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Circular economy in modular construction: An Australian case study

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ABSTRACT

The global building and construction sector is known for its low resource efficiency which leads to a significant waste generation rate. Therefore, the management of construction and demolition (C&D) waste has become a priority issue in many countries. The use of products with recycled content (PwRC)-emerged from C&D waste materials-in modular construction is a sustainable strategy to enhance resource circularity and circular economy in the sector. Despite this, there are significant challenges in making this a reality. Hence, this study was conducted to explore the factors influencing the optimal utilisation of PwRC in prefabricated construction products. A case study approach was adopted to understand how the industry perceives the use of these resources in this construction methodology. The results showed that several factors influence their utilisation in Australian modular construction. This study proposes a framework developed to guide efforts in enhancing the uptake of PwRC in modular construction.

Abbreviation	Full word
C&D	Construction and Demolition
DfMA	Design for Manufacturing and Assembly
ESG	Environmental, Social and Governance
HSEQ	Health, Safety, Environment and Quality
IS	Infrastructure Sustainability
ISO	International Standardisation Organisation
KPI	Key Performance Indicator
LEED	Leadership in Energy and Environmental Design
MCDM	Multi-Criteria Decision Making
MMC	Modern Methods of Construction
NCC	National Construction Code
NGER	National Greenhouse and Energy Reporting
PwRC	Products with Recycled Content
PaaS	Product-as-a-Service
SDG	Sustainable Development Goals
SME	Small and Medium-sized Enterprise

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1. Introduction

The global building and construction sector has long been recognised for its historically low resource efficiency [1], a trend that has led to relatively high waste generation in construction projects. With growing public awareness of the environmental, social and economic consequences of low resource efficiency and high consumption rates, governments worldwide have explored numerous strategies to enhance processes aimed at minimising waste generation [2].

In recent years, the circular economy term has become the overarching concept guiding the efforts toward more sustainable production and consumption. This concept overlaps with other sustainability initiatives such as Sustainable Development Goals (SDG), Waste Management Hierarchy, Net Zero Carbon and Zero Waste. In 2024, the International Standardisation Organisation (ISO) released three standards specifically addressing circular economy aspects. These standards are known as the ISO 59000 family of standards and aim to establish a common language and conceptual framework for the implementation of a circular economy in different industries and contexts [3]. These policies are in addition to multiple other ISO Standards that were published before which target organisational environmental performance and waste minimisation practices such as ISO 14001 [62].

Among various waste streams, significant attention has been directed towards construction and demolition (C&D) waste in the transition to a circular economy. This waste stream is consistently among the largest contributors to global solid waste materials (Shooshtarian et al., 2022). Hence, managing C&D waste has become critical for enhancing resource efficiency, reducing landfill dependency and promoting sustainable building practices in the sector. One of the most effective waste management techniques in this sector is the incorporation of products with recycled content (PwRC) into construction projects. This strategy has proven to be in particular an effective approach to enhancing the circularity of construction materials [4]. This strategy helps to reduce reliance on virgin materials, lower the sector's environmental footprint and promote resource efficiency. In general, the complexity of construction projects, with diverse processes, methodologies and components allows for high uptake of PwRC. However, this potential remains largely untapped, presenting ample opportunities for further development and growth.

One of the less-explored territories in the sector is the utilisation of these resources in modular construction. Modular construction is a building method where individual components, or modules, are prefabricated in a factory-controlled environment and then transported to the construction site [5]. These modules are typically designed to fit together seamlessly to form a complete structure, such as a home or commercial building. Prefabrication is revolutionising the construction sector at every level by bridging construction and manufacturing [6]. This concept is encapsulated in the definition of industrialised construction, which involves the prefabrication, modularisation and standardisation of construction processes and assets in controlled factory environments [7]. The factory setting allows for greater exploration and application of PwRC, which may be challenging to implement in conventional construction environments.

Despite the wealth of research on circular economy and modular construction as distinct themes, there is a notable gap in studies that specifically explore the challenges, drivers and strategies for enhancing the use of PwRC within this construction methodology ([61]; [8]). Many existing studies focus on the individual aspects of the circular implementation of economy principles or the benefits of modular construction [60]; prefabAUS 2023), but few address the integration of these two areas [9]. Focusing on this integration sheds light on the factors driving its success and unlocks opportunities to enhance resource circularity in Modern Methods of Construction (MMC).

To address this gap this research aimed to identify the main challenges, motivations and strategies for using PwRC in modular construction using a case study methodology. The case study is a large organisation known as a global leader in prefabrication manufacturing, with facilities across Australia. The study examined perceptions across diverse stakeholder groups in the organisation's construction materials supply chain regarding the use of PwRC in prefabricated products. Therefore, the research scope excludes higher-level circular economy strategies, such as "rethink" and "refuse," focusing instead on recycling activities. As presented below, three research objectives guided the achievement of the research aim.

1. To explore the main benefits and motivations of integration of PwRC into modular construction products
2. To understand the main barriers and strategies to enhance the use of PwRC in modular construction
3. To develop a framework to guide the successful incorporation of PwRC in modular construction

2. Literature review

Modular construction has the potential to transform project management for construction firms, with onsite construction projects completed in as little as 12 weeks instead of the traditional 12-month timeline [10]. Modular design enhances these firms' ability to handle multiple projects simultaneously without compromising quality or risking damage to their reputation [11]. The use of modular construction provides several benefits as outlined in Table 1. These advantages encompass social, environmental and economic aspects, offering a more sustainable construction approach overall.

In modular construction, bulk material orders allow manufacturers to fabricate multiple modules simultaneously, leading to lower prices from suppliers and reduced labour and transportation needs. This results in cost and time savings for the project. Additionally, prefabricated construction reduces the on-site labour force, lowering total labour costs by approximately 25 % compared to traditional methods; this is specifically evidenced when the labour force has to be deployed in regional areas. It is well documented that when construction phase activities overlap with prefabricated construction, there is a reduction in construction time of approximately 40 % compared to traditional construction methods [12]. One study focused on dwellings only, indicates that modular construction can cut construction times by as much as 50 % and reduce costs by up to 20 % [13]. Another analysis estimates claimed offsite construction is

three times more productive than onsite [7].

Another key benefit is the immunity to weather disruptions, allowing for year-round production and the potential for multiple shifts, leading to optimal utilisation of plant and equipment. This high utilisation rate helps justify investments in new modular technologies. Furthermore, the controlled factory environment enhances safety, resulting in fewer days lost to injuries compared to onsite construction. Offsite construction also enables concurrent work processes, such as foundation and wall construction, which can then be integrated onsite. Additionally, the use of digital technologies is more extensive in a factory setting, providing greater precision in cost estimation and delivery times. Process control technologies and automation reduce time and waste, leading to fewer defects and the need for rework (prefabAUS 2023). In terms of construction work safety, the adoption of this technology can provide a safer working environment which can result in the reduction of safety incidents by up to 80 % [14].

This type of construction also offers environmental advantages, including decreased construction waste and CO_2 emissions, as well

Table 1
Summary of the major advantages and disadvantages of modular construction.

