Journal of Building Engineering 102 (2025) 111805

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Sustainability of prefabricated construction in Australia: Industry perspectives on challenges and opportunities

Matthew Daly [a,b,*], Leela Kempton [a], Tim McCarthy [a]

[a]. University of Wollongong, Wollongong, Australia
[b]. University of Technology Sydney, Sydney, Australia

ARTICLE INFO

Keywords:
Sustainability
Prefabricated construction
Building
Life cycle analysis
Waste
Modular

ABSTRACT

The building construction industry serves an important role in working towards at least 10 of the United Nation Sustainable Development Goals (SDGs), making sustainability considerations crucial. Alternative construction methods such as prefabrication have been sought to improve sustainability. In Australia, the prefabricated building industry is still relatively immature, primarily targeting either rural/remote constructions or large repeatable commercial designs. There has been little exploration of sustainability or quantifiable data to assess the state of the industry. This paper reviews global understandings of sustainability in prefabricated construction and presents results from the first stage of an exploration into the issue in Australia. This work has been conducted as part of the Australian Manufacturing Growth Centre's 'Prefabrication Innovation Hub'. Drawing on insights from 21 stakeholders from the prefabrication industry, it presents a snapshot of current approaches to, and consideration of, environmental, economic and social sustainability within Australian prefabricated building construction. The paper discusses key challenges currently faced, as well as the areas that provide most opportunity for constructive change. Findings show that whilst sustainability considerations are currently limited, there is an awareness that environmental impacts may be a strength of the industry and there is strong potential to explore the processes being undertaken and identify quantifiable measures of sustainability. Although the prefabrication industry in Australia is still developing, it is likely that in the near future the industry will be faced with choices to adopt more sustainable processes as more advanced manufacturing processes are incorporated into industry practice.

1. Introduction

The construction industry is a major component of the global economy, and must play a key role in realising the vision of social, economic and environmental sustainability as outlined in the UN Sustainable Development Goals (SDGs) [1]. The construction industry's impacts reach across all 17 goals, and will play a critical role in the outcomes for 10 key SDGs [2]. However, significantly reducing the impacts from the built environment and associated building construction provides one of the largest challenges for governments looking to meet international climate commitments [3]. In 2020, the construction and operation of buildings was responsible for 37 % (11.7 gigatons) of global energy-related CO_2 emissions, and 36 % of global energy demand (149 EJ) [4]. The construction and materials alone - excluding operations - accounted for 10 % of energy-related CO_2 emissions in 2020. To achieve the

* Corresponding author. University of Technology Sydney, Australia.
E-mail address: matthew.daly@uts.edu.au (M. Daly).

https://doi.org/10.1016/j.jobe.2025.111805
Received 24 May 2024; Received in revised form 17 December 2024; Accepted 6 January 2025
Available online 28 January 2025
2352-7102/

Paris Agreement targets, the global buildings' sector must almost completely decarbonize by 2050, whilst at the same time meeting a projected doubling of demand for energy services in buildings and at least a doubling of floor space (*ibid*).

In addition to energy related CO_2 emissions, the construction sector is a major contributer to the consumption of natural resources, with material use by the global construction sector tripling from 6.7 GT in 2000 to 17.5 GT in 2017 [5]. This material consumption is largely concrete and aggregates – which together account for more than two thirds of the material use by weight. These non-metallic minerals account for almost half of global material usage and this usage is projected to double over the next 50 years [6]. A corollary of this resource consumption is the associated waste generation, with the construction sector estimated to contribute to 38 % of all solid waste generated in Australia [7]. Efforts to reduce the environmental impacts of the buildings sector have historically placed more emphasis on the operational life of buildings, as this accounts for the majority of lifecycle impacts. Currently, research estimates that between 80% and 90 % of energy use and greenhouse gas (GHG) emissions are generated during the operational life of a building [8], with the remaining 10%–20 % coming from material manufacture, construction (including transport) and demolition. However, as the energy efficiency of buildings operations improves, and energy production is increasingly decarbonised, the impacts from construction, and the manufacture of raw materials, known as embodied carbon in buildings, become increasingly significant. It has been estimated that for Australian buildings, embodied emissions will account for 85 % of total carbon emissions by 2050 [9]. It is therefore imperative that the whole of life carbon emissions are taken into account when considering the sustainability of construction.

As the whole life cycle of buildings is considered, attention has turned towards innovation in construction practices and material usage in an effort to improve sustainability. One approach is prefabrication, also known as off-site manufacture, which can take advantage of production in a controlled factory environment to address some of the challenges of traditional construction [10]. Existing research indicates that prefabrication can deliver a number of sustainability benefits in building construction, particularly through improved material efficiency in design and construction, reduced labour demand, and improved waste management processes [11–14]. However, the extent of these benefits are largely contextual, depending on the prevailing construction materials, processes, and measurement approach [15].

This is not a new approach to building, with the off-site manufacturing industry well established in a number of advanced economies globally. In Sweden, for example 84 % of detached dwellings, and approximately 20 % of apartments are prefabricated, with close to 20 % of dwellings in The Netherlands and 12%–16 % in Japan [16,17], Clear data on the uptake of prefabrication in the Australian building construction industry is rare. The best available data indicates the prefabrication of buildings represents only a small portion of the Australian domestic residential housing market, estimated at 3 % in 2015 [18]. The state of Victoria is seen as leading the country in off-site construction and yet only 5 % of homes constructed in Victoria in 2016 were prefabricated [19]. Even if considering the entire $150 billion building and construction industry (including commercial, tourism and mining construction), prefabricated construction accounts for less than 5 % [16]. This small portion is largely dominated by the offsite fabrication of roof trusses, window fittings and pre-cast prestressed concrete slabs [18], although this is a dynamic market with frequent changes. While substantially less than some other advanced economies, this is comparable to the United States (3 %–7 %) and the United Kingdom (2 %–7 %) [17].

In the Australian context, the potential sustainability impacts of the predicted growth of this industry have yet to be fully explored. The aim of this paper, therefore, is to explore the current status and understanding of sustainability of the Australian prefabricated construction industry, based on a qualitative investigation with industry leaders. The objectives of this study were: identify current awareness of potential sustainability benefits within the prefabricated construction industry, investigate the extent to which best practice in sustainability is incorporated into the industry, and to identify the challenges and opportunities faced by the industry to improve sustainability in its construction practices.

This paper is structured as follows: Section 2 provides the background to prefabricated construction, relevant sustainability frameworks, and reviews current understanding of sustainability in prefabricated construction. Section 3 (methodology) describes the scope of research on which this paper is based. The results of the qualitative investigation of the sustainability in prefabricated construction in Australia are presented in Section 4, covering the awareness and extent of implementation of sustainability practices. A review of the challenges and opportunities related to sustainability for the prefabricated construction industry is discussed in section 5, along with a summary of the pathways identified to progress the industry, followed by conclusions.

Table 1
Modular building sustainability performance criteria (adapted by listing in ranked order from Kamali, Hewage and Milani [20]).

Environmental	Economic	Social
Energy performance and efficiency strategies (EP)	Design and construction time (DCT)	Workforce health and safety (WHS)
Waste management (WM)	Design and construction costs (DCC)	Safety and security of building (SSB)
Material consumption in construction (MC)	Investment and related risks (IR)	Affordability (A)
Site disruption and appropriate strategies (SD)	Durability of building (DB)	Community disturbance (CD)
Embodied Energy (EE)	Integrated management (IM)	Functionality and usability of the physical space (FU)
Renewable and environmentally preferable products (REP)	Operational costs (OC)	User acceptance and satisfaction (UAS)
Greenhouse gas emissions (GE)	Flexibility of building (FB)	Aesthetic options and beauty of the building (AB)
Renewable energy use (RE)	Maintenance costs (MC)	Influence on the local economy (ILE)
Regional (local) materials (RM)	End of life costs (EC)	Neighbourhood accessibility and amenities (NAA)
Site selection (SS)		Health, comfort and well-being of occupants (HO)
Water and wastewater efficiency strategies (WE)		Influence on local social development (ISD)
Alternative transportation (AT)		Cultural and heritage conservation (CHC)

2. Current understandings of sustainability in prefabricated construction

Prefabricated construction, also known as offsite manufacture, modular construction or industrialised building systems, refers to any method of construction where components, modules or even entire buildings are constructed 'off-site' in a factory environment and subsequently transported to the final building location. Categorisation of prefabricated construction occurs based on the degree of prefabrication, ranging from components and sub-assembly, to panelised systems, semi-volumetric systems (e.g. volumetric bathroom pods in conventional unit construction) and at the upper end of the scale fully volumetric construction [13]. Less commonly, it can be categorised based on the percentage of total project comprised of prefabricated elements (ibid).

Sustainability in the context of construction is about more than just environmental impact – assessing sustainability requires a suitable framework to ensure all relevant indicators are considered. One such framework that has been proposed in the context of prefabricated construction was developed by Kamali et al [20], through review of literature and expert interviews (show in Table 1). The indicators take a triple bottom line approach, considering environmental, economic and social factors. This work prioritised the indicators based on surveys with practitioners familiar with the North American construction industry, with this ranking reflected in Table 1. The breadth of these indicators captures the role of the construction industry in working towards 10 key SDGs [1], identified by Fei et al [2] as: sustainable cities and communities (SDG 11); climate action (SDG 13); clean water and sanitation (SDG 6); responsible consumption and production (SDG 12); industry, innovation and infrastructure (SDG 9); life on land (Biodiversity) (SDG 15); gender equality (SDG 5); good health and well-being (SDG 3); affordable and clean energy (SDG 7); decent work and economic growth (SDG 8). This illustrates the potentially broad impact that may arise from the adoption of different construction methods.

