij}^N, \forall i \ \epsilon \ 1, 2, \ldots, m \tag{7}$$

$$\text{Min } \lambda_b = \sum_{j=1}^{m} \left(W_j - \sigma_j^N\right)^2 \tag{8}$$

$$\text{Min } \lambda_c = \sum_{j=1}^{m} \left(W_j - \pi_j^N\right)^2 \tag{9}$$

$$\text{subject to } \sum_{j=1}^{m} W_j = 1 \tag{10}$$

$$W_j \leq 1, \forall i \in 1, 2, \ldots, m \tag{11}$$

$$W_j \geq 1, \forall i \in 1, 2, \ldots, m \tag{12}$$

Based on this step, Equation (13) is used to describe the optimization model:

$$\max Z = \lambda_a - \beta(\lambda_b + \lambda_c) \text{ subject to } \lambda_a \leq S_i, \forall i \in 1, 2, \ldots, m \tag{13}$$

$$S_i = \sum_{j=1}^{n} W_j n_{ij}, \forall i \in 1, 2, \ldots, m$$

$$\lambda_b = \sum_{j=1}^{n} \left(W_j - \sigma_j^N\right)^2$$

$$\lambda_c = \sum_{j=1}^{n} \left(W_j - \pi_j^N\right)^2$$

$$\sum_{j=1}^{n} W_j = 1,$$

$W_j \leq 1, \forall j \in 1, 2, \ldots, n$
$W_j \geq \varepsilon, \forall j \in 1, 2, \ldots, n$
The definition of variables for the fifth step is as follows;
λ_a: the weight of the a-th criteria
λ_b: the deviation of the criterion weights of the reference point of within-criteria
λ_c: the deviation of criteria weights of the reference point of between-criteria
W_j: the weight of the criteria
S_i: the overall performance of alternatives

It is necessary to maximize Z and minimize deviations of criterion weight from the corresponding reference points. Therefore, the deviation of λ_c and λ_b with a coefficient β is subtracted from the performance of the option λ_a. The coefficient (β) determines the overall performance and weights the criteria based on the expert's judgment. While solving the above mathematical model, the overall performance score (S_i) of each alternative and its objective weight (W_j) is determined. An alternative with a higher S_i value is considered better than those with a lower i^{th} value.

2.4. TOPSIS method

The TOPSIS method was applied to validate the SECA analysis by comparing the rankings produced by both methods. The TOPSIS analysis was conducted to assess the robustness and consistency of the SECA-derived rankings. Having a high correlation coefficient (r) between SECA and TOPSIS rankings indicates that the SECA analysis results are valid and reliable. To ensure consistency across both methods, the same weights which are determined in the fourth step of the SECA method were directly applied in the second step of the TOPSIS method. Because the TOPSIS method is recommended for its ability to handle complex MCDM problems and to rank alternatives based on their relative closeness to the ideal solution (Hwang and Yoon [64]), so it is employed here to validate the SECA analysis results by cross-verifying the ranking of reuse alternatives in this study. This method identifies the best alternative as the one that has the shortest distance to the positive-ideal solution (the theoretical best-case scenario) and the longest distance from the negative-ideal solution (the theoretical worst-case scenario) [65]. Tzeng and Huang [66] present the TOPSIS method as follows.

Step One create the normalized decision matrix.

The decision matrix consists of m alternatives and n criteria. x_{ij} represent the original value of the i^{th} alternative for the j^{th} criterion. The r_{ij} represent the normalized value of the i^{th} alternative for the j^{th} criterion.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{l=1}^{m} x_{ij}^2}} \tag{14}$$

Step Two create the weighted normalized decision matrix.

After normalization, weights are applied to each criterion. The term w_j represents the weight assigned to the j th criterion.

$$v_{ij} = w_j r_{ij} \text{ where } \sum_{j=1}^{n} w_j \tag{15}$$

Step Three Determination of positive-ideal and negative-ideal solutions.

Define the positive-ideal and negative-ideal solutions for each criterion in the following way.

$$A^* = \left\{ \left(max\ \ v_{ij} \mid \mathrm{j}\, \epsilon\, J \right) or \left(\min v_{ij} \mid j\, \epsilon\, J' \right), i = 1, 2, \ldots, m \right. \tag{16}$$

$$= \left\{ v_1^*, v_2^*, \ldots, v_n^* \right\}$$

$$A^- = \left\{ \left(min\ \ v_{ij} \mid \mathrm{j}\, \epsilon\, J \right) or \left(\max v_{ij} \mid j\, \epsilon\, J' \right), i = 1, 2, \ldots, m \right. \tag{17}$$

$$= \left\{ v_1^-, v_2^-, \ldots, v_n^- \right\}$$

Step Four Distance calculation.

Calculate the distance of each alternative from both the positive-ideal and negative-ideal solutions.

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^* \right)^2}, for\ i = 1, 2, \ldots, \mathrm{m} \tag{18}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2}, for\ i = 1, 2, \ldots, \mathrm{m} \tag{19}$$

Step Five Closeness coefficient calculation and ranking.

Compute the closeness coefficient for each alternative, which represents its relative proximity to the ideal solution.

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, 0 \ < \ C_i^* < 1, i = 1, 2, \ldots, m \tag{20}$$

The best alternative can, therefore, be found according to the preference order of C_i^*. More value and close to 1 is the better alternative closer to the positive-ideal solution.

3. Results

Based on the quantitative survey data collected from the respondents, this section comprises four main sections: including the adoption of CE, the impact of prefabricated construction on the CE, the reuse barriers, and the viable reuse options among alternatives for timber materials and components of prefabricated timber buildings after their EOU. Detailed results are presented below for each section.