	Advantages	Description	References	Disadvantages	Description	References
Economic benefits	Faster construction	Modular construction involves simultaneous off-site fabrication and on-site foundation work, reducing overall construction time.	Lee et al. [39], Salama et al. [40]	Transportation costs	Shipping large modules to the site can be expensive	Mignacca et al. [41], Almashaqbeh and El-Rayes [42]
	Cost-effective (affordable)	Prefabricated modules are produced in a controlled environment which may result in reducing labour and material costs. Furthermore, with a wide range of designs and inclusions, the final cost of the project may be lower than expected, depending on the contextual factors.	Chauhan et al. [43], Almashaqbeh and El-Rayes [44]	Limited customisation	Modular designs often have limitations in terms of architectural creativity and flexibility due to the predetermined transportation height/ width limitations.	Jansson et al. [45], Ali et al. [46]
	Improved construction quality	Factory-controlled construction ensures higher quality control compared to traditional on-site construction. Design for manufacturing and assembly (DfMA) advantages are exploited for subassemblies reducing errors and quality hold points.	Gao et al. [47], Rankohi et al. [48]	Dependency on factory production and limitations on the material selections	Delays in the factory can lead to project delays.	Mossman and Sarhan [49], Ji et al. [50]
Socio-environmental benefits	Less disturbance to building site local residents' everyday lives	Less disturbance to the building site's neighbours by minimising on-site noise and dust pollution and project completion time.	Loo et al. [51], prefabAUS (2023)	Size limitations	Restrictions on the dimensions of a prefabricated structure might exist due to regulations concerning the width of roads allowable for transportation.	Almashaqbeh and El-Rayes [42], Sobczyk et al. [52]
	Reduced material waste	Precise manufacturing processes minimise waste or reuse/repurpose waste that would otherwise be disposed of.	Tam and Hao [53], Ajayi [54]	Potential for damage	Modules can be susceptible to damage during transportation and installation.	Valinejadshoubi et al. [55], Godbole et al. [56]
	Safer working conditions	With much of the construction work done off-site, on-site workers are exposed to fewer hazards and other conditions such as weather.	Ahn et al. [57], [60]	Requires skilled labour	Specialised skills and expertise are needed for module fabrication and on-site assembly and commissioning.	Ginigaddara et al. [58]
	Post-disaster housing management	Rapid deployment of housing units to areas affected by disasters, providing quick and efficient temporary housing solutions for displaced individuals and communities.		High running costs	It requires high investment and running costs as well as additional project planning.	Xue et al. [59], prefabAUS (2023)

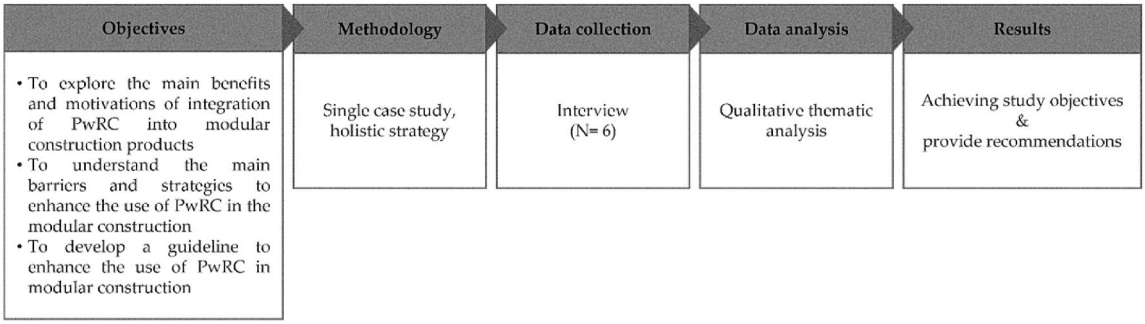

Fig. 1. Research process.

as reduced disturbance to neighbouring sites by minimising on-site noise and dust pollution. A recent report by the Waste & Resources Action Program shows that 90 % of waste reduction can be obtained by optimising the use of off-site construction [15]. Roughly similar figures were found in a case study [16] conducted in Australia. The authors of this case study inferred that there is an inversely proportional relationship between the level of prefabrication and waste generation.

However, this construction technology comes with some limitations. As outlined in Table 1, there are seven primary limitations in modular construction and these can multiply if modular construction organisations fail to adopt best management practices. Limitations exist at various stages of off-site construction, from planning and design to manufacturing and installation. This is inherent in all construction and not unique to modular construction however forward planning is strategically important as there is little time to figure out issues in this form of construction.

In theory, the use of PwRC in construction can offer a range of benefits that justify their procurement in modular construction. These benefits have been documented in several reviews and practical studies [4,17,18]. These benefits include a reduction in waste disposal, construction costs and carbon footprint. Realising these benefits, however, overly depends on several internal and external factors. While PwRC can be advantageous in some contexts, it may be less appealing economically, environmentally, and socially in others. Globally, many policies and initiatives support the use of PwRC in construction projects to facilitate the sector's transition to a circular economy. For instance, the recently published Australia's Circular Economy Framework emphasises that fostering PwRC markets, alongside integrating circular economy principles into new construction and improved design, are key enablers for advancing the CE in the Australian built environment sector in the next ten years [19]. Earlier, the European Union introduced the Waste Framework Directive (2008/98/EC) to promote this integration, and their mandatory Green Public Procurement helps create and

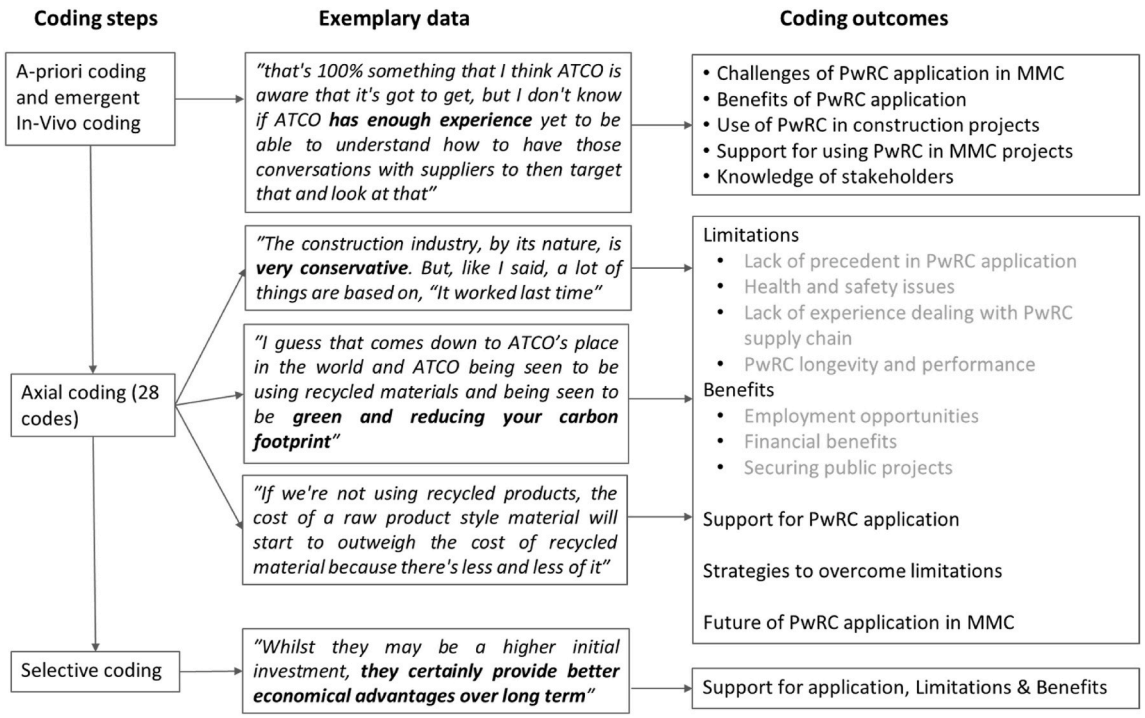

Fig. 2. Coding diagram illustrating the formation of concepts from data.

stimulate end-markets for PwRC [20].