There is a strong body of research exploring various sustainability impacts from prefabricated construction, which includes studies considering an holistic approach to sustainability (e.g. Kamali and Hewage [11] and Lopez-Guerrero et al. (2022), as well as studies that have focused in on more specific aspects such as waste generation (e.g. Ref. [21,22]). Overviews of some of the findings of the literature for environmental, economic and social factors, mapped against the indicators developed by Kamali et al. [20] are given in Tables 2–4. Overall, current research supports prefabrication as a construction approach that can deliver sustainability benefits. However, there is diversity and nuance in the findings, depending on factors such as measurement methodology (choice of indicators and comparison benchmarking), construction processes (e.g. degree of prefabrication, production technology), energy resources and material usage (e.g. timber, steel, concrete etc.). Construction is a complex activity, and any evaluation of triple bottom line sustainability must be grounded in the context of the region of activity [15].

The majority of research to date has focused on environmental impacts, with less considering economic and social sustainability [13,15]. A large-scale review of 67 papers by López-Guerrero et al [13] found that only 8 % of studies considered all three aspects of environmental, economic and social sustainability. Of the studies reviewed, half were in China (24) or Malaysia (11), and only five (5) studies focused on Australia [14,23–26]. In addition to the lack of focus on social and economic performance of prefabricated construction, there was also found to be gaps in the research around reusability and prefabrication levels considered.

Table 2
Summary of previous findings from research on environmental sustainability of prefabricated construction.

Indicator	Overview of findings	References
Energy performance and efficiency strategies	Whilst the energy efficiency of the buildings constructed is impacted more by the design and materials than the construction method, prefabricated constructions have shown a great potential to product high levels of energy efficient designs.	[50,51]
Waste management	Considered one of the greatest comparative advantages of prefabrication. Significant reductions in waste generation on site, and better management of waste within factory, with overall average reduction of 61 %.	[13,21,52,53]
Materials consumption in production	Material usage, and extent of optimisation, varies by material and methodology. Overview analysis found an overall average reduction in material use of 21 %, with 43 materials/components performing better, and 22 performing worse.	[13,31]
Embodied energy	Findings for embodied energy suggest a reduction (~9 %–10 % reduction), with large variation.	[23,54,55]
Renewable and environmentally preferable products	Limited discussion on the links between modular construction and uptake of these building materials and products.	[20]
Greenhouse gas emissions	Studies suggest a reduction in embodied carbon from prefabrication (average reduction of ~15 %), and operational carbon (~3 %), but there can be a wide range.	[23,54–56]
Renewable energy use	Data is scarce on uptake however there is potential to increase proportion of construction energy from renewable sources in the factory.	[15,57]
Regional (local) materials	Increased usage of local materials suppliers, and corresponding reduction in transportation distances recognised as an important aspect, although research examining this was scarce.	[15,26]
Site Selection	Link between construction method and site location typically related to access or other aspects. Little discussion in the literature from an environmental perspective.	[14,20]
Water and wastewater efficiency strategies	Little quantitative evaluation has been performed. Key factors are electricity usage (and generation type) in construction and use in concrete. Average comparative reduction of 11 %.	[13,30]
Alternative transportation	Reduced materials transportation to site. Vehicular congestions and transportation related issues can be reduced by up to 70 %	[13]
Other	Air and soil pollution: Ozone depletion potential, smog potential and photochemical smog are all highly dependent on transportation assumptions. Small positive benefit seen. Noise and dust emissions: Shown to obtain average decreases of 33.89 % and 20.47 % for dust and noise pollution due to reduced construction works on site.	[11,58–60]

Table 3
Summary of previous findings from research on economic sustainability of prefabricated construction.

Indicator	Overview of findings	References
Design and construction time	Recognised as a key advantage, as can concurrently schedule works and avoid weather delays. Measured reduction in construction times from 15 % to 76 %.	[11,13]
Design and construction costs	Huge variation, based methodologies, and other factors. Ranges from −72 % (more expensive) to +64 % (cheaper).	[13,33]
Investment and related risks	The upfront cost of implementing off-site manufacturing techniques is a commonly cited factor for low uptake of this type of construction. The financing and cash flow typically differs from conventional construction, changing the risk profile that builders are accustomed too.	[34]
Durability of building	Higher quality construction and finishing is discussed as a potential benefit, however there is limited evidence on durability. There is the potential for prefabricated components to be more difficult to repair.	[20]
Integrated management	Significant potential for improving collaboration, workflow and supply chain management through the integration of Building information modelling (BIM) with Design for Manufacture Assembly. Actual implementation varies.	[14]

Table 4
Summary of previous findings from research on social sustainability of prefabricated construction.

Indicator	Overview of findings	References
Workforce health and safety	Accident rates were reduced by 63 % due to less or no use of scaffolding, as well as fewer activities, less work at heights and fewer workers on-site.	[27]
Safety and security of building	There is a lack of technical standards and knowledge around aspects such as fire and acoustic performance outside certain markets	[14,61]
Affordability	Majority of studies indicate higher costs overall for prefabricated construction compared with traditional, although there is potential for costs to decrease when applied to multiple projects.	[15,34,62]
Community disturbance	Building off-site generally reduces disturbance to the community from building construction, particularly through on-site noise and disruption.	[14]
Functionality and usability of the physical space	Designs of modular spaces can pose a challenge when considering additional loads from lifting, transportation and connections between modules.	[14]
Other	Standardised workplace environment, with highly organised operations and better supervision results in improved productivity. Learning curve for workers in factory undertaking repetitive tasks is simpler resulting in higher quality. Modular construction requires less skilled work on site.	[11]

From an environmental perspective, as seen in Table 2, one of the major advantages of prefabricated or offsite construction identified is reducing waste in construction [12,27]. In one survey of 51 industry respondents on the sustainable performance of prefabricated systems, the impact on construction waste was one of the highest positive indicators [28]. Also, in a review of 86 case studies on prefabrication, 30.2 % analysed waste reduction either quantitatively or qualitatively, and all found that prefabrication had a positive impact on waste, with an average reduction of 60.9 % [13]. However, there is great uncertainty when it comes to quantifying the reduction that can be achieved, particularly as it is heavily dependent on the approach taken. Average values of waste reduction reported vary between 10 and 100 % [13]. Many of the studies which have investigated waste, however, are based on subjective data, or have inconsistencies in measuring methodologies [29]. For example, Quale et al [30] found that the reduction in wood wastage by adopting modular construction was offset by the extra bracing and support required to support the studied modular panels.

The utilisation of precision manufacturing technology, as well as the controlled environment of the factory, are also seen to provide greater material efficiency as well as greater opportunity for capture, segregation and reuse of materials [23]. This, in turn, provides scope for more sustainable construction practices, including better quantification and reduction of life cycle impacts and waste generation [13].

Findings around economic sustainability are summarised in Table 3. Prefabrication is widely seen as providing greater control of construction timelines, costs, quality and processes [31–33], due to the controlled environment in which construction is undertaken. Assessment of the impact of prefabrication on cost is varied [13], and challenges regarding investment risks have also been highlighted [34].

Research considering social sustainability of prefabricated construction is provided in Table 4. It is considered that the controlled production environment makes it easier to provide safer work environments to employees [27] and can also make construction jobs accessible to a wider and more diverse workforce [11].

Whilst there is extensive international research on sustainability in prefabrication, there has been limited work done in the Australian context. Aye et al [23] used a case study approach, finding mixed results regarding the quantified embodied energy and material use impacts of using prefabricated steel or timber in a multi-residential construction. Hammad et al [24] developed and tested a decision support tool for contrasting conventional and modular construction methods based on selected sustainability criteria, which found advantages in terms of minimizing pollution and risk of injury when compared with the conventional construction. Hu et al [25] took a broader perspective, with a content analysis of sustainability perceptions based on the websites of PrefabAus (the peak industry body for prefabrication in Australia) members. This found public-facing mention of environmental, social and economic sustainability, with '*High Quality*' and '*Customer-focused approach and customisation*' the most valued [25]. Navaratnam et al [14] undertook a broad survey of the construction industry perception on aspects of prefabrication such as economic, technical, cultural, along with sustainability. They found that sustainability considerations were the third ranking priority factor when deciding to use prefabrication, behind experience and familiarity. Finally, Zhang et al [35] looked broadly at challenges facing the Australian prefabricated construction industry, and identified twenty one recommendations, however, sustainability was not the primary focus.

The potential for positive sustainability impacts from increased prefabricated construction, along with the challenges and opportunities, are closely linked to the prevailing construction industry context. This study has sought to build on existing research by developing a more nuanced understanding of the current perspectives, challenges, and the possible future trajectory of sustainability in prefabricated construction in Australia, through in-depth discussion with industry leaders.

3. Methodology

This paper draws on in-depth data collected as part of research by the University of Wollongong as a member of the Prefab Innovation Hub, in partnership with the Advanced Manufacturing Growth Centre (AMGC). Previous studies exploring the Australian prefabricated construction industry have adopted survey [14] or publicly available content analysis [25] approaches. To explore the sustainability challenges and opportunities in greater depth, a qualitative approach was adopted as per Heffernan et al [36], as illustrated in Fig. 1. This involved a series of semi-structured interviews conducted with professionals involved in the manufacture, supply or use in construction of prefabricated buildings or components in Australia. The purpose of the interviews was to identify the level of awareness of sustainability issues and the extent of implementation of sustainability practices.

3.1. Sample selection

Prior to the commencement of interviews in June 2022, the authors compiled a database of eighty-four (84) companies active in the prefabricated construction space in Australia to be targeted as potential participants. This was comprised of the seventy-two members of the National peak body for the industry – PrefabAUS - listed on their online database, with an additional twelve companies added that were not members, but were attending industry conferences and events, or advertising in relevant publications. This represents a purposive sampling approach, as participants were selected due to their expected knowledge and experience within the prefabricated construction industry. While not exhaustive, this database provided broad reach across prefabrication industry stakeholders. A target of between 15 and 30 interviews was set, as based on Warren [37] this number reaches an appropriate balance of time, resources and likelihood of diminishing returns for academic publication [37].