3.1. CE adoption in the australian construction industry

According to the survey respondents, CE awareness among Australian construction companies is on the rise, but its implementation is still in its nascent stages. Approximately 33 % of the respondents reported that they had already applied some CE principles without noticing. Moreover, 12 % of the participants reported that they were aware of CE concepts and they were curious about how to apply them. The CE principles of the greatest interest include recycling and reuse (42 %), minimizing waste (32 %), and prioritizing regenerative resources (18 %). Besides, 29 % of the respondents reported that they had initiated some CE practices in their companies. However, only 6 % indicated that their companies have successfully integrated CE into their products and are endorsed by external bodies or customers.

3.2. Impact of prefabricated construction on the CE

According to the survey results, prefabrication has the potential to play a significant role to achieve CE purposes. Approximately 65 % of the respondents reported that prefabrication is conducive to achieving CE purposes as it reduces construction waste, and 55 % expressed confidence in its ability to promote efficient use of resources. Moreover, 43 % of the respondents emphasized the role of prefabrication in achieving circularity by facilitating easier deconstruction, material reuse, and recycling and incorporating sustainable materials and construction practices. In addition to this, 37 % of the respondents reported the potential of prefabrication to achieve circularity by improving the durability and lifespan of the structures. Overall, the respondents considered prefabricated construction as an important method of achieving CE purposes in the Australian construction sector.

3.3. Barriers to timber materials and elements reuse

Based on the survey responses, only 12 % of the respondents had the experience of reusing timber elements and components. Survey respondents pointed to the quality and condition of timber elements after EOU, along with the cost of reprocessing timber components and DfR, as the most significant challenges. Process requirements for reusing timber elements, low market demand, and lack of awareness were identified as additional challenges. Fig. 3 provides a list of all timber reuse barriers along with the percentage of respondents which selected each one. Based on these figures, respondents regard the economic barrier as the most important challenge, followed by the technical barrier.

In relation to the economic barrier, the concept of DfR refers to constructing components that can be disassembled and reused for future construction projects after their EOU. For this approach to work, connections and materials must be carefully selected to separate the elements without causing significant damage. Clearly, DfR is costly. Timber reuse is also hindered by the cost of reprocessing the timber for its next use.

From a technical perspective, disassembling timber connections can be cumbersome due to their complexity. There is the first step forward in providing scientific guidelines for assessing and preparing reclaimed timber for the disassembling and repurposing process. Designing without consideration for future disassembly can further complicate the issue. Timber members embedded with screws and fixings have a direct impact on their next use. Moreover, there is a shortage of training to ensure that relevant personnel are equipped with the necessary skills to carry out the procedures. A further impediment is the scarcity of specialized skills for handling and processing timber and timber reuse techniques, making their advantages difficult to understand and implement. In order to provide more technical knowledge, training programs may need to focus on the deconstruction process. Another technical barrier is the absence of certification for the quality and condition of timber elements after their EOU. Since reused timber must meet rigorous standards, its certification can be difficult without clear and formalized guidelines. Additionally, the structural integrity of wood subject to repeated use can deteriorate over time, compromising its durability and safety. Additionally, cross-contamination of timber components during the reprocessing stage places workers at risk of exposure to toxic chemicals.

As for the social barriers, the markets for reused materials and products specifically for reused timber remain underdeveloped in Australia. The low market demand for reclaimed timber limits the scope of timber reuse programs.

3.4. Identifying the most viable reuse option for materials

This section focuses on identifying the most viable reuse option for materials by analyzing and comparing multiple criteria. Two

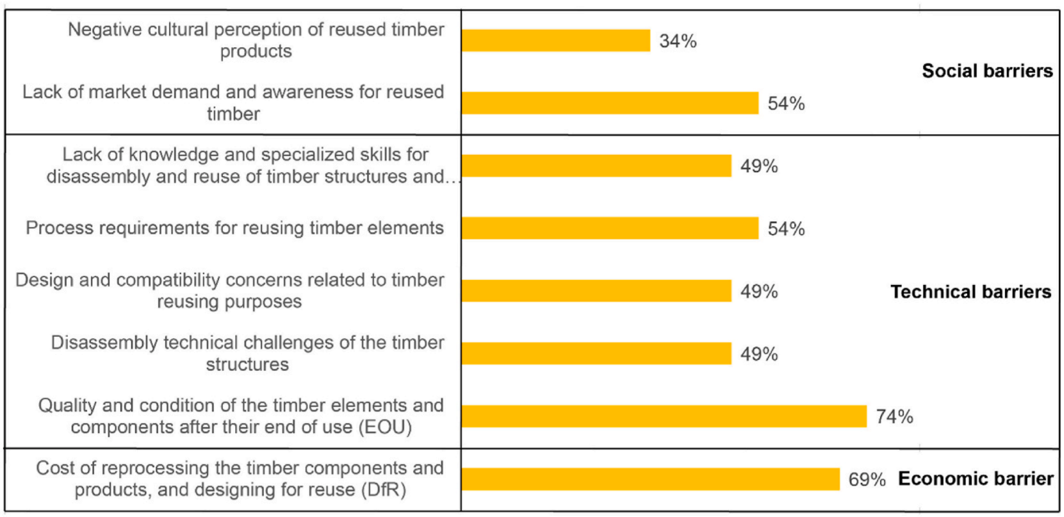


Fig. 3. Barriers to reusing timber elements and components.

methods, SECA and TOPSIS, are applied to evaluate and validate the reuse options systematically.