As indicated earlier, minimal research has examined the factors involved in the process of PwRC utilisation in modular construction. Most existing studies merely propose incorporating these resources as an implementation circular economy strategy ([61]; [8]), without examining the factors affecting this process. For instance, in a recent review study on emerging trends in prefabricated buildings adopting a circular economy approach, the author [8] merely noted that PwRC usage can help fulfil current circular economy demands and improve environmental performance. Other studies also concentrate on the technical aspects of this integration, such as embodied carbon [21] or PwRC quality and performance [9]. We contend that understanding how the sector perceives these resources is the first step in planning their sustainable use in modular construction—a gap this study aims to address.

3. Methodology

3.1. Research design

A qualitative case study analysis was conducted to understand Australians' experience in the application of PwRC in modular construction through a series of semi-structured interviews. While this qualitative single-case study approach may limit the broader generalisability of the findings, its in-depth nature seeks to provide valuable insights into the critical factors driving such applications. Moreover, this method is commonly employed in similar studies within the field of C&D waste management and circular economy [22–24]. The type of case study used in this research project was descriptive and involved a single and holistic strategy in which one case with one unit of analysis was explored. The research process adopted in this study is illustrated in Fig. 1.

3.2. Case study description and selection criteria

In consultation with the project partners and experts in the field of circular economy, the criteria for the selection of the case study were set. The case study had to meet the following criteria.

- *Use of PwRC in modular construction*
- *Its recent application in the organisation projects*
- *Ease of access to key stakeholders*

ATCO Structures and Logistics (ATCO S&L) is a private company that earns most of its revenue from the commercial and industrial building construction sector. It is engaged in the construction, sale and hire of transportable buildings. In 2024, this manufacturing organisation is projected to hold 6.5 % of the market share for prefabricated metal building manufacturing, ranking it as the second-largest manufacturer in Australia in this category [25]. The company operates sales offices and manufacturing facilities throughout Australia. The main ATCO S&L modular products include commercial offices, government facilities (e.g. emergency, health and custodial services), sporting facilities and educational facilities. These products are (custom) designed, manufactured, transported and installed by ATCO S&L either temporarily or permanently.

3.3. Data collection and processing

After identifying the project, ATCO S&L, the perceptions of key stakeholder groups playing an essential role in using PwRC were sought through conducting a series of interviews. The interviewees were selected in consultation with the ATCO S&L sustainability team. An invitation email was sent to each stakeholder to arrange suitable interview times. The online interviews were conducted between March 2024 and April 2024 using the Microsoft Teams online platform. Each interview took a maximum of 1 h and was recorded for transcription purposes. Three types of questions were asked during interviews: participants' details, their experience using the PwRC modular construction and the enablers of and barriers to using such resources in this section of the industry.

Table 2
Summary of participants' profiles in the case study.

Stakeholder type	Experience/expertise	Participant code
Technical Manager	25 years of experience in various sub-fields of MMC in Europe, North America, Africa and Australia. Management of engineering and compliance aspects of the organisation's modular products.	P_1
Design Manager	More than 15 years of experience in the Australian MMC industry with responsibilities including detailing, designing and estimation	P_2
Operations Manager	More than 25 years of working experience in the Australian MMC industry.	P_3
Branch Manager	Extensive experience working in the study organisation's business development sales departments.	P_4
National HSEQ[a] Manager	A manager with experience in different fields and employment sectors including work health and safety, construction markets and education and training.	P_5
Supplier	Representative of supplying organisation (steel) with expertise in sustainability and extensive experience in the steel manufacturing industry.	P_6

[a] HSEQ: Health, Safety, Environment and Quality.

3.4. Data analysis

Audio data captured from 6 interviewees were carefully transcribed by a professional transcriber using the word-for-word method prior to the quality verification of the text data by the research team. The transcripts were analysed using the NVivo Pro 12 software [26], which facilitates codifying text-based qualitative data. In this study, the case project itself served as the unit of analysis, allowing the researchers to evaluate various aspects within the bounded system in relation to the research objectives. The following steps were taken to analyse the qualitative data in this study.

Firstly, a data reduction method, thematic analysis, was used to condense the data while retaining the essential elements that are necessary for addressing the research objectives [27]. The thematic analysis provided the emerging themes [28].

The study used a combined approach of deductive and inductive reasoning to analyse the qualitative data. Initially, a deductive coding system was applied with NVivo 12 software, while new codes were generated inductively from the interview data. Prior to the analysis, a set of a priori codes was established to guide the analysis. The deductive (a-priori) codes were informed by the established concepts in the previous literature such as barriers and drivers to the optimal use of PwRC in construction projects [4,29], interview questions and study objectives. The initial coding involved pre-established codes (a-priori codes) to guide the analysis (Fig. 2). Concurrently, in-vivo codes were inductively created from the emerging interview data. The analysis then advanced to axial coding, where the data was recategorised into new categories, resulting in 28 distinct codes. This process facilitated the identification of links between the initial 51 codes. The diagram below showcases the coding process with sample data.

The analysis was conducted by a team of three authors to minimise bias and ensure the validity of the a-priori codes [30] while also ensuring that the saturation level was achieved. The inter-coder reliability rating demonstrated a satisfactory level of agreement, with 70 % consensus among the authors [31]. This meticulous approach resulted in a robust and rigorous analysis, contributing to the credibility of the study findings.

Furthermore, to better compare the qualitative data, quantitative descriptive analysis methods were adopted. The frequency of distribution of various categories of factors identified in the interviews was the main statistical measure used to conduct these comparisons.

4. Results

4.1. Descriptive findings: participants profile

Six key stakeholders who influence the use of PwRC in modular construction products were interviewed in the first half of 2024. The interviewees were experienced individuals with a significant track record of involvement in modular construction in Australia. As outlined in Table 2, each of these participants possessed complementary skills and experiences crucial to the inquiry—ensuring that data saturation was achieved without the need for further participants. Five of these interviewees were employed in different departments of ATCO S&L and were based in Queensland at the time of the interviews.

The technical manager of the study organisation (P_1) was a design engineer by background with extensive engagement in a wide range of activities within the MMC context on a global scale. He also managed the compliance and engineering aspects of the

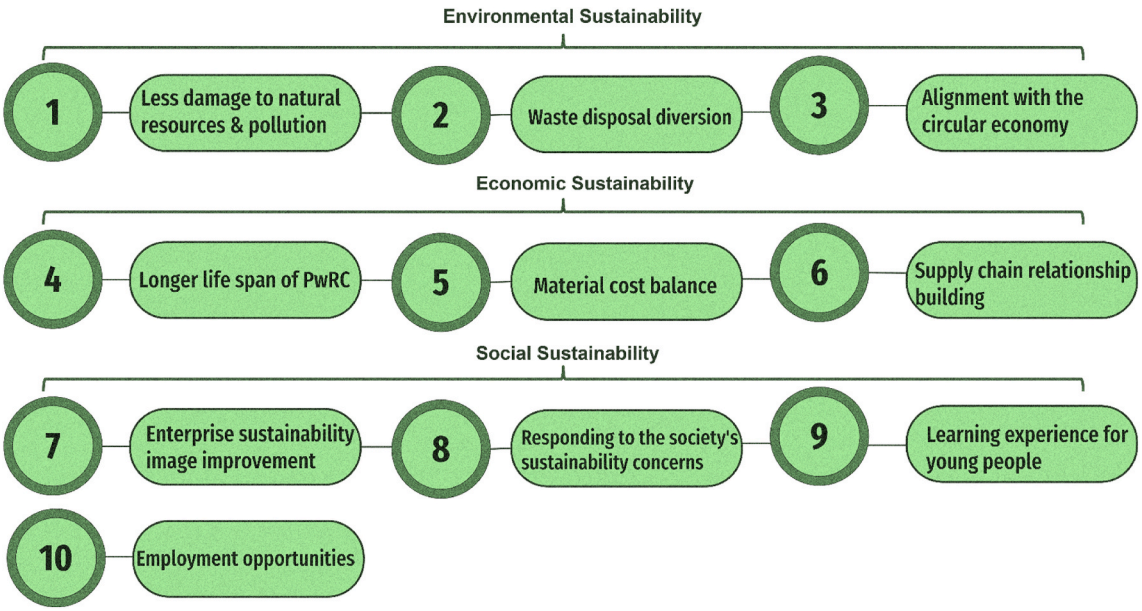

Fig. 3. The major sustainability benefits of using PwRC in modular construction.