3.2. Recruitment

The entire database list received an invitation to participate. Recruitment occurred through multiple channels, including advertisement in newsletters and mail-outs from the PrefabAUS, open invitation at industry conference presentation by the research team, and direct email approach to existing industry contacts and relevant companies that did not respond to other recruitment methods. Of those contacted, 35 responded with an interest in participating, but 14 subsequently did not participate. In total, 21 interviews were conducted, with 24 professionals from 19 different companies within the industry, one peak organisation and a government-level client. Overall, more than one-quarter of the members of the peak body for prefabricated construction in Australia were involved in the research. Details of the key characteristics of the participant organisations are shown in Fig. 2. The interviewees typically held a management or director-level roles in their organisation, with sufficient understanding of their products and services to provide meaningful answers to the research questions (see Table 5). By the completion of interviews, a degree of theoretical saturation was occurring, with the same themes emerging across interviews [38].

3.3. Data collection and analysis

Informed consent was obtained from all participants prior to the interviews, and the research team emphasised that all data would be treated anonymously, and participants could withdraw from the research after the interview if required. This approach was designed to encourage open and honest responses in the semi-structured interviews. The interview questions were divided into five sections. The first focused on the interviewee's background, the work performed by their company and their use of prefabrication. The second section focused on the workflow of the company and their position within the wider supply chain. The third section focused on understanding their material flow, particular variety and volume of material usage, and understanding the types and fate of waste streams. Next, questions focused on the understanding and application of broader sustainability considerations such as embodied carbon, operational performance, product end-of-life, and key challenges to improving sustainability. Finally, broader questions about potential changes to improve sustainability were asked. The interview guide is provided as Appendix A. The interviews were

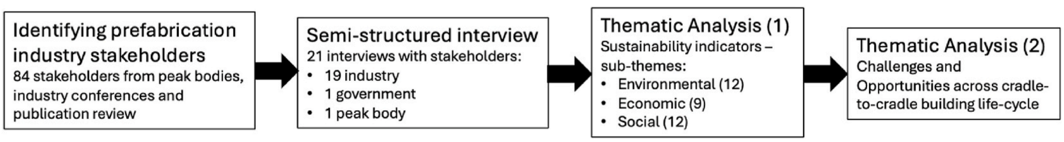

Fig. 1. Summary of research approach.

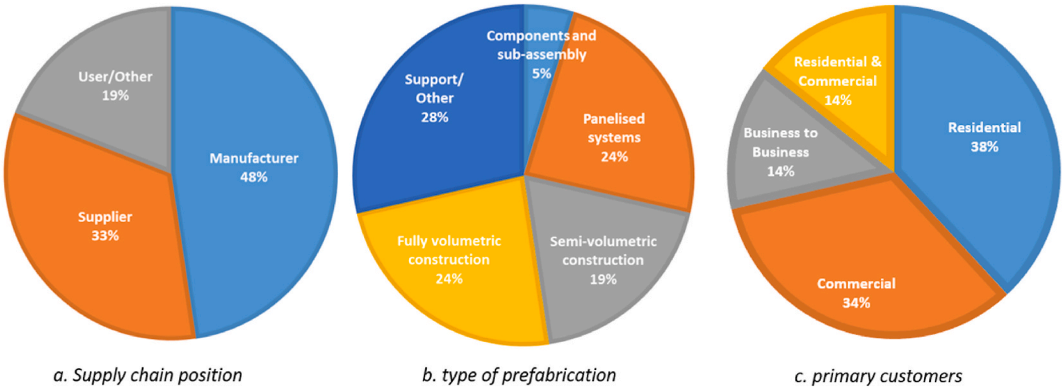

Fig. 2. Key characteristics of organisations involved in research (n = 21).

Table 5
Industry role of interviewees.

Position/Role	TOTAL
Managing director, Owner, CEO	6
Director	6
Manager	4
Sustainability Manager	2
Other	3

conducted via online video calls, typically lasting between 45 and 90 min. Interviews were recorded and transcribed using a mix of proprietary AI generated transcriptions (using Zoom and Otter.ai) and manual review of AI transcriptions. Two researchers were present during the majority of interviews, and detailed notes were also taken.

Thematic analysis, one of the most widely used methods of qualitative data analysis, was the primary method employed [39]. Primary themes (environmental, economic and social) and sub-themes were initially derived from the sustainability framework identified from the extant literature (Kamali et al [20] - refer to Table 1). There were 12 environmental indicators (sub-themes), 9 economic and 12 social. Additional themes based on the research interest, specifically the state of prefabrication in Australia and future challenges, were added at the start of analysis. In addition to this, ten additional sub-themes were added (four environmental, four economic and two social) as they emerged from the data, with interviews retrospectively checked after identifying these themes [40]. Transcripts from the interviews were coded in NVIVO12 qualitative data analysis software against all of these sub-themes. Themes that occurred most frequently across interviews were identified, and this was used as the basis for in-depth analysis of these high frequency themes [41]. Further to the coding and thematic analysis, additional readings of the transcript outside of NVIVO was employed through a process of progressive meaning making across the breadth of interview data [42]. This dual approach was adopted to mitigate against any undue influence from the use of a particular tool – in this case NVIVO – in the analysis.

Results from the thematic analysis were used to compare the perceived sustainability benefits of prefabricated construction in Australia with those noted in other literature studies. They were also used to identify the specific challenges and opportunities within the industry to progress towards sustainability. From these, a roadmap towards sustainability for the industry is proposed.

4. Results

4.1. State of the prefabrication industry in Australia

The scope of this study was geographically focused on Australia, a geographically large country with a relatively small population, surrounded by oceans, and with significant diversity in size, and industrial and construction activity between states [43]. Multiple interviewees described the Australian prefabrication industry as less advanced than the United States and Europe, both in terms of sophistication of manufacturing techniques and the sustainability and energy efficiency of the modular constructions being undertaken. In comparison to these regions, the industry was viewed as a small niche in Australia, with businesses at diverse levels of maturity. While a small number of bigger players had adopted cutting edge technologies and production-line processes, there are also '*a lot of people … claiming to be modular, and then basically building conventionally in a shed and transporting it to site' (Interviewee 1)*. The companies engaged in the research ranged from smaller organisations (<10 employees) working in small sheds on private land while trying to finance larger operations, to large, heavily automated, robot-driven manufacturing. The industry in Australia was described as being 15 years behind the world leaders, and also to not have progressed as quickly as was being predicted 10 years ago. Whilst not necessarily true across the whole industry, the repetition within interviews of this assessment is indicative of a widespread perspective. The conservative nature of the building industry in Australia, some major collapses of prefabricated manufacturers, limitations in the prefabrication supply chains, and generally benign weather conditions for traditional construction were all given as contributing factors for the current status of the industry. As has been the case for many years, those in the industry are predicting significant growth in coming years, with one participant recalling predictions for off-site construction to account for 25 % of the overall industry by 2025. Currently accounting for less than 5 % of output, it is unlikely that this will eventuate. Perhaps more realistically, market analysts are predicting a compound annual growth rate of 7.5 % for much of the decade [44]. Research participants were seeing this reflected in growing acceptance of prefabrication in the market.

> *"The demand from customers to see a house that's manufactured - or pre-made, or prebuilt, or prefabricated - is far more … culturally acceptable now than it would have been 10 years ago … that cultural shift is happening" (Interviewee 4).*

One of the limitations identified for the current market is that manufacturers frequently act as both the manufacturer, marketing, and customer interface, with no intermediaries. This was described as providing challenges in managing customer requirements and limiting the ability to focus on improving manufacturing efficiencies. International approaches that separated these business functions were held up as desirable future models.

> *"In the US [United States] they also have a much greater sales and marketing model that deals with the interaction with the customer rather than being direct between manufacturing and marketing as it is in Australia." (Interviewee 2)*

Typically, companies have focused on a single niche market for their product, e.g. small residential, commercial holiday cabins, school infrastructure etc. Four of the companies interviewed were focusing solely on commercial markets. However, those that have focused purely on the residential market (five of the companies interviewed) noted that they needed repeatable work in order to grow their business. This repeatable work – multiple constructions of the same or similar design - lends itself preferentially to commercial work, which is difficult to break into as a smaller player. In residential construction, the use of modular elements needs to be combined with responsiveness to customer personal preference to achieve a good outcome.

4.2. Industry perspectives on sustainability

One of the objectives of this study was to understand current perceptions of sustainability amongst those working in the Australian prefabrication industry. Given the broad definition of what can be encompassed by sustainability, this was undertaken by thematically analysing interview data against literature-derived sustainability criteria. Broadly, the status of the industry in Australia can be described as one still working to establish and expand, meaning sustainability is a secondary priority; first a viable business needed to be created. However, industry stakeholders are seeing a growing value being placed on sustainability in the market:

> *'Sustainability five years ago … was a great secondary advantage … the clients will go price first, time, quality, other things, and there's sustainability that might be number six, seven … "yeah great, it's a nice to have." [In the] last two years the market has drastically shifted … Sustainability now is a huge driver. It's … equal [number] one with price' (Interviewee 12)*

The twenty-one interviews were coded according to the sustainability criteria listed in Kamala et al. (2018), with additional codes added when issues emerged that were not adequately captured by existing codes. Understandings of sustainability covered the three main categories of environmental, economic and social sustainability, with a strong bias towards environmental issues. The largest proportion of the coded references (48 %) related to environmental indicators (see Fig. 3). Economic factors were the second most common at 32 %. All the interviews except one mentioned at least one indicator related to economic sustainability. Social factors were the least represented, with only 20 % of the indicators mentioned relating to social factors, however, 17 out of 21 interviews mentioned at least one of the indicators associated with social sustainability. When split by position in the supply chain, a similar pattern emerges

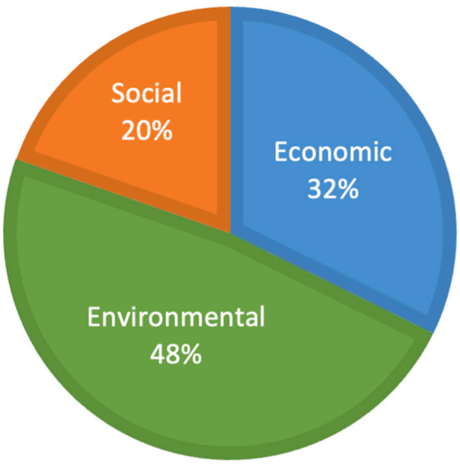

Fig. 3. Relative frequency of sustainability themes.

from manufactures, suppliers and other categories, with particularly consistent results for environmental indicators. However, amongst end-users, economic themes were noticeably more prevalent (See Fig. 4), and an increase in social indicators was also seen.