3.4.1. SECA analysis

Creating the decision-making matrix based on the experts' opinions is the first step in the SECA method. In the table representation of the decision-making matrix below, the rows feature five reuse alternatives, while the columns list the 20 criteria. Experts completed this decision-making matrix on a 1 to 5 scale, evaluating the performance of alternatives relative to each criterion. Table 2 shows the decision-making matrix obtained by aggregating the expert scores using the arithmetic mean method (Equation (1)). A normalizing approach for the decision-making matrix was used for the next stage as presented in Table 3. The elements of this matrix were normalized based on the benefit or cost criterion using Equations (2) and (3). Normalizing alternative scores ensures comparability of different criteria including positive criteria such as quality and negative criteria such as cost. As part of the normalizing process, the criteria was measured on a common scale and enabled meaningful, accurate comparisons, as well as the aggregations of scores.

The next step was to calculate standard deviations and conflict levels to assess variation both within and between criteria. In this stage, the degree of correlation difference between the two criteria was calculated. The first step was to compute the r_{jl}, a measure of the correlation between criteria, which was calculated using the two columns of the normalized decision matrix (each of which represent a criterion). After subtracting the correlation values of each criterion from 1, row-wise summation was performed. Table 4 shows the result of the degree of conflict (π_j) based on equation (4). On this basis, conflicts or disagreements among criteria were quantified. High values indicate a greater degree of conflict between the criteria, suggesting a high degree of incongruence between them when evaluated against each other as alternatives.

The next stage was to calculate the normalized values of π_j and σ_j,. The value of π_j was computed in the previous step, and for normalization, each π_j was divided by the total sum of all π_j values. For the normalized value of σ_j, first, σ_j was calculated and then each σ_j was divided by the total sum of all σ_j values. Table 5 indicates a result from the normalized values of π_j and σ_j, based on equations (5) and (6). Table 5 shows that efficient resource consumption (C2) for reusing timber of prefabricated timber buildings was associated with the highest normalized standard deviation, indicating that all alternatives performed more strongly under this criterion compared to others. Moreover, the design and compatibility criterion (C15) demonstrated the least contrast in terms of the performance of the alternatives, with minimal disparity in experts' opinions. The conflict between criteria was diminished when they were coordinated. Furthermore, there is a direct correlation between the degree of conflict between the two criteria and their effectiveness in the decision-making process. As illustrated in Table 5, the disassembly technical challenges criterion (C14) demonstrated the strongest correlation with other criteria. At the same time, waste generation (C1) related to reusing timber from prefabricated buildings showed the weakest correlation. From these results, C1 emerges as the least important criterion, while C14 emerges as the most important.

The software was used to formulate and analyze the nonlinear optimization model for this stage. In this model, the weights of the criteria and scores for the alternatives were calculated with each run β values ranging from 0.1 to 7. Various coefficient values between 0.1 and 7 were considered in the written code. Then, the weights of the criteria against different values of β (based on Equations (7)–(12)) were calculated. Based on this calculation, criterion weights were ranked acceptable for β values more than 1, since some criteria had the same β value for less than 1. For instance, the weight of C1 and C10 were the same and equal to 0.0010 for $\beta = 0.5$, thus $\beta = 0.5$ is unacceptable for determining the weight of the final criterion. In addition, the sum of criterion weights (for all β values) equaled 1, indicating that the weight sum constraint was met.

In the next stage, the performance of alternatives for β values ranging from 0.1 to 7 was obtained simultaneously by criterion weight. Based on these values, alternatives were ranked acceptable for $\beta \geq 5$, since some alternatives had the same β value for less than 5. For instance, the weight of A1 and A4 were the same and equal to 0.8313 for $\beta = 4$, thus $\beta = 4$ is not acceptable for ranking the alternatives practically. Thus, for values of $\beta \geq 5$, the performance of alternatives was used for ranking purposes. Fig. 4 indicates the variation of criterion weight for different values of β. Due to the stability of the criterion weight, the final weights for each set obtained from different β values were chosen. As shown in Fig. 4, the distributions of criterion weight was stable and showed minimal changes for $\beta \geq 6$, and their distribution variation was lower than the values of less than 6. Based on this, a final $\beta = 6$ was assigned to each of the final criterion weight which implied the converged values for the alternatives and the weight of the criteria. Among all criteria, the disassembly technical challenges criterion (C14) demonstrated the highest weight at 0.0782, with a value of $\beta = 6$, making it the most effective criterion according to expert assessments.

Fig. 5 provides a graphical representation of the performance of alternatives for different values of β. It specifies that the overall performance score of alternatives was stable for $\beta \geq 6$. In contrast to instances where values were less than 6, the overall performance scores were unscattered. The highest overall performance score for the alternatives and the peak objective function value (Z) indicated that $\beta = 6$ was the most suitable value for this coefficient.

Weight (W_j) was assigned to the criteria according to both the above analysis and equation (13), and performance scores (S_i) were calculated using the alternatives, as shown in Tables 5 and 6, respectively. In Table 5, the order of criteria was determined by using the value of the weights, where the criteria with the maximum value of W_j was ranked first, followed by the criteria with a lower value of W_j. The results indicate that the C14 criteria (disassembly technical challenges), ranked highest with a weight of 7.828 %; the market demand criteria (C11) weighed 7.53 % and ranked second, followed by the stakeholders' acceptance criteria (C8), which weighed 7.052 % and ranked third. By using the S_i value in Table 6, the order of alternatives was determined, and the alternative with the highest S_i value was ranked first, followed by the alternative with a lower value of S_i. Based on the S_i value of the alternatives, adaptive reuse alternative (A5), ranked first with a S_i value of 0.9569, the second biocycling alternative (A2) ranked second with a S_i value of 0.8342 while the transformation alternative (A4) ranked third with a S_i value of 0.83. The full ranking of both criteria and alternatives is provided below.