organisation's modular products. The design manager of ATCO S&L (P_1) had worked for the organisation for more than 10 years, with the overall responsibility of designing modular buildings. The operations manager (P_3) had also extensive experience in the building and construction sector particularly in the MMC industry. The organisation branch manager (P_4) had stayed with the ATCO S&L for 14 years, with a speciality in business development and sales and marketing. The Health, Safety, Environment and Quality (HSEQ) manager of the organisation (P_5) had expertise in various fields and employment sectors. The last interviewee (P_6) was the representative of an organisation that supplied recycled steel to ATCO S&L.

When asked about their history of involvement in C&D waste management in their current or previous roles, the participants reported varying levels of exposure to this field. P_1 primary experience in this field relates to the design engineering of modular components to reduce waste generation. P_4 indicated that ATCO S&L is involved in waste minimisation and reusing the waste, to limit the waste of their products. P_5 reported that his exposure to the waste management industry was through various contracts he had with organisations both in the industry and outside of that. He also mentioned that he is involved in managing waste in ATCO S&L. P_6 mentioned that their organisation is the second biggest recycler of ferrous and nonferrous metals in Australia. The rest of the participants did not have any direct involvement with waste management, as the modular construction industry does not typically generate too much C&D waste during manufacturing, transport, installation or operation.

4.2. C&D waste management and procurement of PwRC

This section outlines the organisation's involvement in C&D waste management and the integration of PwRC in modular building products. It begins by detailing the organisation's strategies for managing C&D waste resources, followed by an overview of their initiatives for reusing modular products and procuring PwRC for new construction and retrofitting projects. Additionally, the contributions of each participant involved in these activities are highlighted where applicable. While some participants were directly involved in the procurement process, others were not, resulting in varying levels of understanding of the organisation's procurement procedures among different participants.

Typically, the off-cuts and waste materials generated during the manufacturing and installation of modular buildings are disposed of in recycling bins. These waste resources are managed through three potential pathways: 1. Collection by third-party waste operators, 2. Reuse in the production of new building products or applications in the retrofitting projects, or 3. Disposal in landfills. To minimise waste generation, the organisation set a criterion for material procurement focusing on the 'packaging materials' issues. P_1 reported that in some cases, the organisation negotiates with the supplier to reduce packaging waste materials. However, in most cases, the off-cuts and other waste materials are dumped into recycling bins, where, as outlined above, they might be reused in ACTO S&L products.

In this section, the organisational procurement model is reviewed and some of the procurement criteria being used are presented. Overall, despite having slightly different procurement criteria, the PwRC procurement model is not different from other alternatives (P_5) and their utilisation is to a limited extent as indicated by P_3.

According to the interviews, there are several factors influencing the procurement of PwRC in ATCO S&L products. These factors are listed in Sections 4.5-4.6. It also appears that there are currently no specific criteria established for the procurement of PwRC. However, the most commonly cited criteria for PwRC procurement include cost, availability, associated risk and suitability.

In ATCO S&L, generally, the design team specifies the construction materials based on the individual designs, which will be passed on to the manufacturing sector to procure. For the procurement of PwRC, these are suppliers that reach out to the organisation to sell their products. They share their products' specifications with the organisation (i.e. compliance team) to review them for fit for purposes point of view of the organisation. Most products are supplied through shorter supply chains with whom ATCO S&L established business arrangements. For instance, P_6, the supplying organisation representative, indicated that they supply steel construction products/materials with a high level of recycled content to ATCO S&L. These materials include angle channels, flats and hot rolled sections. The participant also commented on the upstream material supply chain. They primarily purchase metal waste materials from demolition companies who in turn extract them from building demolition projects. Additionally, they source them from the manufacturing businesses, their manufacturing unit and the general public.

There are four reasons why the organisation tends to choose a shorter supply chain when procuring materials, these include (1) the trust established between parties to avoid falling into the greenwashing trap, (2) avoiding product variability (3) more control over meeting product quality requirements and (4) lower prices. In some cases, the procurement is carried out by other suppliers for specific products e.g. timber products.

4.3. Sustainability benefits

The sustainability advantages of incorporating PwRC in modular construction, as perceived by the research participants, are thoroughly examined. The insights from the interviews provide a valuable complement to the literature review findings discussed before. As illustrated in Fig. 3, the participants identified ten key benefits of such an application that enhance social, environmental and economic sustainability outcomes in modular construction.

4.3.1. Less damage to natural resources & pollution

In participants' views, the use of PwRC in modular construction can enhance the environmental sustainability of the building and construction sector. The reduced need for extracting virgin materials contributes to environmental protection and pollution reduction. P_5 indicated that '*It* [the use of PwRC] *is reducing even the amount of raw product we're taking from the planet, raw deforestation for mines'*

[P_5]

4.3.2. Waste disposal diversion

The application of PwRC can generate demand for waste resources, which in turn reduces the volume of waste sent to landfills. Waste disposal diversion results in improved economic and environmental sustainability in the sector.

4.3.3. Alignment with the circular economy concept

Within the circular economy concept, the use of PwRC is emphasised as a key strategy to maintain the value of materials in the economy for as long as possible. According to P_1, utilising locally sourced PwRC can further enhance the sector's circularity by reducing the need for transportation and energy consumption. *'If the market makes that circle of the circular economy as small as possible, rather than sending, your waste all the way to either China or India or somewhere in Europe or North America to then, be recycled there and probably reused there'* [P_1]. Another participant indicated that '*That's* [using recycled products] *the idea of how you can do more with less. The idea of generating less waste is important, but use less too, use less energy, generate fewer emissions, increased circularity, increasing material efficiency*' [P_6].

4.3.4. Longer life span of PwRC

One participant indicated that some PwRC have better durability compared to products created from virgin materials. According to P_4, this in the long run can provide an economic advantage for the manufacturer of modular products. 'A lot of these recycled products have a longer life span than the other ones. *So, whilst they may be a higher initial investment, they certainly provide better economical advantages over the long term*' [P_4].

4.3.5. Material cost balance

As the consumption of natural resources continues to rise across various industries and for a range of products, their prices will likely increase. Additionally, in certain applications, the use of PwRC may not be technically feasible, leading to intense competition for virgin materials. Therefore, in the future, incorporating PwRC in modular construction could play a significant role in enhancing the economic sustainability of the building and construction sector. P_5 mentioned that '*If we're not using recycled products, the cost of a raw product style material will start to outweigh the cost of recycled material because there's less and less of it' … All of a sudden you're competing for those raw minerals because they're going into producing solar farms and wind farms … which means there's less for general steel production, etc.'*.