4.2.1. Frequency of sustainability themes

Analysis of the frequency that individual sustainability indicators were discussed by participants is shown in Fig. 5. The indicators are grouped by category (environmental, economic and social), and within each category listed in ranked priority order as per Table 1. The interview questions (as listed in Appendix A) were relatively open, with some bias towards sustainability and environmental issues, so the breakdown signals the importance of social and economic sustainability to the interviewees. The comparison between rank order and frequency illustrates areas of agreement and divergence on sustainability perspectives between the literature – grounded in North American experience – and this study of the Australian industry. The three most frequent mentions are all environmental factors – *Waste management*, *Material consumption in construction* and *Energy performance and efficiency strategies*, discussed by 86 %, 81 % and 76 % of the twenty-one interviews respectively. This is consistent with the North American industry perspective [20], though the inclusion of targeted questions around how waste is dealt with in factory construction may have skewed results in this study somewhat. Following these, other high-ranking indicators included economic considerations of *Design and construction time* and *Design and construction costs*, which both were discussed by more than half of interviewees.

In general, within the environmental and economic sustainability themes, the indicators that were ranked more highly corresponded with those that were discussed most frequently by the participant cohort. The key exceptions were that *Site disruption and appropriate strategies* was infrequently encountered in discussion, whilst *Flexibility of building* was commonly mentioned as an economic sustainability theme. Within social themes, there was no obvious connection between the frequency analysis and literature-based rankings. In addition, there were a number of emergent themes that were not adequately covered in the existing indicators. This is discussed in the next section.

4.2.2. Emergent themes and indicators

A number of areas of potential sustainability benefit that weren't covered by the literature derived codes were identified [20]. These are outlined in Table 6. Of these indicators, the two most frequently mentioned were *Transportation to site,* and *Productivity and workplace environment.* The baseline indicator *Alternative transportation* specifically referred to siting of modular buildings in locations that had access to lower impact transportation options (public transport, cycling etc.). The impact of transportation to site was only one factor within the *Embodied energy* indicator. In the Australian context, *Transportation to site* as a standalone sustainability consideration was mentioned as frequently as *Embodied energy.* This is representative of the different nature of the Australia industry, which has a smaller number of manufacturers in centralised locations, whilst one of the primary markets for prefabricated buildings are customers in remote locations requiring transportation significant distances. The second additional indicator – *Productivity and workplace environment* - stressed how the off-site factory construction can lead to better and more controlled productivity – increased output from given resources, separate from simply reducing construction time and costs. This also relates closely to *Workplace diversity and equity*, the offsite workplace environment also has a positive impact on the diversity of the workforce attracted to the site.

These additional themes are important in highlighting issues where the Australian industry may diverge from international experience (e.g. Kamali et al. [20]. Potential causes for other aspects of deviation include both the current developing state of the industry, along with the timing of the research following a series of significant natural disasters in Australia (bushfires and floods). The additional focus on workplace diversity is reflective of the push for industry in Australia, but particularly the construction industry, to build diversity. The following section explores the most prevalent themes of sustainability - based on the outcomes of this thematic frequency analysis - within the Australian prefabrication industry, considering first environmental, then economic, and finally social sustainability.

4.2.3. Indicators of environmental sustainability

The three most commonly discussed sustainability factors related to environmental impact were also the three ranked most important in the literature; *Energy performance and efficiency, Waste management* and *Material consumption in construction.* The most

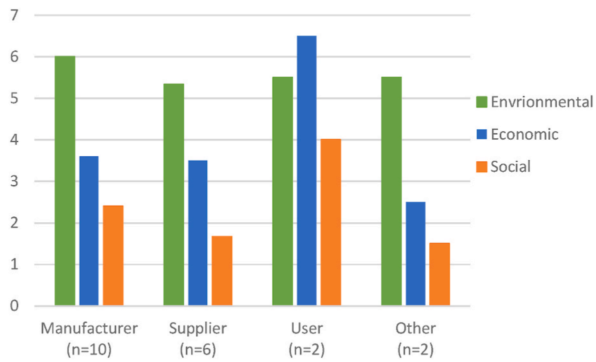

Fig. 4. Average frequency of themes mentioned in interviews across supply chain position of participant companies.

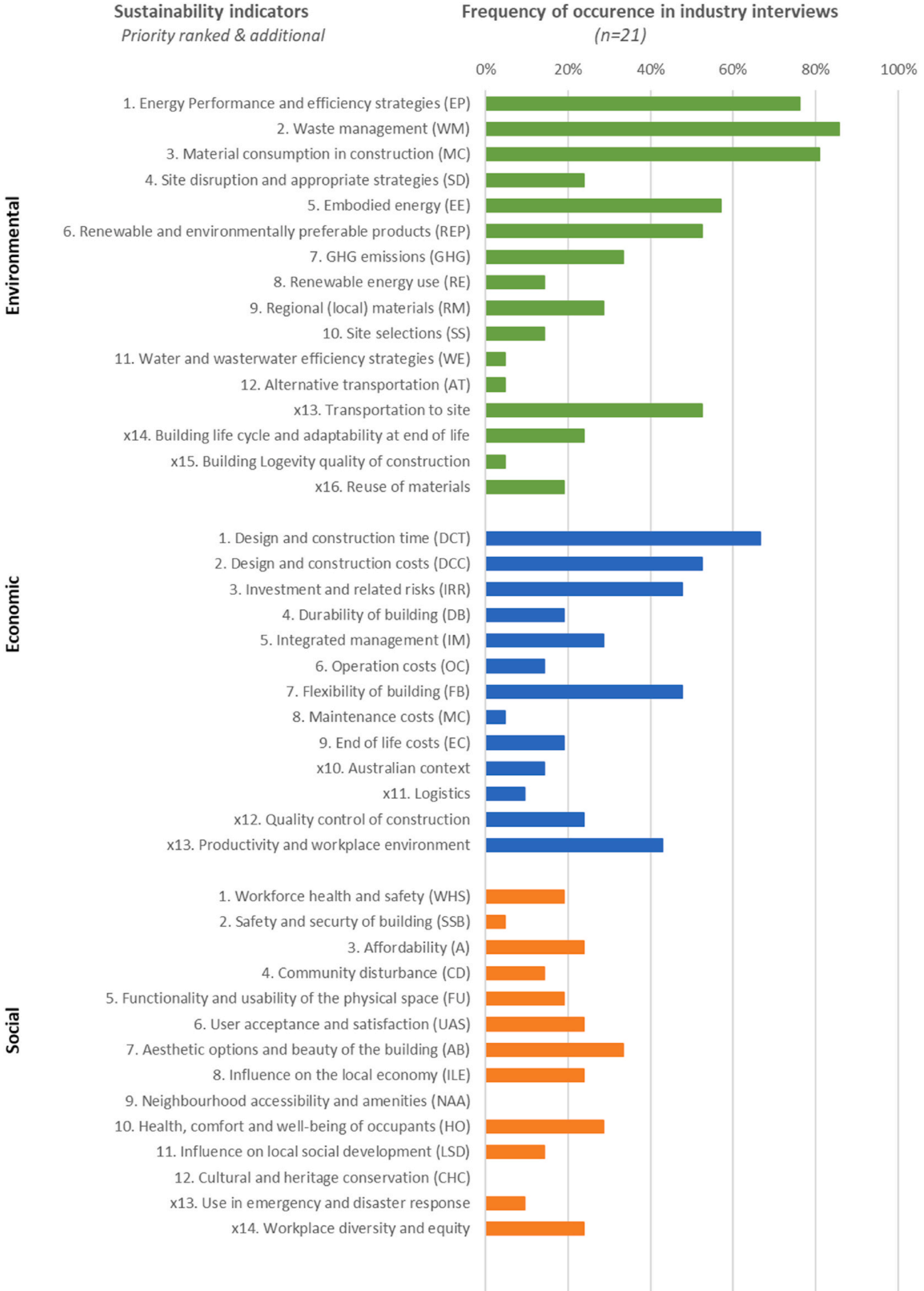

Fig. 5. Frequency of Sustainability indicators coded in industry interviews. The indicators are listed in their priority order as per Kamali et al [20]. Additional indicators are denoted by an 'x' before the number.

notable areas of divergence were the minimal discussion by participants about the potential benefits from reducing on-site disruption from prefabrication, despite experts considering this a major factor. Conversely, the impacts of transportation to site were frequent considerations from an environmental perspective amongst interviewees.

Table 6
Additional aspects of prefabricated construction related to sustainability added as codes during analysis.

Category	Indicator	Quote from interviews
Environmental	Transportation to site	*"From the factory to the site is only, you know, a couple of pilot cars and a truck burning fuel as opposed to trades burning fuel every day back and forth" (Interviewee 1)*
	Building life cycle and adaptability at end of life	*"A lot of building doesn't look at the building life cycle, so what happens at the end of the buildings life … there is a real opportunity that every single part of it can be recycled, either disassembled and redo it as another house" (Interviewee 9)*
	Building longevity/quality of construction	*"Here, we're treating real estate much like a stock market, a lot of time, and we don't see that generational thinking … then it goes to the quality of what we build" (Interviewee 13)*
	Reuse of materials	*"There's nothing that doesn't get recycled and reused on homes … particularly in a production line, 50 of the same houses - if it doesn't get used in the first house it'll get used on the next one" (Interviewee 11)*
Economic	Logistics	*"In anything prefabricated, logistics ultimately play a role in deciding what the size of anything is" (Interviewee 4)*
	Quality control of construction	*"We understand enough about prefabrication to know that the quality of the build is probably going to be far superior than what we can build on site, especially if you're using just a bunch of contractors you can't oversee [the build] properly" (Interviewee 10)*
	Productivity and workplace environment	*"Work in the factory is a controlled environment, a lot more controlled than out on site in the recent rain that we've had, so it means that now guys get to work a lot more days of the year, especially this year" (Interviewee 9)*
Social	Use in emergency and disaster response	*"Schools infrastructure asked us to assist in taking their old steel demountable classrooms, strip them out back to the steel frame and refit them out as emergency housing accommodation up in flood affected areas" (Interviewee 12)*
	Workplace diversity and equity	*"Being in the factory setting, it's quite different to site. Like the people that we can get to work here are a different demographic … it's actually quite flexible in time as well … we've been able to get quite a few of our workers to upskill to something different" (Interviewee 20)*

Details of key factors and challenges discussed in the interviews for these three indicators, along with illustrative quotes, are provided in Table 7.