Table 2
Decision-making matrix based on experts' opinions.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
A1	2.8	2.6	2.8	2.3	2.9	2.8	2.8	3.4	2.6	2.6	3.0	2.8	3.1	2.5	3.2	2.3	3.1	2.8	3.3	3.3
A2	2.8	2.5	2.7	2.6	2.9	3.0	2.8	3.4	2.8	2.5	3.4	2.4	2.9	2.6	3.1	2.7	2.7	2.8	3.5	3.2
A3	3.1	2.8	2.9	2.5	2.8	3.0	3.1	2.8	3.2	3.0	2.5	2.8	3.0	3.0	3.0	2.9	2.8	3.2	2.6	2.8
A4	2.8	3.3	3.2	3.0	3.1	3.2	2.7	2.6	3.2	3.2	2.8	2.8	2.8	2.8	3.0	2.8	2.5	2.8	2.7	2.9
A5	3.9	4.1	3.7	3.6	3.3	3.1	3.7	3.3	3.5	4.1	2.7	3.1	3.3	2.3	3.2	3.4	3.8	3.0	3.8	3.5

Table 3
Normalized decision-making matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
A1	0.70	0.63	0.77	0.65	0.90	0.87	0.77	1.00	0.74	0.63	0.88	0.92	0.93	0.83	1.00	0.66	0.82	0.89	0.87	0.95
A2	0.70	0.61	0.73	0.72	0.90	0.95	0.77	1.00	0.79	0.61	1.00	0.78	0.88	0.86	0.97	0.78	0.71	0.89	0.93	0.90
A3	0.79	0.69	0.80	0.70	0.85	0.95	0.84	0.83	0.90	0.73	0.73	0.89	0.90	1.00	0.95	0.85	0.76	1.00	0.69	0.79
A4	0.70	0.82	0.86	0.84	0.95	1.00	0.73	0.76	0.90	0.78	0.80	0.92	0.85	0.92	0.95	0.83	0.67	0.87	0.71	0.83
A5	1.00	1.00	1.00	1.00	1.00	0.97	1.00	0.95	1.00	1.00	0.78	1.00	1.00	0.75	1.00	1.00	1.00	0.95	1.00	1.00

Table 4
Value of the Degree of Conflict (π_j) for each criterion.

	C1	C2	C3	C4	C5	C6	…	C15	C16	C17	C18	C19	C20	π_j
C1	0.00	0.16	0.14	0.20	0.39	0.69	…	0.59	0.14	0.12	0.46	0.51	0.51	8.568
C2	0.16	0.00	0.01	0.04	0.15	0.39	…	0.81	0.14	0.36	0.84	0.73	0.64	9.549
C3	0.14	0.01	0.00	0.07	0.16	0.48	…	0.73	0.18	0.29	0.81	0.71	0.59	9.348
C4	0.20	0.04	0.07	0.00	0.10	0.31	…	0.79	0.13	0.42	0.96	0.59	0.58	9.591
C5	0.39	0.15	0.16	0.10	0.00	0.53	…	0.56	0.42	0.45	1.33	0.45	0.35	10.793
C6	0.69	0.39	0.48	0.31	0.53	0.00	…	1.53	0.26	1.14	1.00	1.17	1.29	16.197
C7	0.02	0.28	0.25	0.31	0.51	0.83	…	0.52	0.21	0.09	0.39	0.45	0.48	9.001
C8	0.89	1.26	1.21	1.16	0.97	1.65	…	0.17	1.27	0.54	1.08	0.17	0.25	17.826
C9	0.20	0.11	0.14	0.15	0.44	0.24	…	1.17	0.04	0.55	0.54	1.01	1.02	11.235
C10	0.09	0.02	0.02	0.07	0.24	0.44	…	0.80	0.10	0.29	0.67	0.73	0.66	9.174
C11	1.49	1.56	1.59	1.35	1.09	1.31	…	0.71	1.53	1.29	1.61	0.52	0.68	24.187
C12	0.30	0.19	0.13	0.35	0.38	0.86	…	0.65	0.50	0.29	0.78	0.90	0.62	11.535
C13	0.13	0.40	0.33	0.46	0.50	1.17	…	0.24	0.50	0.00	0.57	0.34	0.26	9.734
C14	1.53	1.48	1.51	1.56	1.77	0.88	…	1.89	1.23	1.74	0.70	1.92	1.98	28.310
C15	0.59	0.81	0.73	0.79	0.56	1.53	…	0.00	1.05	0.23	1.13	0.14	0.04	13.763
C16	0.14	0.14	0.18	0.13	0.42	0.26	…	1.05	0.00	0.48	0.53	0.78	0.88	10.379
C17	0.12	0.36	0.29	0.42	0.45	1.14	…	0.23	0.48	0.00	0.62	0.32	0.24	9.466
C18	0.46	0.84	0.81	0.96	1.33	1.00	…	1.13	0.53	0.62	0.00	1.14	1.24	16.414
C19	0.51	0.73	0.71	0.59	0.45	1.17	…	0.14	0.78	0.32	1.14	0.00	0.08	12.656
C20	0.51	0.64	0.59	0.58	0.35	1.29	…	0.04	0.88	0.24	1.24	0.08	0.00	12.396

Table 5
Values of the normalized Standard Deviations (σ_j), the Degree of Conflict (π_j), weights, and ranking of the criteria based on the final (β) value.