4.3.6. Supply chain relationship building

Given the reasons mentioned above, the use of sustainable materials is expected to increase across various industries. Therefore, it is prudent to begin adopting PwRC, which will, in turn, help establish an effective supply chain for these products. Working with an established supply chain will enhance the economic sustainability of the modular manufacturing industry. P_4 indicated that the early

Fig. 4. The main challenges of using PwRC in modular construction.

development of such supply chains is a key to success in this space.

4.3.7. Enterprise sustainability image improvement

The use of PwRC can enhance the enterprise's social image of businesses operating within the building and construction sector. Amid growing criticism of the sector for its unsustainable practices, applying these products not only bolsters social sustainability but, as noted by P_4, also presents economic benefits by collaborating with organisations that fund sustainability-driven projects or aim to position themselves as sustainable businesses.

4.3.8. Responding to the society's sustainability concerns

Societies worldwide, especially in developed nations, have gained greater awareness of environmental sustainability. As a result, there has been a significant increase in demand for sustainable practices and policies in different industries and sectors over the recent years. The use of PwRC can contribute to the overall sustainability of the sector, effectively addressing this growing demand. P_5 indicated that *'We can see socially that society is pushing more and more and more for sustainability. They want green energy, they want less products and pollution … they want to know that the people that they're getting things from are having the least amount of impact on the earth for their future generations and for their own health'*.

4.3.9. A learning experience for young people

Two participants (P_1 and P_2) highlighted that incorporating PwRC in modular products, particularly in educational settings, provides young people with valuable learning experiences. This exposure not only demonstrates the practical use of such products in buildings and modular structures but also nurtures a mindset aligned with sustainability principles. Consequently, this can further enhance the social sustainability of the sector. P_1 stated that '*daughter's school, they were having modular buildings installed and like everything else on a school site, gets turned into a learning experience for the children … and the story, where you're able to tell the story of a, particularly a modular constructed building, probably as a narrative*'.

4.3.10. Creation of employment opportunities

The process of converting waste materials into products typically involves multiple labour-intensive steps, generating more employment opportunities compared to waste landfilling. Consequently, utilising PwRC in modular construction can significantly enhance social sustainability by promoting waste recovery activities and the associated job creation. In P_6's view, '*It provides an economic return to those who return it to us as recyclers, the demolition companies, the manufacturers … there's a social impact around that from an employment point of view'*.

4.4. Challenges of using PwRC in modular construction

The number of challenges identified as hindering the application of PwRC in the modular construction sector far exceeded our expectations. After consolidating some challenge categories, 16 categories emerged. These categories include a broad range of issues, including supply chain, cost, organisational limitations and technical complexities. Fig. 4 illustrates these ten categories. The most commonly mentioned challenge category among these is 'cost complexities' followed by the 'industry conservative approach' and 'availability of PwRC'. The following sections provide insights into the industry perceptions regarding these challenge categories; they are presented in no specific order. The challenges highlighted in this section offer a foundation for advancing the modular construction industry, particularly in enhancing the incorporation of PwRC in modular products.

4.4.1. Project characteristics

The quality and quantity of PwRC utilisation in construction projects depend on various factors related to the project's nature, including both physical and non-physical aspects. These factors can hinder or complicate the use of PwRC in construction projects. As outlined by P_4, these factors can include the building's age, the project's size and the allocated budget. *'So we have buildings that are two months old and we have buildings that are 20 years old. And obviously, the specification between those two buildings varies a lot'* [P_4].

4.4.2. Cost complexities

The issue of cost complexities was cited by several research participants. This issue has three dimensions and can be divided into three subcategories based on the interviewees' responses: 1) The higher cost of PwRC compared to conventional materials, 2) Market interventions by competitors against PwRC supply and 3) The client's willingness to pay extra for PwRC.

4.4.3. Industry conservative approach

The building and construction sector is often viewed as resistant to innovation and change, with a strong aversion to the risks that come with any change. The industry's supply chain processes have evolved over decades and any change request is seen as disruptive, leading to various complications. This resistance is especially evident among senior managers, who tend to rely on familiar supply chains and products. P_1 described conservatism as a sign of ignorance. Below are some comments from participants on this issue: '*The construction industry, by its nature, is very conservative. But, like I said, a lot of things are based on, "It worked last time. I will do it again" … But I think it's a lack of imagination, is probably another way of looking at it and using a conservative, conservatism in the way of ignorance'* [P_1]

4.4.4. Greenwashing and product misrepresentation

This category refers to a well-established concept in the recycling practice and research. It is the practice of misleading end users by falsely claiming or exaggerating the environmental benefits or recycled content of a product. One participant (P_1) suggested that greenwashed products could pose a challenge to the seamless acceptance of PwRC in the sector. P_1 expressed that *'They all currently have drawbacks in their credentials as being completely recycled material. Having recently done some testing on some materials where they say, "Oh, it was made from this and this" and so due diligence and only a few hundred dollars later, I can get a test done and have it put to them that it's actually not what you say it is. So you actually misrepresenting your product'*.

4.4.5. Limited availability of PwRC and an immature supply chain

The limited availability of PwRC was a concern raised by three participants, who highlighted its significance given the volume and industrialised nature of modular construction. They pointed out that in modular construction the components must be readily available and supplied to manufacturing sites on time to prevent any disruption to the sequential production processes. P_1 highlighted that the availability of some PwRC is constrained by the comparatively small and immature supply chain operating in Australia, which serves a market of 25 million people.

4.4.6. Lack of organisational or regulatory targets for using PwRC

Organisational or regulatory targets can significantly encourage the use of PwRC by providing clear goals and incentives for organisations. These targets provide a structured approach to incorporating PwRC, aligning organisational practices with broader environmental goals. The lack of established targets for using these resources can reduce the motivation, accountability and innovation needed to effectively incorporate them into construction projects. The findings from the interviews indicate that, at present, there are no targets for using PwRC in modular construction within the study organisation, nor is there any policy in place to encourage their use. *'But at this point, we're not yet into that area. We're not yet sure, we're still in the reviewing process stage of those products* [PwRC] *and like assessment, but it hasn't been making up a firm call on those alternative reusable materials*' [P_2].

4.4.7. Lack of precedent in PwRC application

One participant observed that the modular construction industry tends to be cautious about using products that lack market testing. Demonstrated performance from previous use can build market confidence and foster wider adoption of these products. P_2 noted that while laboratory tests are a useful way to understand the nature of a product, they do not equate to assessing its actual utilisation and performance in modular components.

4.4.8. Health and safety issues

The use of PwRC presents health and safety complications. Physical and chemical changes during recycling processes can cause the industry to be cautious about using recycled materials due to potential health and safety issues. P_2 highlighted that it is not advisable to use PwRC which lacks accompanying safety data.

4.4.9. Lack of certification for recycled products

As indicated in the previous category, the unknown nature of recycled materials can hinder their widespread application in modular construction. The lack of a formal assessment of PwRC performance, safety and quality can lead to uncertainty and reluctance in their adoption, as stakeholders may have insufficient information to evaluate their suitability and reliability for construction projects.