While there were many similar themes discussed across interviews, the focus of participant companies tended to be on particular environmental aspects. For instance, some were concentrating on design efficiencies to minimise waste generation, while others focused more on choices of materials, whilst others were exploring modularity in design to allow houses to grow with occupants. The diversity of perspectives on how the industry are delivering environmental benefits from prefabricated construction reflects the

Table 7
Details of the industry perspectives on key aspects of environmental sustainability.

Indicator	Key factors	Challenges	Quotes from interviews	Key interviewees
Energy performance and efficiency	• Interest within industry to pursue sustainable designs • Prefabrication suited to zoning and air tightness (e.g. Passive House[a]) • Design and manufacturing software often has inbuilt energy efficiency and life cycle analysis components	• Lack of interest in the market for energy efficiency (cost driven) • Thermal bridging from steel framing usage • Minimum standard regulations don't always apply to 'movable homes' • Lightweight – lack of thermal mass	*"you're able to add certain extra elements and steps in a factory that … it's harder to get consistent [onsite] … You can really get that extra benefit, and we found that when we did prefabrication in Sydney … we got air changes down" (Interview 16)*	*1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 17, 19*
Waste management	• Easier to collect, store and thereafter reuse waste materials • Waste materials less likely to be contaminated, dirtied or damaged • Equipment in factories to assist with management (forklifts, cranes) • Still depends on waste management practices and culture	• Storage space can be limited • Time pressures of production line environment	*"Whenever you're building on site there's 10 % waste guaranteed, generally more and there's limited opportunity to reuse or recycle that waste, just because it's too expensive. By building in a factory, we order what we need, so for our wall sheet, we will order to the nearest full pack because we know that any leftover sheets we will use on the next job." (Interview 9)*	*1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 17, 18, 20, 21*
Material consumption in construction	• Integration of digital design tools to optimise material choice, sizing and cutting • Repetition of tasks in production line to minimise wastage and improve task control	• Tensions between material choice for production efficiency vs environmental benefits • Trade-offs for steel vs timber for framing.	*"some of that waste stream discussion is around that sort of detailing and shop drawing process around optimizing what use of material sizes, so sheet sizes and lengths. Making sure we're minimizing cuts. Minimizing cuts of timber also minimizes wastage" (Interview 4)*	*2, 3, 4, 5, 6, 7, 8, 9, 12, 13, 14, 15, 16, 17, 18, 20, 21*

[a] Passive House is a design standard which aims to minimise heating and cooling energy requirements through the use of high levels of insulation, airtightness and mechanical ventilation systems. See https://passivehouseaustralia.org/.

diversity of maturity, scale and scope of the current industry. There was a broad opinion that increasing use of prefabrication would improve the environmental impacts of construction, however to a large degree the enacted environmental sustainability practices focused heavily on good manufacturing practices: improving production efficiency and reducing waste. There is very little evidence of quantifiable assessment of the sustainability.

4.2.4. Indicators of economic sustainability

The impacts on *Design and construction time*, *Design and construction costs,* and *Investment and related risks* are seen as key indicators of economic sustainability by the Australian industry. International studies generally recognised these as key benefits, though report large variations in the measured extent that these indicators can be improved through prefabrication [11,13]. *Productivity within the workplace environment* was another important concern of participants, mentioned almost as frequently as the first three indicators. The key factors, challenges and supporting quotes of these indicators are shown in Table 8.

Economic considerations were at the forefront of discussions with industry members. Considering that the primary focus of the research centred on environmental sustainability, the consistency with which economic considerations were discussed - around cost, scheduling and production efficiency – strongly reflects the drivers in the Australian industry at present.

4.2.5. Indicators of social sustainability

Although the social sustainability indicators were the least commonly discussed throughout the interviews, over 80 % of the interviewees mentioned at least one indicator related to social sustainability. The most frequently mentioned indicator was *Aesthetics and beauty of the building,* this was often in the context of a challenge to the general market perception that prefabricated construction results in unattractive, mass-standardised design. Perceptions of prefabricated buildings is not an issue that has been highlighted in previous considerations of social aspects of sustainability (e.g. Navaratnam et al. [14]. Other important indicators were both *Workplace health and safety*, and the emergent theme of *Workplace equity and diversity.* These are aspects that are discussed as benefits of prefabricated construction [27], but have not been highlighted as either challenges or benefits of the Australian industry currently [35]. There was less of a link between the literature ranking of indicators and their number of mentions in the interviews across the social issues than for environmental and economic sustainability. The key factors, challenges and supporting quotes of these indicators are shown in Table 9.

The social impacts of prefabricated construction are also important considerations for the overall sustainability of the industry. While not as widely discussed as environmental and economic issues, for those interviewees that did discuss them, they were very important considerations. The companies with larger workforces tended to have a greater focus on social considerations. As the interviews revealed, there are a number of potential social benefits linked to factory-based construction, which warrant ongoing support and exploration.

Table 8
Details of the industry perspectives on most key aspects of economic sustainability.

Indicator	Key factors	Challenges	Quotes from interviews	Key interviewees
Design and construction time	• Compression of schedule due to parallel tracks • More predictable scheduling • Reduced interaction of trades on-site • Protection from weather delays • Factory environment supports automation for productivity improvements	• Limited use of automation in Australia	*"you take some of the components that are on a critical path and put them in a factory and … reduce the timeline … [this provides the] customer appeal of getting their home faster" (Interview 16)*	2, 4, 5, 7, 8, 9, 11, 12, 14, 16, 17, 18, 19, 21
Design and construction cost	• Cost savings from speed and certainty in scheduling • Particular benefits for remote location builds, removes need to relocate skilled trades for long builds.	• Many cost savings rely on use of repeatable designs • Bespoke designs less cost-efficient with advanced manufacturing	*"If it's just purely an environmental benefit that doesn't bring them commercial benefit, you're going to have a hard time selling that to them." (Interview 2)*	*3, 7, 9, 10, 11, 12, 13, 15, 18, 19, 21*
Investment and related risk	• Significant capital required upfront to establish manufacturing facilities	• A number of collapses of prefabricated manufacturers in Australian industry • Frontloaded investment creates risks	*"I can tell you some companies in Australia doing prefab well, also went into liquidation. Significant capital expenditure without a certainty of pipeline of work. You have a manufacturing facility that stops for a day or a week or a month, it starts to eat itself alive." (Interview 16)*	2, 4, 5, 9, 11, 15, 16, 17, 19, 20
Productivity in workplace environment	• Potential to provide better workplace conditions • Efficiency and quality control in factory setting • Supervision of multiple jobs simultaneously. • Opportunities for multiple shifts over 24 h operations	• Time required to retrain from site to factory environment • Inexperience with on-site assembly of prefabricated components	*"So there's SOPs, standard procedures where almost everyone for every process checks the pods so that we're very confident by the time it leaves it will be right … it cuts down massively the amount of labour on site in defect recognition" (Interview 20)*	1, 4, 5, 7, 9, 12, 14, 15, 20, 21

Table 9
Details of the industry perspectives on key aspects of social sustainability.

Indicator	Key factors	Challenges	Quotes from interviews	Key interviewees
Aesthetics and beauty of the building	• A balance between standard offerings and customisation is required for efficiency	• Typically draw from a limited pool of material choice to provide consistency of construction and simplification of supply chain	*"the term we use is "mass customised" … There are commonalities between all of them [jobs] and the design principles that we fall into to make our system work. But they need to be tweaked and adjusted to suit the architectural requirements and spatials of each project." (Interview 20)*	3, 4, 11, 12, 16, 17, 20
Workforce health and safety	• Controlled environment of the factory more easily allows risks to be identified and mitigated • Equipment and machinery readily available to assist • Less people and less time on construction site reduces the risk to workers	• Need to ensure actual improvements, not just shifting of risk from site to factory	*"I'm able to pull scaffolding down 55 percent quicker than what I would have done if I did it traditionally. Well, the two largest injuries and incidents of the country are always falls from height and fallen objects. How do you put a, you know, put a figure on that?" (Interview 16)*	*12, 14, 16, 21*
Workplace equity and diversity	• Ability to provide stable location of employment, and defined work hours • Factory locations (regional areas, outside of CBDs) make commuting easier	• Construction industry environment still typically 'machoistic'	*"So I think, being in the factory setting, it's quite different to site. Like the people that we can get to work here are a different demographic. It will be mums and dads that don't have trades" (Interview 20)*	8, 14, 16, 20, 21

4.2.6. Summary

The analysis of industry stakeholder perspectives reveals a broad awareness of sustainability within the Australian prefabricated construction sector, however, significant barriers and challenges remain before its full potential can be realised. Given the critical role of sustainable construction in achieving climate targets and SDGs [2,3], alongside the well documented opportunities presented by prefabricated construction [11–14], this study highlights key areas requiring further focus and development. The sustainability indicator framework employed in this paper, adapted from Kamali et al. [20], provided a robust means of evaluating sustainability performance across environmental, economic, and social dimensions. While the framework was extensive, it was not fully comprehensive, revealing areas for refinement This reinforces the influence of local contextual factors, from geography and climate to the regulatory and financial environments, on both the building construction industry, and its sustainability priorities. Despite widespread recognition of the potential sustainability benefits of prefabricated construction, the implementation of strategies and the systematic measurement of sustainability outcomes remain inconsistent and, in most cases, limited.