Name	Code	Normalized Standard Deviations (σ_j)	Normalized Degree of Conflict (π_j)	W_j	Rank
Amount of waste generated	C1	0.0643	0.0329	4.265 %	14
Efficient resource consumption	C2	0.0798	0.0367	4.886 %	7
The amount of greenhouse gas emissions produced	C3	0.0528	0.0359	4.195 %	16
Cost of labor	C4	0.0698	0.0369	4.485 %	12
Cost of processing	C5	0.0291	0.0415	3.909 %	19
Cost associated with the design	C6	0.0245	0.0623	4.573 %	11
Cost of transportation	C7	0.0533	0.0346	4.155 %	18
Degree of stakeholders' acceptance	C8	0.0546	0.0685	7.052 %	3
Degree of contributions to local development	C9	0.0521	0.0432	4.349 %	13
Positive cultural perceptions	C10	0.0772	0.0353	4.684 %	9
Market demand	C11	0.0519	0.0930	7.530 %	2
Local community engagement	C12	0.0388	0.0443	4.647 %	10
Absence of potential safety and health risks	C13	0.0287	0.0374	3.825 %	20
Disassembly technical challenges	C14	0.0465	0.1088	7.828 %	1
Design and compatibility concerns	C15	0.0131	0.0529	4.195 %	17
Simplicity of operation	C16	0.0616	0.0399	4.265 %	15
Availability of local infrastructure and equipment	C17	0.0648	0.0364	5.065 %	6
Specialized skills requirements	C18	0.0262	0.0631	4.835 %	8
Meeting quality standards	C19	0.0679	0.0487	6.059 %	4
Compiles with relevant laws and regulations	C20	0.0432	0.0477	5.198 %	5

The adaptive reuse alternative emerged as the most viable reuse option with the highest score and weight, indicating its strong potential for successful implementation in the context of prefabricated timber buildings. These rankings were mainly based on the key criteria obtained from Table 5, which determined that disassembly technical challenges, market demand, and degree of stakeholders' acceptance were the three most important criteria with the highest percentages of weights. Lower-ranked criteria, such as the absence of potential safety and health risks and the cost of processing, although important, prove to be less impactful in this context. This ranking indicates the complexity of determinating the best reuse alternative for prefabricated timber buildings due to the multidimensional aspects that must be taken into account. The rankings outlined in Table 6 provide a clear decision-making framework that aligns with the critical criteria presented in Table 5.

3.4.2. TOPSIS analysis

To ensure the validity and reliability of the SECA analysis results, the TOPSIS method was conducted. First, by using equation (14), a standardized matrix was created based on the scores provided by the experts. Then, the weighted normalized matrix was obtained on the basis of equation (15). Subsequently, the adjusted values of the evaluation matrices were substituted into equations (16) and (17) to obtain positive-ideal (S_i^*) and negative-ideal solutions (S_i^-). The distances between each alternative and the positive and negative ideal solutions were calculated on the basis of equations (18) and (19). Finally, the closeness coefficient (C_i^*) was obtained from equation (20). The results are presented in Table 7.

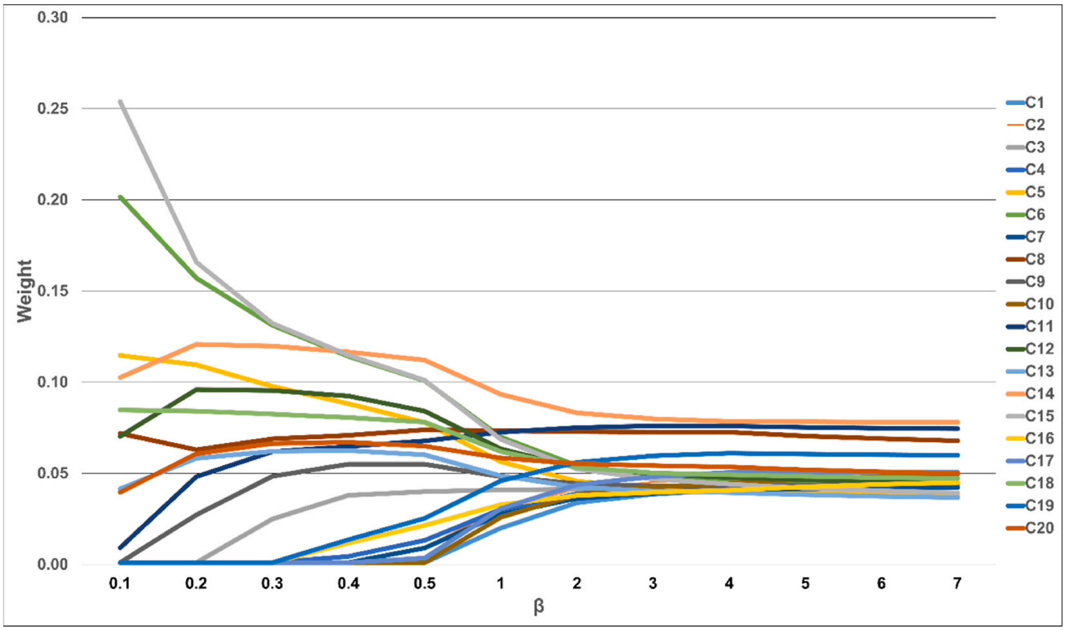


Fig. 4. Changes in criteria weights across various (β) values.