4.4.10. PwRC longevity and performance

In the building and construction sector, the longevity and performance of materials are crucial for the successful delivery of

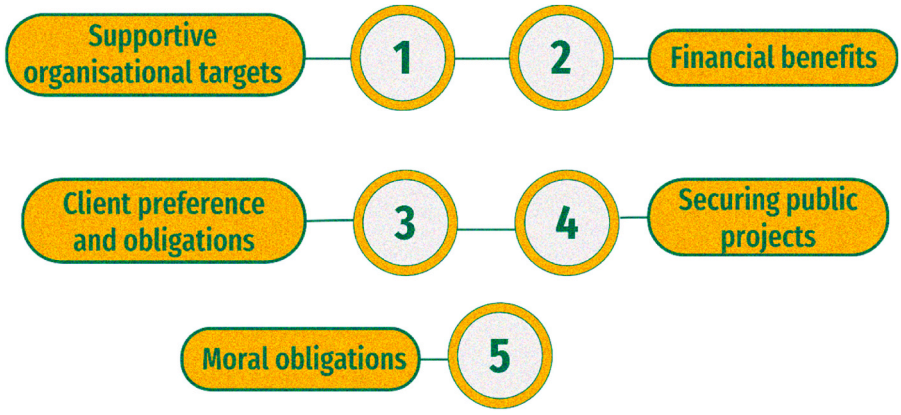

Fig. 5. Major drivers for using PwRC in the case study.

projects. Uncertainty regarding the longevity and performance of PwRC has been cited as a major factor limiting their use in modular construction. Several participants emphasised the importance of addressing this concern when considering the procurement of PwRC. For instance, P_3 noted that *'I think businesses would be open to using recycled materials as long as there was longevity in the material'*.

4.4.11. Lack of experience dealing with the PwRC supply chain

The study organisation currently has limited capacity to incorporate PwRC into its modular products. One participant reported that the organisation does not have a procurement strategy specific to PwRC. Consequently, their ability to effectively engage with the PwRC supply chain is also constrained. Two participants (P_5 and P_6) observed that this limitation could affect their procurement processes, even if the organisation is willing to enhance its sustainability impacts through the use of PwRC. P_5 explained that *'that's 100 % something that I think ATCO is aware that it's got to get, but I don't know if ATCO has enough experience yet to be able to understand how to have those conversations with suppliers to then target that and look at that'*.

4.4.12. Reliance on mainstream supply chain

The study organisation predominantly depends on mainstream, or shorter supply chains-as described by P_1- for material procurement. Although this procurement strategy offers practical benefits, such as greater control, it can significantly hinder the adoption of PwRC. Indeed, this limited pool of suppliers may struggle to provide a diverse range of PwRC that meet the requirements. P_6 mentioned that *'what I mean by a shorter supply chain is, if we have an established supplier who holds stock, who we deal with very well, we already have the correct payment terms and all that other kind of stuff'* [P_6].

4.4.13. Varying PwRC specs in modular construction

It is a fact that sometimes the application requirements vary between modular and standard construction. As such, PwRC suppliers need to meet varying requirements for the same material if they want to be engaged in both modular and standard construction markets. Two participants raised their concerns about this issue. As shared by P_2, *'the majority of all these sales reps, "Yes, it meets the requirement of the NCC* [National Construction Code]*" … But when it comes to construction then, if we applied in a different way, it's not going to meet the requirements, or it was going to lose the warranty of those products'*.

4.4.14. Limited reporting capacity

Both the organisation and the supply chain lack a mature infrastructure for reporting on PwRC usage. The absence of data needed for planning and decision-making in modular construction can discourage key stakeholders, including sustainability-focused clients, from using PwRC in projects. P_5 reflected that *'sometimes we end up finding in construction, we're ticking a box without actually having any data that are useable from that and the industry's not there necessarily learning … we've got limited data on the used side as opposed to the purchase side and we're trying to get on top of that'*.

4.4.15. Limited capacity to integrate PwRC into production processes

Despite the organisation having its own manufacturing unit, its current business model does not promote the internal integration of recycled materials into modular components. According to P_5, the organisation typically purchases final products that may or may not include recycled content, a practice that appears to be standard across the industry. This approach significantly limits the potential to optimise the use of PwRC in modular construction, as it hinders the organisation's ability to directly influence and incorporate sustainable materials into its production processes.

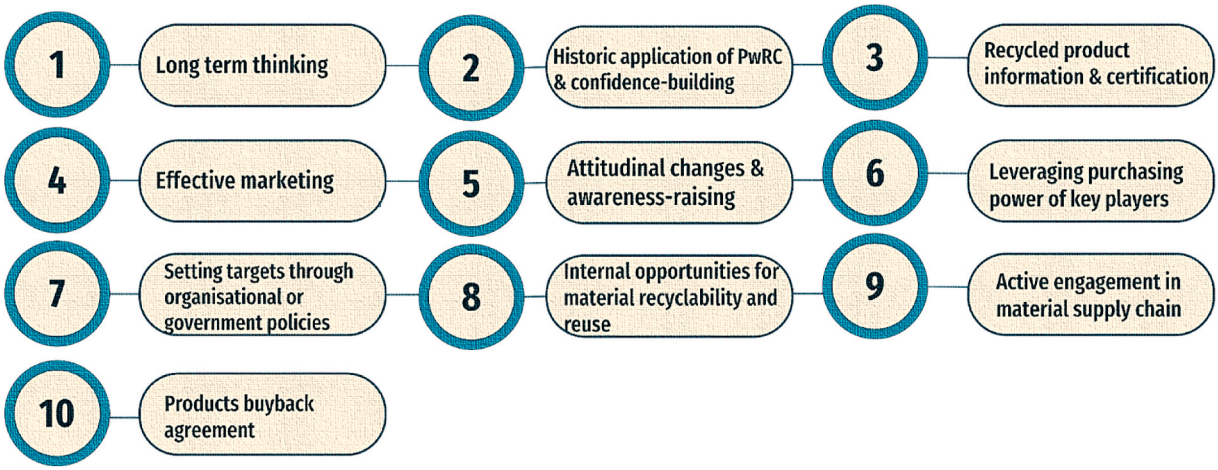

Fig. 6. Strategies to enhance the use of PwRC in modular construction.

4.4.16. Short-term thinking in the decision-making process

Short-term thinking in decision-making can restrict the organisation's ability to embrace innovation and change, especially in areas like the circular economy in modular construction. Given that the benefits of sustainability initiatives often accrue over the long term, transforming decision-making processes to prioritise long-term outcomes is crucial. P_4 stated that *'One of the challenges with short-term thinking is that there's a cost involved to it … You know, if sustainability is #1, then yeah, we're looking great. However, if the price is #1, then those options can look quite expensive in the short term'*.

4.5. Drivers of using PwRC in modular construction

The analysis of interviews showed that there could be six major drivers for using PwRC in modular construction. These factors are illustrated below (Fig. 5).

4.5.1. Supportive organisational targets

The incorporation of PwRC into modular products can be influenced by organisational targets/Key performance indicators (KPIs). These targets catalyse the required change in the organisational procurement model.

4.5.2. Financial benefits

The other motivating factor relates to whether these materials generate any financial benefits (Fig. 5). According to the interviews (P_1, P_2 *and* P_4), this factor can be a significant change facilitator in the decision-making process. However, these criteria vary depending on the material. For instance, the recycled alternative in steel is generally more cost-effective than in timber products. Furthermore, the long-term financial benefits of utilising these resources can be realised by integrating the reuse of waste materials into standard business practices. Over time, this will lead to a reduction in production and operational costs (P_4).