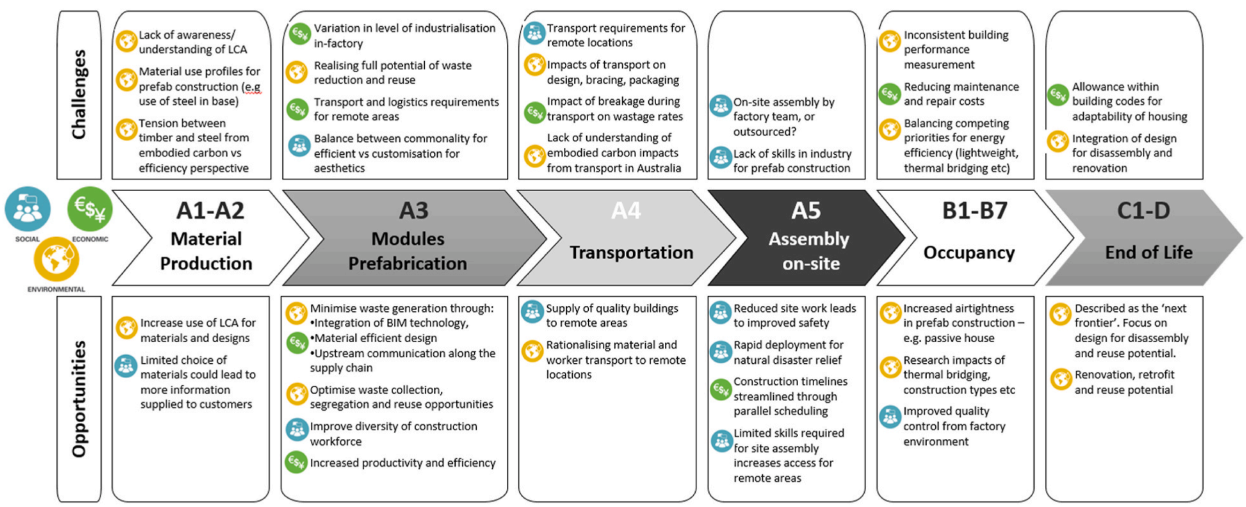

Fig. 6. Challenges and opportunities facing the sector across the cradle-to-cradle life-cycle stages (A1-D) modified to prefabricated construction process.

5. Discussion

5.1. Sustainability challenges and opportunities for australian prefabricated construction

Addressing the gaps in implementation of sustainability best practice will be essential for unlocking the potential of prefabrication to deliver meaningful, quantifiable contributions to sustainability within the Australian construction industry. Previous research has highlighted that economic and social impacts are considered as important as environmental impacts [25], which is supported by this research. Other research in Australia has also identified that representatives of the construction industry indicated they would choose prefabrication over tradition construction methods if sustainability was a primary focus [14]. However, the in-depth discussions from this research found that the ability to measure the sustainability benefits of prefabricated construction was limited, and there was little impetus to implement and improve upon these advantages, particularly from an environmental perspective. The drivers and incentives that currently exist in the industry were focused on growth and consolidation of the market, not exploiting sustainability advantages. From the analysis, multiple challenges and opportunities to improve the approach of the prefabricated building industry to sustainability are apparent, spanning the whole building life cycle, from material production all the way to end-of-life disposal or reuse. These key challenges facing the industry, and the opportunities to overcome them, are summarised across the key life cycle stages in Fig. 6, and discussed in the following sections.

Material production: Understanding the life-cycle impacts of the materials used in construction is a growing focus at a policy level across the construction industry [45], but one which is only being considered in detail by a minority of the industry. Improving the process of assessing and selecting materials to extend beyond cost and practicalities – be that through life cycle assessment, understanding of embodied carbon (particularly sequestered carbon impacts of timber), or through toxicity of materials used – should be a growing focus. There is a need for clearer ways to "calculate and demonstrate what the savings are to the market …. not just [as] a rhetoric tool" (Interviewee 12). Previous research shows that there is significant variation in positive and negative impacts, depending on specific material choices [13,31]. Tension in the industry exists between the efficiency of steel construction and low wastage rates, with the embodied carbon benefits of timber construction. The centralisation of construction in the factory represents a reduction in the supply chain length that supports this more detailed analysis of material sourcing and choice, to optimise for environmental benefits. There is also an opportunity to provide customers with more information regarding the materials used in the building construction, including developing inventories of the footprints of prefabricated components [46], as products used becomes more standardised within factories or across industries.

Modular prefabrication: Within the factory, there is work to do industry-wide in order to move beyond relying on the inherent benefits of operating in a factory and fully realise the potential for waste reduction and reuse. At an industry level, this is challenging to implement given the wide variation in level of industrialisation of processes, customer requirements and locations. However, this also represents the low-hanging fruit whereby the sharing of knowledge and best-practices – along with collecting supporting data - amongst the industry can deliver substantial improvements. Particular opportunities exist through the increased uptake of digital technologies (e.g. BIM) and industrialisation processes, which was discussed by numerous interviewees but not currently in widespread use by any of them. This supports previous findings, both in terms of the expected benefits from BIM, and also the slow implementation [24]. This has already been shown to lead to increase material efficiency, reduced waste generation and increased productivity in the workplace [14].

Transportation: The geography and population density of Australia increases the significance of transportation in embodied energy and carbon calculations, particularly when the industry is small, and factories are few in number. Transportation over long distances also increase packaging requirements, and potential for damage products to occur during this stage. Yet there are also significant benefits from economic perspective from centralising production and shipping the building, rather than transporting many workers to remote locations [47]. These challenges are well understood (e.g. Ref. [48]). However, mapping these trade-offs in an Australian context, particularly the implications of different levels of prefabrication (from panelised to modular) on transport impacts, can help the industry both optimise its offerings to the market and its contribution to further decarbonising construction.

Assembly on-site: The challenges and opportunities from moving from construction on-site to assembly only are largely social and economic. Currently some manufacturers will outsource on-site assembly, while others use the factory team to also erect buildings in-place. The skills profile required for site work has the potential to change with different degrees of prefabrication, with the potential to increase the diversity of participation in the construction workforce. This was widely seen as a huge benefit of a growth in prefabrication, with centralised prefabrication also leading to greater efficiency (interviewee 4) and a more stable environment leading to greater diversity (interviewee 16). As assembly requires reduced skill levels, it allows for remote areas with limited availability of specialised skills to access higher quality construction, as documented in a rural post-disaster context by Boehme et al [49]. Additional opportunities – recognised in the literature - are also associated with on-site assembly including improved site safety, rapid deployment of buildings in times of natural disasters and parallel scheduling of work to streamline construction processes [14,27].

Occupation and Operation: The performance of prefabricated buildings during their lifespan as occupied buildings is another area that presents potential future challenges. The market for prefabricated residential homes is still relatively small in Australia, and transitioning from designing temporary buildings (e.g. holiday cabins or school classrooms) to full time homes will change some of the drivers around comfort, usability and energy use. This has implications for environmental, economic and social sustainability indicators for the industry. Whilst typically it is the design and material choices, rather than construction process that has the major impact on factors such as energy consumption [50,51], there are some specific issues linked to the designs that are more common in prefabrication (e.g. lightweight, steel frame) which would benefit from further study and guidance to incorporate best practice knowledge into current designs. Opportunities for improved performance through tighter quality control on construction aspects such as airtightness should also be explored further by the industry. Durability and maintenance requirements for prefabricated buildings and components are areas that have been less well studied [15], and less of a focus during discussions with industry, however is an area the industry should be looking to address going forward.

End of life - Greater consideration of the fate of buildings as they reach the end-of-life, and incorporating design-for-disassembly concepts into the early stages are challenges that the industry is currently only thinking about in a niche way, yet has the potential for significant benefits [23,33]. While the more standardised processes create opportunities for potentially greater reuse of components, there are significant challenges. Current buildings codes or rating systems give minimal consideration of the implication of adaptable designs, or reuse of previous materials. Any new construction generated from reused components may need to be modified to comply with subsequent changes in the construction code. However, greater decarbonisation of the building industry demands an increase in material reuse, making this a strong opportunity for the sector.

5.2. Pathways to sustainability in the prefabrication industry

There are many positives for construction sustainability that could be realised from an increase in prefabricated construction in Australia. However, there is work required by the prefabrication industry to overcome the challenges currently faced and realise the opportunities. Based on the analysis in this paper, there is a staged approach required, with many actions that can be taken now, as well as others that require more detailed planning, evidence collection and long-term thinking to fully realise.

5.2.1. Short-term

Key to the progression of the prefabricated construction industry towards sustainability are short-term actions that can be taken within the industry right now. Across the board, there is a significant need to build the evidence base across the prefabricated construction industry to support or challenge the sustainability claims in an Australian context. This was recognised by some in the industry as a key opportunity for improvement into the future.

- *"We need to start to develop more simple ways … to calculate and demonstrate what the savings are to the market because they want something of substance, not just [a] rhetorical tool." (Interviewee 12)*

Evidence to support the sustainability of prefabricated construction should include a standardised waste measurement methodology, both for prefabricated and conventional construction. This would allow for the collection of data to monitor and report on the progress of the industry towards improved sustainability performance.

It would also be useful for the industry to develop structured guidance for both manufacturers and procurers on in-factory sustainability practices, covering environmental, social and economic indicators. Ongoing surveys and monitoring of industry practices would be useful in tracking performance against this guidance, as well as supporting the dissemination of knowledge from industry leaders. A regular, industry wide survey capturing the key sustainability indicators and performance against these would assist in tracking the progression of the industry and identifying areas for improvement.

5.2.2. Medium-term

Whilst it will require substantial effort and time to implement, it is seen as strategically important for the construction industry to support the continued development of Environmental Product Disclosures (EPDs) for Australian construction materials, along with LCA databases, to improve LCA analysis. The prefabricated industry occupies a unique space within this area due to the narrow range of materials typically used, and the replicability of whole building designs. As the industry moves towards decarbonisation, and hence towards assessing embodied carbon in buildings, if the prefabricated industry has invested into building the skills required in this area, and developing the background information available, it will be well placed to exploit the opportunities to be a front runner in this space.