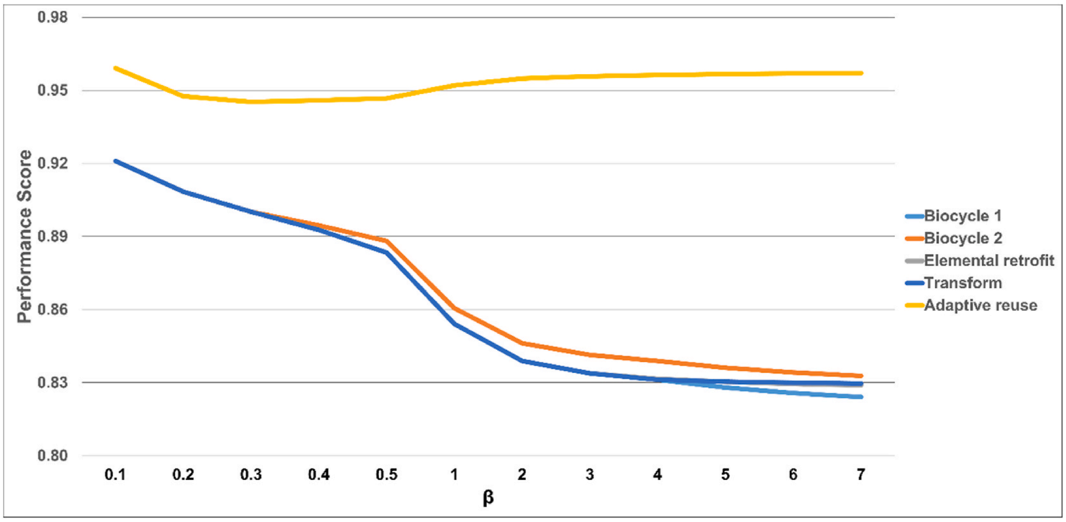


Fig. 5. Variation of alternative scores and overall performance for different (β) values.

Table 6
Overall performance score (S_i), objective weights (W_j) and ranking of each alternative based on the final (β) value.

Name	Code	S_i	W_j	Rank
Biocycle 1	A1	0.8258	19.31 %	5
Biocycle 2	A2	0.8342	19.51 %	2
Elemental retrofit	A3	0.8295	19.40 %	4
Transform	A4	0.8300	19.41 %	3
Adaptive reuse	A5	0.9569	22.38 %	1

The results of the TOPSIS analysis were as follows: Ranked first was the adaptive reuse option (0.685), with biocycle 2 option (0.412) coming in second, while the transformation option occupied third place (0.369). The only difference between the results from the two methods is that the options ranked at 4th and 5th place have switched places, while the rankings from 1 to 3 remain

Table 7
Distance (S_i) and closeness coefficient (C_i^*) calculations of each alternative based on the TOPSIS method.

Code	S_i^*	S_i^-	C_i^*	Rank
A1	0.0250	0.0143	0.363	4
A2	0.0245	0.0172	0.412	2
A3	0.0247	0.0140	0.362	5
A4	0.0237	0.0138	0.369	3
A5	0.0135	0.0292	0.685	1

unchanged. The correlation coefficient between the rankings was 0.9, indicating a very strong correlation between the TOPSIS and SECA analysis results. In order to capture the magnitude differences between the SECA and TOPSIS scores and provide a nuanced understanding of the relationship between the results of the two methods, Pearson correlation analysis [67], was conducted. The Pearson correlation coefficient was calculated as 0.994, indicating a very strong positive linear relationship. The high values from both Spearman's and Pearson's correlations (0.9 and 0.994) demonstrate the reliability and alignment of SECA and TOPSIS in evaluating reuse options. The use of both methods ensures a comprehensive validation of the MCDM results. This consistency across these MCDM analyses reinforces the reliability of the SECA findings. In conclusion, the adaptive reuse alternative emerged as the most viable reuse option with the highest score aligned with the SECA results.

4. Discussion

This study integrated a methodological approach to evaluate timber reuse options for prefabricated timber buildings after their EOU. The results demonstrate increasing traction for CE adoption within the Australian construction industry. This finding aligns with Halog and Anieke [68], who concluded that CE had been widely accepted in the Australian construction industry. However, contrasting perspectives, such as those of Lim et al. [69], argue that the Australian construction industry is not yet prepared for applying CE strategies.

The findings further corroborate Shooshtarian et al. [70], who emphasize that the degree of CE awareness among Australian construction professionals directly affects the adoption of CE practices. Higher levels of awareness correlate with an increased likelihood of embracing CE strategies and recognizing their benefits. Nevertheless, persistent challenges remain regarding the practical implementation of these strategies.

This study underscores the significant potential of prefabricated construction in facilitating material reuse. This result is consistent with Minunno et al. [41], who highlight the capacity of prefabricated construction to promote the practice of CE principles with the use of recycled, repurposed, and remanufactured products. Moreover, Elmualim et al. [71] emphasize the potential of prefabrication to increase resource use efficiency and eliminate construction waste, while O'Grady et al. [72], demonstrate its contribution to circularity by extending the structural durability and lifespan of structures while simplifying the deconstruction process.

4.1. Barriers to timber materials and elements reuse

The first objective of this study was to identify barriers to reusing timber materials and components from prefabricated buildings after their EOU. The findings (Section 3.3 and Fig. 3) revealed eight barriers grouped into technical, economic, and social categories. Economic barriers include the cost associated with reprocessing timber components and implementing DfR.