4.5.3. Client's preference and obligations

The third factor relates to the client's preference for using PwRC. This inclination may stem from their need to showcase their sustainability commitments, whether by reporting to public agencies, aiming for formal recognition through a sustainability rating system, or publicly promoting their dedication to sustainability. The client's preference typically is translated into contractual obligations. In this space, the government plays a key role in pushing a sustainability agenda including using PwRC in their assets and construction projects.

4.5.4. Securing public projects

In some cases, the client for ATCO S&L products is the government which is typically in favour of enhancing sustainability in their procurement (P_4). The growing demand for environmentally sustainable practices, including the use of green materials in government construction projects, is a significant driving force behind the adoption of PwRC in modular construction.

4.5.5. Moral obligations

The final factor pertains to the moral imperatives and ethical considerations that drive individuals to adopt sustainable practices. According to three participants (P_1, P_4 and P_5) in the organisation, staff would like to push the sustainability agenda: *'We do still have a personal obligation as human beings to try and do our best to make sure that we're not overusing things that we don't need to. So, there's a moral obligation there*' [P_4].

4.6. Strategies to optimise the use of PwRC in modular construction

The next section of the interview focused on strategies to effectively remove or minimise the challenges associated with utilising PwRC in modular construction. The analysis of interviews identified 10 major strategies that companies involved in modular construction in Australia can employ to increase the uptake of PwRC in their products. These strategies fall into three key domains: organisational capacity building, supply chain management assessment and improvement and sustainable business decision-making. Among these, the categories of "attitudinal changes and awareness raising" and "internal opportunities for material recyclability and reuse" were found to have the most significant positive impact. The identified categories are illustrated in Fig. 6.

4.6.1. Long-term thinking

The long-term thinking approach involves planning and deciding with a focus on future outcomes rather than just immediate benefits. At present, the use of PwRC does not necessarily yield immediate economic benefits, with both potential and tangible advantages often materialising only over the long term. Therefore, organisations in the modular construction sector aiming to enhance sustainability and achieve their business objectives must adopt long-term thinking in their decision-making processes, particularly when it comes to incorporating PwRC into their products. This point was made by P_4 who suggested that long-term thinking is the key to success: *'These days, a lot of businesses are making a lot more long-term decisions as opposed to short-term decisions within the business to ensure that we're doing the right things to put us in a good frame coming into the next five, ten, twenty years'* [P_4].

4.6.2. Historic application of PwRC and confidence-building

The successful application of PwRC across the industry can significantly boost confidence in utilising these resources. Two

participants in this study emphasised that their organisation would be more likely to adopt PwRC in their products if these materials had been used in real-life projects and relevant data were available. Creating demonstration modular projects where the study organisation successfully integrates PwRC offers a unique opportunity to lead the market and set a precedent in this area.

4.6.3. Recycled product information and certification

Three participants noted that certified information on PwRC can inform their procurement process. However, the effectiveness of this process can be hindered by the existence of various certification schemes and different product information. To address this, the organisation should develop new or utilise existing standard templates to ensure consistent and reliable product information is received. In this process, consulting with trusted third-party PwRC certifiers and major suppliers is essential. Such a template should outline the product's features (such as physical and chemical characteristics) as well as its functions (including quality, longevity and performance). The template must align with sustainability reporting requirements, including Green Star, Infrastructure Sustainability (IS) rating, Leadership in Energy and Environmental Design (LEED) and the National Greenhouse and Energy Reporting (NGER). According to P_2, the product information should be prepared and produced to demonstrate their conformity with the NCC.

4.6.4. Effective marketing

Being able to communicate the sustainability practice of the organisation can offer a series of benefits. According to P_5, these benefits may include having a positive return on the business and more clients would like to work with the organisation compared to their competitors. Sustainability is a key selling point for businesses in the current and future industry climates. The use of these products in modular construction can be aligned with many sustainability initiatives including Environmental, Social and Governance (ESG) and SDGs; Reporting the achievement of these goals, along with promoting the improved organisation's socio-environmental profile through targeted marketing tools, can enhance visibility across industry, government sectors and the general public. This increased visibility can lead to greater customer reach, stronger brand recognition and enhanced credibility within the market. Effective marketing strategies are essential for achieving the best outcomes. These strategies should communicate and highlight the journey behind the use of PwRC, the organisation's achievements and the benefits they offer, ensuring maximum visibility and impact.

4.6.5. Attitudinal changes and awareness-raising

Several challenges highlighted in Fig. 4 can be effectively addressed with this strategy. In particular, it can help overcome the industry's conservative approach and short-term thinking in decision-making. By raising awareness among key stakeholders about the potential and actual benefits of using PwRC, this strategy can accelerate the procurement and application of these products in modular construction projects.

4.6.6. Leveraging the purchasing power of key players

Key players in the modular construction industry, such as ATCO S&L, possess significant influence to make the use of PwRC a standard practice across the sector. As market leaders, these companies should focus on building internal capacity to effectively procure and integrate PwRC into their products. Once these practices are established as the industry norm, it will encourage small and medium-sized enterprises (SMEs) to adopt similar procurement strategies, further embedding PwRC use in the industry. According to P_4, their purchasing power can generate sustainable demand for these products, potentially leading to economies of scale and a reduction in production costs. The organisation and the recycling industry can capitalise on the advantages of mass production, leading to enhanced profit margins.

4.6.7. Setting targets through organisational or government policies

Setting targets for using recycled content in products can guide processes involved in the procurement and application of PwRC in construction projects. Reasonably set targets can drive numerous changes within organisations, including fostering innovation, promoting accountability, building market demand and encouraging collaboration across material supply chains. According to P_3, the

Table 3
Participants' views regarding the future of PwRC applications in modular construction.

Participant	Key point	Quote
P_1	**Challenges posed by sector conservatism**	*I think the future applications of recycled materials will be in new product development because the construction industry, by its nature, is very conservative. But, like I said, a lot of things are based on, "It worked last time. I will do it again". And so, you always end up with an 'It's almost like a generational change'.*
P_2	**Initially complex, ultimately ubiquitous**	*I think it can be complicated for a start, but then for a certain period of time in that transition period, I think everyone will start picking up and say, "OK, yeah, it's worth going with recycle*
P_3	**Mainstream upon sector's adoption**	*If there's a place for recycled material in construction, there's probably no problem in a ship to modular construction to utilise those projects, those products.*
P_4	**Expanding with growing PwRC development**	*I think it's only gonna get bigger and bigger, personally. More and more products are being delivered and created with recycled materials.*
P_5	**Dependent on the industry mindset transformation**	*It's not so much the need for modular to look at how we generate a product in the first place. It's what products are out there and how do we use them in our existing processes? It's more getting the big players in the modular industry … to change their mindset so that they can accept* […] *like for different with a better outcome.*
P_6	**Growth driven by urban development needs**	*As countries and as cities develop, that supply chain of recycled material increases because you put it in once and as you redevelop, rip down, repair, rebuild, that steel comes back out and into the recycling channel*

Fig. 7. A framework to influence stakeholders for optimal uptake of PwRC in modular construction.

government can play a pivotal role in setting these targets by developing policies such as sustainable procurement guidelines.

4.6.8. Internal opportunities for material recyclability and reuse

Organisations in modular construction can plan for maximum recyclability and reuse by incorporating these considerations throughout their manufacturing, operation and execution phases. Such incorporation can be more effectively implemented through adopting a circular economy business model. This way they can influence their internal stakeholders to advance the circularity of their products. Almost all participants in this study emphasised the importance of exploring opportunities to capture the value of waste resources and enhance the utilisation of PwRC in modular construction. For example, P_1 and P_4 stressed the need to revisit their production line to evaluate opportunities for material recyclability and reuse. Similarly, P_6 noted that their organisation aims to recapture product waste resources for repurposing and reuse through extended producer responsibility practices.