5.2.3. Long-term

Over a longer timeframe, considerations focused particularly on the end-of-life and design for disassembly of prefabricated products are seen as the next frontier for future research to harness the sustainability opportunities of prefabricated construction. This should include the implications of material choice and construction methodologies on the reuse or end-of-life of prefabricated buildings, as well as adaptability of designs for alternative uses or a second life.

6. Conclusions

This paper has presented findings from investigating the current perceptions on sustainability and potential future pathways for the prefabricated construction industry in Australia. Through twenty-one semi-structured interviews with industry stakeholders, the research explored the potential sustainability benefits, challenges and opportunities of prefabrication, applying a thematic analysis based on the triple-bottom line sustainability criteria, as called for by López-Guerrero et al [13]. The study contextualised sustainability indicators developed by Kamali et al. [20] to the Australian setting, identifying additional locally relevant indicators. The findings demonstrate growing interest in, and need for, leveraging prefabrication methods to achieve better sustainability outcomes, despite multiple barriers to achieving best practice in sustainability. Although the extent of prefabricated construction in Australia is relatively low, it is viewed as a growth industry with the potential to address some of the significant challenges the wider construction industry will face in coming decades.

For industry in Australia, the perception of sustainability benefits of prefabrication stretched across all categories of environmental, economic and social, and reflected well the framework of criteria established from literature. Similar to other studies in the literature, there was a strong focus on environmental sustainability features. Whilst environmental benefits, in particular production efficiency and waste reduction, were discussed, there was minimal evidence provided to quantify the impact of these aspects. The economic discussion highlighted the need for designs to be economically sustainable and affordable, with opportunities seen in designing to be adaptable or for staged construction to enable improved financial planning. Balance is required between the capital required to establish manufacturing facilities and the market demand available, to offset investment risks. Social sustainability aspects included a reduction in the number of workers required on construction sites, improved safety, and a potentially more inclusive workplace in the factory setting. Additionally, the issue of transportation to site was identified as an additional consideration in Australia not included in the literature, due to the long distances required for transport of buildings and the remote locations where they are sent. This is both a challenge to the industry, as well as an opportunity where prefabrication provides a benefit over traditional construction.

The key areas of challenge and opportunity in moving towards sustainability for the industry identified from the interviews, were discussed across the stages of the building lifecycle. This highlighted that there are actions that can be taken at each stage of the project lifecycle from material production, modular prefabrication, transportation to assembly, operation and end of life considerations. In particular, increasing the uptake of Life Cycle Analysis was identified as critical for improving transparency and enabling targeted improvements. There is great potential for impact in the modular prefabrication stage through design and material efficiencies. Opportunities for improvement were also identified with a focus on the downstream end of construction through improved building energy efficiency, fast deployment for natural disaster relief and designing for disassembly and reuse. These challenges and opportunities highlight the potential of the industry and well as the need for improvement.

While the qualitative nature of this research revealed insights into the barriers and opportunities facing the industry, the lack of quantitative data regarding the environmental, economic and social indicators discussed throughout is a key limitation. Building a robust evidence base through on-site case studies and industry-wide surveys will be essential to benchmarking current performance and driving continual improvement. Future research should focus on building this evidence base to inform the industry action over the short, medium and long-term, both through the collection of specific on-site case study data, and establishment of industry-wide surveys. This would provide a valuable means to establish a benchmark of current industry performance, as well as track progress against to ensure continual improvement in the drive to improve sustainability.

CRediT authorship contribution statement

Matthew Daly: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Leela Kempton:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Tim McCarthy:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matthew Daly reports financial support was provided by Advanced Manufacturing Growth Centre. Leela Kempton reports financial support was provided by Advanced Manufacturing Growth Centre. Timothy McCarthy reports financial support was provided by Advanced Manufacturing Growth 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.

Acknowledgements

Funding: This research has been supported by the Australian Manufacturing Growth Centre, under the 'Prefab Innovation Hub'. The authors would like to acknowledge the assistance of PrefabAUS and the industry representatives who have taken part in this study.

APPENDIX A. – Interview Guide

1. Introduction and existing market characterisation:

- Can you please provide an overview of your organisation/role and position in the wider supply chain?
- Using the example of a new build home, can you please explain the construction/manufacturing process from the point that you first become involved until the end of your involvement (or expected involvement)
- Can you please give a brief description of the work you perform and its associated value stream?
- What are the major value adding processes? What do you do that adds value? (for example, installation, procurement and consultancy)

2. Supply chain analysis:

Customer:

- Describe your main customers (government, social housing, individual householders, developers etc)
- How many customers do you have and where are they located?
- Please state the average time between when a firm order is placed and when the product (retrofit, installation, construction etc.) is delivered.
- State the frequency of deliveries to your customers for the specified product.

Product:

- Product variety – please state the number of variants of the specified product.
- Annual volume – What was the last years total sales volume? Please also specify the units.
- What other/how many organisations are carrying out activities on the product before end use? (for example, installation, additional tradesman assistance such as carpentry/electrical etc).
- What other/how many subcontractors do you work with?

Suppliers:

- How many different suppliers do you require for the specified product and where are they located?
- Supplier delivery lead time – please state the average time between when you place a firm order with your suppliers and when they deliver the product.
- On the whole, how close a relationship do you have with your suppliers? (For example, ranging from partnership to adversarial).
- Where are you experiencing bottlenecks or restraints to capacity and capability?

3. Material flow (inputs and outputs):

- What are the key materials you use in your manufacturing process? Please talk me through:
  - Most important by volume
  - Any innovative material uses
  - Key material constraints or risks (of shortages) you face? (time, availability, quality?)
- Do you use any recycled materials in manufacturing?
- What are the packaging and transportation requirements of your products?
- Describe your major waste streams from manufacturing as well as from construction on site (type, volume etc) and what happens to those waste streams (recycled on site, recycled externally, landfill)
- Describe the end of life considerations for your components – reusability, deconstructability, recycling potential etc.

4. Sustainability

- What are key sustainability features (energy, water, waste etc) of your products or buildings?
- What are the key sustainability features (energy, water, waste etc) of your construction/manufacturing processes?
- What is your level of understanding of the embodied and operational energy/GHG/other metric impacts of a typical product?
- What forms of sustainability assessments do you need to conduct? E.g. LCA, BASIX, NatHERS, GreenStar, blower door testing? Waste auditing?
  - At what stage of the building process? (Business system level, Design, as-built etc)
  - Who considers sustainability? (in-house team, product manager, consultant etc)
- How have your regular business practices changed in response to evolving sustainability considerations. e.g. materials, processes, future planning etc.
- What are the key challenges your business faces in terms of improving sustainability?

5. Improvements:

- What do you see as the single biggest thing your organisation could do to improve lifecycle sustainability of your products?
- How could this change be best assisted?
  - By industry
  - By research
  - By government

Data availability

Data will be made available on request.

References

[1] United Nations, Transforming Our World: the 2030 Agenda for Sustainable Development, United Nations, Department of Economic and Social Affairs, New York, 2015, https://doi.org/10.1007/s13398-014-0173-7.2.

[2] W. Fei, A. Opoku, K. Agyekum, J.A. Oppon, V. Ahmed, C. Chen, K.L. Lok, The critical role of the construction industry in achieving the sustainable development goals (Sdgs): delivering projects for the common good, Sustain. Times 13 (2021), https://doi.org/10.3390/su13169112.

[3] ASBEC, Low Carbon, High Performance: How Buildings Can Make a Major Contribution to Australia's Emissions and Productivity Goals, 2016.

[4] United Nations Environment Programme, Executive Summary - 2021 Global Status Report for Buildings and Construction: towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector, 2021. Nairobi.

[5] B. Huang, X. Gao, X. Xu, J. Song, Y. Geng, J. Sarkis, T. Fishman, H. Kua, J. Nakatani, A life cycle thinking framework to mitigate the environmental impact of building materials, One Earth 3 (2020) 564–573, https://doi.org/10.1016/J.ONEEAR.2020.10.010/ATTACHMENT/21466AA9-D9C5-4970-8BCF-99FCF0DB5908/MMC1.PDF.

[6] OECD, Global Material Resources Outlook to 2060, Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences, OECD, Paris, 2019, https://doi.org/10.1787/9789264307452-EN.

[7] J. Pickin, C. Wardle, K. O'farrell, L. Stovell, P. Nyunt, S. Guazzo, Y. Lin, G. Caggiati-Shortell, P. Chakma, C. Edwards, B. Lindley, G. Latimer, J. Downes, I. Axiö, R. Reviewers, National Waste Report 2022, 2022.

[8] The Institution of Structural Engineers, Carbon: Embod. Operat. (2022) [WWW Document]. URL, https://www.istructe.org/resources/guidance/carbon-embodied-operational/. (Accessed 8 November 2022).

[9] GBCA and Thinkstep-anz, Embodied Carbon and Embodied Energy in Australia's Buildings, 2021. Sydney.

[10] I. Shufrin, E. Pasternak, A. Dyskin, Environmentally friendly smart construction—review of recent developments and opportunities, Appl. Sci. 13 (23) (2023) 12891, https://doi.org/10.3390/app132312891.

[11] M. Kamali, K. Hewage, Life cycle performance of modular buildings: a critical review, Renew. Sustain. Energy Rev. 62 (2016) 1171–1183, https://doi.org/10.1016/j.rser.2016.05.031.

[12] E. Attouri, Z. Lafhaj, L. Ducoulombier, B. Linéatte, The current use of industrialized construction techniques in France: benefits, limits and future expectations, Clean. Eng. Technol. 7 (2022) 100436, https://doi.org/10.1016/J.CLET.2022.100436.

[13] R.E. López-Guerrero, S. Vera, M. Carpio, A quantitative and qualitative evaluation of the sustainability of industrialised building systems: a bibliographic review and analysis of case studies, Renew. Sustain. Energy Rev. 157 (2022), https://doi.org/10.1016/j.rser.2021.112034.

[14] S. Navaratnam, A. Satheeskumar, G. Zhang, K. Nguyen, S. Venkatesan, K. Poologanathan, The challenges confronting the growth of sustainable prefabricated building construction in Australia: construction industry views, J. Build. Eng. 48 (2022) 103935, https://doi.org/10.1016/j.jobe.2021.103935.