Technical barriers involve the quality and condition of timber elements post-EOU, challenges in disassembly, design and compatibility issues, process requirements, and insufficient specialized skills and knowledge for reuse. Social barriers are linked to limited market demand, low awareness, and negative cultural perceptions of reused timber. The identification and categorization of these barriers provide a material-specific focus that advances understanding of CE practices in timber construction and bridges gaps in addressing barriers unique to prefabricated structures.

The barriers mentioned above were not examined entirely in other similar studies, and this study redresses the gap by offering a focused categorization for the timber reuse barriers. Niu et al. [6] examined barriers to reusing C&DW timber in Finland, identifying several technical, economic, and value chain challenges. These included barriers such as the design of timber for one-time use only, doubts about long-term quality, lack of reuse motivation, lack of destinations for reused timber, and feasibility constraints. Economic barriers highlighted in their study included concerns about cost efficiency, profitability, and the feasibility of sorting C&D timber waste. Value chain barriers, such as the uncertain popularity of wood construction, labor- and cost-intensive waste sorting, and the cost of demolition compared to the total construction cost, were also discussed. While their study offers valuable insights, its focus is limited to a specific regional context and lacks a comprehensive categorization of barriers.

Unlike previous studies such as Niu et al. [6], this study categorizes barriers into technical, economic, and social barriers, specifically addressing the unique challenges associated with prefabricated timber structures. Additionally, the categorization presented in this study offers a more comprehensive perspective by identifying detailed technical challenges such as the need for specialized skills and the complexities of disassembly, which were not explicitly examined in their study. While their study primarily focuses on value chain barriers, this study extends the analysis to include additional barriers to timber reuse. These include social obstacles, insufficient training opportunities for staff to develop specialized skills, process complexities, design and compatibility concerns, and technical challenges associated with disassembly.

In a study by Ormondroyd et al. [18] challenges of reusing timber in the UK by explaining scale, efficiency, and safety issues were presented. Grading requirements, unknown timber histories, and imbalances in availability and demand were also underscored. Additionally, Ormondroyd et al. [18] noted the environmental impact of removing chemical contaminants. While the prior study focuses on barriers such as demolition scale, grading requirements, and contamination concerns, additional barriers are addressed in the present study. These additional barriers include design and compatibility issues, the shortage of knowledge and specialized skills for disassembly and reuse, as well as the costs associated with reprocessing timber and implementing DfR. Moreover, our study offers a structured understanding of the barriers to timber reuse by considering them within social, technical, and economic frameworks.

4.2. Identifying the most viable reuse option

The second objective of this study was to determine the most viable reuse option for prefabricated timber buildings after their EOU. Findings from the SECA model (Section 3.4) indicated adaptive reuse as the most viable alternative, achieving the highest performance score (0.9569), followed by biocycle 2, transformation, elemental retrofit, and biocycle 1 (Table 6). Adaptive reuse significantly outperformed other alternatives, aligning with the SECA model's goal of maximizing the overall performance of reuse options. Experts prioritized disassembling timber components for biomass energy extraction over repurposing for garden beds or particle boards, highlighting the preference for biocycle 2 over biocycle 1 (Table 6).

Key criteria influencing reuse decisions included disassembly technical challenges, market demand, and stakeholder acceptance (Table 5). The legal and technical categories emerged as the most significant determinants. Validation of SECA results through TOPSIS analysis demonstrated strong alignment ($r = 0.9$), confirming adaptive reuse as the most viable reuse alternative and underscoring the robustness of the findings (refer to Table 7). The consistency between SECA and TOPSIS results reinforces the criteria's validity and demonstrates this study's contribution to advancing timber reuse practices. These insights provide valuable guidance for industry stakeholders in promoting circularity within timber construction.

Compared to Milošević et al. [28], who assessed adaptive reuse potential for industrial buildings using locational, physical, and spatial criteria, the present study incorporates a more comprehensive methodological approach. While their approach emphasized site-related factors, it did not account for material-specific reuse barriers. In contrast, the present study addresses these gaps by focusing on prefabricated timber buildings and evaluating options based on environmental, technical, economic, legal, and social considerations.

Similarly, Chen et al. [29] evaluated adaptive reuse for historical museums using economic, natural, and social factors but did not assess reuse alternatives for specific building materials. The present study distinguishes itself by systematically ranking both criteria and alternatives for prefabricated timber buildings, providing industry-specific insights that are actionable and grounded in real-world practices. Unlike Haroun et al. [30], who evaluated the reuse of heritage buildings without addressing cultural factors, the present study integrates these factors to reflect stakeholder priorities and market dynamics.

The results of this study are particularly relevant to practitioners, as they offer actionable insights into the viability of adaptive reuse. Real-world applications such as the Mercury Store in Brooklyn [73] and Wooden Structure at Launchlabs, located in Based, Switzerland [74] highlight the potential of adaptive reuse to create versatile, multifunctional spaces while preserving the aesthetic and structural integrity of timber buildings. For example, techniques like scarf jointing and demountable timber components demonstrate innovative solutions to technical challenges, which will inspire similar projects in Australia.

Unlike previous studies such as Milošević et al. [28], this research integrates all relevant criteria into a balanced decision-making framework, identifying potential tradeoffs and synergies. Contextual and cultural factors, such as regulatory constraints and market demand, were also considered, addressing critical gaps in the literature. By grounding the findings in data from Australian practitioners, this study provides practical guidance tailored to local market conditions, offering a roadmap for implementing adaptive reuse strategies in Australia's construction industry.