4.6.9. Active engagement in the material supply chain

Modular construction companies should actively engage in the material supply chain to influence their external stakeholders to achieve material circularity outcomes. Changes within the supply chain should focus on waste reduction, increased utilisation of recycled content and the enhancement of PwRC quality, longevity and performance. According to P_4, these changes should stem from strategic partnerships with material suppliers involved in PwRC production and supply. *'We could start to look at creating partnerships with companies who sell the products that we require for sustainable or recycled materials so that we can look to get better buying power and therefore create a lower price point for our clients'* [P_4]

4.6.10. Product buyback agreements

The final strategy involves creating contracts that explicitly stipulate a product buyback agreement between modular manufacturers and end-users. Given that modular products are not always used permanently, a buyback arrangement provides an opportunity for manufacturers to repurchase these items from end-users. According to P_1, this agreement offers mutual benefits: end-users can generate revenue by selling unused products, while manufacturers gain the opportunity to recover modular products either fully or partially. The materials salvaged from these end-of-life modular products can then be repurposed in new modular builds, promoting sustainability and resource efficiency.

4.7. The future of PwRC applications in modular construction

The interviewees suggested that a broader application of PwRC in the modular construction industry is plausible in the future. However, several participants emphasised the necessity of specific changes for this to materialise. These changes include overcoming the sector's conservative approach, its mindset transformation, preparing for a transitional phase and achieving greater adoption within the conventional construction sector. Table 3 presents the key points highlighted by participants in response to this question.

5. Discussion

5.1. A framework to enhance PwRC uptake in modular construction

The following framework is proposed based on the findings of the literature review and the insights captured in the interviews. The framework guides efforts in removing the identified obstacle to sustainable and optimal uptake of PwRC in modular construction. As outlined in Fig. 7, the framework consists of four components. These components, along with the embedded strategies, address multiple facets of the transition to a circular economy by strengthening the industry's overall capacity to adopt and integrate these resources effectively. These aspects are categorised under organisational capacity, supply chain development and stimulation, quality of recycled products and developing supportive regulations and policies.

While a systems approach is ideal for implementing these strategies in parallel, the reality often falls short due to a variety of internal and external factors. Some of these challenges are rooted in the cash flow dynamics of the construction materials market, which tends to align with the existing industry's interests, preferences and arrangements. Therefore, a practical approach would likely involve prioritising implementation through the use of a multi-criteria decision-making (MCDM) method. This should analyse the strategies' impacts on and influences from various stakeholders and businesses, evaluate the benefits concerning the three pillars of sustainability, assess the associated risks (including likelihood, severity, and impact), and consider the time horizon by distinguishing between short-term and long-term outcomes.

The development and application of MCDM tools to identify key options and criteria for sustainable building, particularly the use of PwRC in construction projects, have been well documented in previous literature [32]; [22,29,33]. For instance, Jato-Espino et al. [32] reviewed the application of 22 different MCDM methods in various areas of the construction industry and identified the most suitable ones for construction projects. A study by Knoeri et al. [29] determined the most important criteria for using PwRC in construction projects in Switzerland. This evidence underscores the importance of having a real-time understanding of the context before making decisions about the implementation of enabling strategies in the field of the circular economy. In turn, this will provide organisations and businesses with confidence that the strategies implemented will achieve the expected outcomes.

5.2. Business model

As previously noted, the effective use of PwRC in optimal quantities is closely tied to the operational practices of the business in question. This includes factors such as supply chain management, procurement policies, resource allocation, and the company's overall commitment to sustainability. The integration of PwRC requires alignment with these business processes to ensure consistent material availability, quality control, and adherence to project timelines. Furthermore, the success of implementing PwRC often depends on the business's ability to collaborate with stakeholders, adapt to market demands, and remain flexible in the face of regulatory and industry shifts. Ultimately, it is the business's operational efficiency and strategic approach that determine whether PwRC can be adopted at scale and deliver its intended environmental, social, and economic benefits.

As identified in this study, developing practices in large modular construction businesses leading to optimal use of PwRC is not easy. One participant expressed that '*the problem is most likely that the majority of people that are in senior positions in the larger modular firms have spent most of their career in those businesses, so they're so comfortable and familiar with what they've done and their supply chain*' [P_5]. Hence, creating new business models based on the circularity principle can change the ecosystem in favour of these goals.

In recent years, there has been a significant surge in studies exploring circular business models [34]; [22,35,36], reflecting growing interest in sustainable practices and the transition to a circular economy across various industries. Research from a European study [22] suggests that the proposed circular business model holds considerable potential to make reuse price-competitive with traditional linear production practices, deliver value to customers and partners within the value chain, and significantly reduce environmental impacts.

The Product-as-a-Service (PaaS) business model offers significant benefits for modular construction in the context of the circular economy, especially when using PwRC [37]. In PaaS, manufacturers retain ownership of their products and provide them as services, maintaining responsibility for maintenance, upgrades, and eventual disposal or recycling [34]. This model aligns with modular construction by allowing buildings to be easily disassembled and reassembled, making it feasible to swap, upgrade, or refurbish parts instead of discarding them. By integrating PwRC into modular components, companies can extend the lifecycle of products, encouraging a "closed-loop" approach where components and materials are continually reused or repurposed [61]. Additionally, PaaS incentivises manufacturers to prioritise durability and easy recyclability in their products, as they benefit directly from extending life and reducing the waste of their components [38]. Applying this model also facilitates the implementation of extended producer responsibility [63] in the building and construction sector.

6. Conclusions

The use of PwRC in the building and construction sector has been reported as a vital step towards a circular economy. However, the research on the use of PwRC in modular construction is scarce. This research has addressed this gap by conducting a case study investigating the main challenges, strategies, benefits and motivations of using these resources in prefabricated products. The findings suggest that the research participants assume that the use of PwRC can offer several sustainability benefits in social, environmental and economic domains. However, it was indicated that the obstacles to achieving these benefits are very and varied (see Fig. 4). The study proposed a framework (see Fig. 7) aimed at guiding industry efforts to overcome these obstacles. Additionally, the research suggests

that the use of PwRC in modular construction is anticipated to rise as the availability of PwRC increases and more buildings are constructed (see Table 3).

While this research informs the future research agenda in numerous directions, three specific areas warrant further exploration due to their potential impact on facilitating the transition of modular construction toward a circular economy. These areas encompass the development and validation of specific circular business models for modular products, the effective education of key stakeholders who influence the reuse of PwRC, and the creation of an MCDM tool to facilitate the transition to a circular economy.

The research findings also offer valuable insights for the policy-making sector. Currently, in many countries, policymakers are exploring strategies to mainstream materials reuse in businesses operating within industrial buildings and other sectors of the built environment. For example, findings such as the absence of regulatory targets and the prevalence of greenwashing activities should be taken into account when developing new policies.

Although the findings are derived from a single case study and should be approached cautiously regarding generalisability, the organisation under investigation operates similarly to other prefabrication manufacturing organisations in the Australian context. This parallel suggests that the insights gained may be relevant for broader applications within the industry.

CRediT authorship contribution statement

Salman Shooshtarian: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter SP. Wong:** Writing – review & editing, Validation, Resources, Project administration, Investigation, Data curation, Conceptualization. **Tayyab Maqsood:** Validation, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Peter SP Wong reports financial support was provided by Australia Sustainable Built Environment National Research Centre. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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