4.3. Theoretical and practical implications

Theoretically, this study contributes to the MCDM literature by extending the application of the SECA and TOPSIS methods in the context of timber construction. We demonstrate the theoretical possibility of applying CE principles to prefabricated timber buildings based on the findings of this study. In doing so, our study meets the demand for evidence-based research on reuse of prefabricated timber buildings after their EOU. From a broader, societal perspective, this study advances CE principles which are crucial for carbon emissions and reducing waste in the construction sector. Moreover, by integrating the SECA method within the MCDM framework and using the TOPSIS method employed for validation, this study develops a methodological approach to evaluating sustainable construction practices. Overall, this research highlights the importance of integrating personal and contextual criteria into timber reuse in developing a more sophisticated understanding of its complexities.

From a more practical standpoint, it is important to inform industry stakeholders of the capability of DfR to improve the circularity of their work and support them in developing timber construction practices that are consistent with CE principles. This study will help guide the evolution of strategies and policies towards more sustainable material use in construction projects. Policymakers and industry practitioners will gain actionable insights into reusing timber materials from the study's comprehensive outline of key barriers such as the quality and condition of the timber elements and components after their EOU, and the cost associated with DfR and with the reprocessing of timber components and products. By using key criteria and the reuse alternative ranking in this study, decision-makers are supported by a clear framework with clearly identified criteria to ensure greater sustainability of their projects. Furthermore, the examination of Australian-specific barriers underscores the need for targeted interventions that address both market and regulatory challenges, ultimately promoting greater adoption of timber reuse practices. The results are in line with sustainable development goals (SDGs) number 11 (sustainable cities and communities) and 12 (responsible consumption and production). Overall, the approach taken by this study offers a practical way forward for maintaining the circulation of prefabricated timber buildings with strategies that benefit both the environment and urban communities.

4.4. Limitations and future directions

When the specific country, sample size, and demographic distribution are taken into account, it is possible that the survey results here are not generalizable to the broader perspective of the industry. Despite the robust analytical framework provided by the SECA and TOPSIS methods, the weighting process is dependent on the particular criteria used. To address these limitations, the sample size could be increased to allow for a more representative demographic distribution. Future studies should aim to examine the application of SECA and TOPSIS methods to different building types and materials so that this approach can be tested in diverse contexts. Further enhancement of the efficiency and feasibility of timber reuse could be achieved by exploring integrated advanced technologies such as artificial intelligence. Finally, the adoption of CE principles in the construction sector would be more effective if comparative studies were conducted across different regions and countries.

5. Conclusion

This study develops a comprehensive framework for implementing DfR in timber construction by identifying, evaluating, and prioritizing various reuse options for timber components. It outlines key barriers to the reuse of timber materials which must be addressed to promote circularity within the sector. With a structured ranking method, the research presents viable reuse options for prefabricated timber buildings post-use. The use of the SECA method, validated by the TOPSIS approach, confirms adaptive reuse as the most viable option among alternatives.

As the first application of the SECA method to timber reuse in prefabricated buildings, this study makes substantial progress in the research on circularity in construction. The method effectively integrates the assessment of criteria and alternatives, allowing for greater decision-making accuracy in reuse material selection. Key factors that shape the selection of reuse options include disassembly challenges, market demand, and stakeholder acceptance. The quality and condition of timber components at EOU, along with the costs pertaining to reprocessing, were identified as significant barriers to effective reuse. The study also underscores the need to address process requirements and the low market demand for and awareness of reused timber.

By integrating SECA and TOPSIS methods, this study adopts a novel approach for analyzing and optimizing reuse strategies, offering a methodological advancement in decision-making for CE practices. The novel methodological approach integrates quantitative and qualitative data, enabling a comprehensive assessment that leverages the strengths of both data types.

This approach addresses a critical gap in existing research, where empirical evidence on practical options for timber reuse remains limited. While reuse is widely perceived as an effective strategy to reduce building waste, there is a notable lack of practical and feasible reuse solutions, further emphasizing the importance of this investigation.

Due to the variability in construction resource availability and equipment across different countries, the novel approach of this paper, including the identified solutions, can be adapted, re-ranked, or reprioritized in future investigations to suit domestic building industries. These localized studies would contribute to a collective understanding, eventually enabling reuse options' generalization and theoretical modeling of the reuse-oriented circularity.

In future applications, the framework developed in this study can be adapted to other construction materials and contexts, providing a scalable model for assessing reuse strategies across diverse construction scenarios. The methodology of the investigation lays the foundation for exploring different ways to reuse materials, encouraging sustainable design beyond timber, and supporting the shift toward circularity in construction. The findings will benefit researchers, industry stakeholders, and policymakers alike, enabling the formulation and confluence of adaptive reuse strategies aimed at mitigating waste and reducing embodied carbon emissions. Moreover, the thorough exploration of barriers to timber reuse undertaken by this research is critical for engaging industry stakeholders in the effort to implement strategies that aim to enhance sustainability and yield cost savings. For professionals and policymakers, the theoretical and empirical insights from this research lay the groundwork for developing effective reuse strategies that promote sustainable timber construction practices in the post-use phase.

Ultimately, by identifying key decision criteria and barriers, this study paves a robust foundation for policymakers to develop practical strategies, such as establishing deconstruction standards, with the longer view of promoting reuse as a fundamental element of circular economy practices in the construction industry.

CRediT authorship contribution statement

Mohsen Ghobadi: Writing – review & editing, Writing – original draft, Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Validation. **Samad M.E. Sepasgozar:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Resources.

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.

Data availability

Data will be made available on request.

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