[15] S. Aghasizadeh, A. Tabadkani, A. Hajirasouli, S. Banihashemi, Environmental and economic performance of prefabricated construction: a review, Environ. Impact Assess. Rev. 97 (2022) 106897, https://doi.org/10.1016/j.eiar.2022.106897.

[16] AMGC, Prefab Innovation Hub: Feasibility Study, Advanced Manufacturing Growth Centre, 2019.

[17] D. Steinhardt, K. Manley, Adoption of prefabricated housing-the role of country context, Sustain. Cities Soc. 22 (2016) 126–135, https://doi.org/10.1016/j.scs.2016.02.008.

[18] SBENRC, Investigating the Mainstreaming of Building Manufacture in Australia: A Sustainable Built Environment National Research Centre (SBEnrc) Industry Report, Curtin University, Brisbane, Australia, 2015. Perth, Griffith University.

[19] Office of Projects Victoria, Offsite Construction Guide: Delivering Victorian Projects with Modern Methods of Construction, Victorian Government, Melbourne, Australia, 2022.

[20] M. Kamali, K. Hewage, A.S. Milani, Life cycle sustainability performance assessment framework for residential modular buildings: aggregated sustainability indices, Build. Environ. 138 (2018) 21–41, https://doi.org/10.1016/j.buildenv.2018.04.019.

[21] W. Lu, H. Yuan, Investigating waste reduction potential in the upstream processes of offshore prefabrication construction, Renew. Sustain. Energy Rev. 28 (2013) 804–811, https://doi.org/10.1016/j.rser.2013.08.048.

[22] J. Wang, Z. Li, V.W.Y. Tam, Identifying best design strategies for construction waste minimization, J. Clean. Prod. 92 (2015) 237–247, https://doi.org/10.1016/j.jclepro.2014.12.076.

[23] L. Aye, T. Ngo, R.H. Crawford, R. Gammampila, P. Mendis, Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules, Energy Build. 47 (2012) 159–168, https://doi.org/10.1016/j.enbuild.2011.11.049.

[24] A.W. Hammad, A. Akbarnezhad, P. Wu, X. Wang, A. Haddad, Building information modelling-based framework to contrast conventional and modular construction methods through selected sustainability factors, J. Clean. Prod. 228 (2019) 1264–1281, https://doi.org/10.1016/J.JCLEPRO.2019.04.150.

[25] X. Hu, H.Y. Chong, X. Wang, Sustainability perceptions of off-site manufacturing stakeholders in Australia, J. Clean. Prod. 227 (2019) 346–354, https://doi.org/10.1016/J.JCLEPRO.2019.03.258.

[26] M. Sandanayake, W. Luo, G. Zhang, Direct and indirect impact assessment in off-site construction—a case study in China, Sustain. Cities Soc. 48 (2019) 101520, https://doi.org/10.1016/j.scs.2019.101520.

[27] L. Jaillon, C.S. Poon, Y.H. Chiang, Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong, Waste Manag. 29 (2009) 309–320, https://doi.org/10.1016/j.wasman.2008.02.015.

[28] Y. Jiang, D. Zhao, D. Wang, Y. Xing, Sustainable performance of buildings through modular prefabrication in the construction phase: a comparative study, Sustain. Times 11 (2019), https://doi.org/10.3390/SU11205658.

[29] R. Hu, K. Chen, W. Fang, L. Zheng, J. Xu, The technology-environment relationship revisited: evidence from the impact of prefabrication on reducing construction waste, J. Clean. Prod. 341 (2022) 130883, https://doi.org/10.1016/j.jclepro.2022.130883.

[30] J. Quale, M.J. Eckelman, K.W. Williams, G. Sloditskie, J.B. Zimmerman, Construction matters: comparing environmental impacts of building modular and conventional homes in the United States, J. Ind. Ecol. 16 (2012) 243–253, https://doi.org/10.1111/j.1530-9290.2011.00424.x.

[31] M. Kamali, K. Hewage, Development of performance criteria for sustainability evaluation of modular versus conventional construction methods, J. Clean. Prod. 142 (2017) 3592–3606, https://doi.org/10.1016/j.jclepro.2016.10.108.

[32] G. Liu, R. Huang, K. Li, A. Shrestha, X. Fu, Greenhouse gas emissions management in prefabrication and modular construction based on earned value management, J. Construct. Eng. Manag. 148 (2022), https://doi.org/10.1061/(ASCE)CO.1943-7862.0002268.

[33] V. Tavares, J. Gregory, R. Kirchain, F. Freire, What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets? Build. Environ. 206 (2021) 108382 https://doi.org/10.1016/j.buildenv.2021.108382.

[34] M. Sutrisna, B. Cooper-Cooke, J. Goulding, V. Ezcan, Investigating the cost of offsite construction housing in Western Australia, Int. J. Hous. Mark. Anal. 12 (2019) 5–24, https://doi.org/10.1108/IJHMA-05-2018-0029.

[35] Z. Zhang, Y. Tan, L. Shi, L. Hou, G. Zhang, Current state of using prefabricated construction in Australia, Buildings 12 (9) (2022) 1355, https://doi.org/10.3390/buildings12091355.

[36] E.E. Heffernan, W. Pan, X. Liang, P. de Wilde, Zero carbon homes: perceptions from the UK construction industry, Energy Pol. 79 (2015) 23–36, https://doi.org/10.1016/j.enpol.2015.01.005.

[37] C.A.B. Warren, Qualitative interviewing, in: J. Gubrium, J.A. Holstein (Eds.), Handbook of Interview Research: Context and Method, SAGE, Thousand Oaks, California, 2002.

[38] I. Seidman, Interviewing as Qualitative Research: A Guide for Researchers in Education and the Social Sciences, fourth ed., Teachers College Press, New York, 2013.

[39] A. Bryman, Social Research Methods, fourth ed., Oxford University Press, Oxford, 2012.

[40] R. Thornberg, K. Charmaz, Grounded theory and theoretical coding, in: The SAGE Handbook of Qualitative Data Analysis, SAGE, 2014, pp. 153–169.

[41] H. Joffe, L. Yardley, Content and thematic analysis, in: Research Methods for Clinical and Health Psychology, SAGE, London, 2004, pp. 56–68.

[42] P. Srivastava, N. Hopwood, A practical iterative framework for qualitative data analysis, Int. J. Qual. Methods 8 (2009) 76–84.
[43] W. Chancellor, Drivers of productivity: a case study of the Australian construction industry, Constr. Econ. Build. 15 (2015) 85–97, https://doi.org/10.5130/AJCEB.v15i3.4551.
[44] R.M. Petrass, Prefabricated May Be the "Only Viable Option,", besides it's not so "cheap and nasty, 2022. The Fifth Estate.
[45] D. Prasad, M. Dave, A. Kuru, P. Oldfield, L. Ding, C. Noller, B. He, Race to Net Zero Carbon: A Climate Emergency Guide for New and Existing Buildings in Australia, Low Carbon Institute, 2021.
[46] Z.C. Li, V.W.Y. Tam, X. Lai, Y. Zhou, S. Guo, Carbon footprint accounting of prefabricated buildings: a circular economy perspective, Build. Environ. (2024), https://doi.org/10.1016/j.buildenv.2024.111602.
[47] R.M. Lawson, R.G. Ogden, R. Bergin, Application of modular construction in high-rise buildings, J. Architect. Eng. 18 (2012) 148–154, https://doi.org/10.1061/(asce)ae.1943-5568.0000057.
[48] Y. Xiang, K. Ma, A.M. Mahamadu, L. Florez-Perez, K. Zhu, Y. Wu, Embodied carbon determination in the transportation stage of prefabricated constructions: a micro-level model using the bin-packing algorithm and modal analysis model, Energy Build. 279 (2023) 112640.
[49] T. Boehme, J. Fan, T. Birtchnell, J. Aitken, N. Turner, E. Deakins, Social enterprise housing supply chains for resource-constrained communities: a complexity lens approach, Supply Chain Manag.: Int. J. (2023) 1–26, https://doi.org/10.1108/SCM-02-2023-0113. July.
[50] A.W. Abbood, K.M. Al-Obaidi, H. Awang, A. Malek, A. Rahman, Achieving energy efficiency through industrialized building system for residential buildings in Iraq, Int. J. Sustain. Built Environ. 4 (2015) 78–90, https://doi.org/10.1016/j.ijsbe.2015.02.002.
[51] S. Yu, Y. Liu, D. Wang, A.B.S. Bahaj, Y. Wu, J. Liu, Review of thermal and environmental performance of prefabricated buildings: implications to emission reductions in China, Renew. Sustain. Energy Rev. 137 (2021), https://doi.org/10.1016/J.RSER.2020.110472.
[52] Z. Li, G.Q. Shen, M. Alshawi, Measuring the impact of prefabrication on construction waste reduction: an empirical study in China, Resour. Conserv. Recycl. 91 (2014) 27–39, https://doi.org/10.1016/j.resconrec.2014.07.013.
[53] L. Loizou, K. Barati, X. Shen, B. Li, Quantifying advantages of modular construction: waste generation, Buildings 11 (2021) 1–22, https://doi.org/10.3390/buildings11120622.
[54] V. Tavares, N. Lacerda, F. Freire, Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: the "Moby" case study, J. Clean. Prod. 212 (2019) 1044–1053, https://doi.org/10.1016/j.jclepro.2018.12.028.
[55] Y. Teng, W. Pan, Systematic embodied carbon assessment and reduction of prefabricated high-rise public residential buildings in Hong Kong, J. Clean. Prod. 238 (2019) 117791, https://doi.org/10.1016/j.jclepro.2019.117791.
[56] Y. Teng, K. Li, W. Pan, T. Ng, Reducing building life cycle carbon emissions through prefabrication: evidence from and gaps in empirical studies, Build. Environ. 132 (2018) 125–136, https://doi.org/10.1016/j.buildenv.2018.01.026.
[57] H. Pervez, Y. Ali, A. Petrillo, A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: a case of developing country, J. Clean. Prod. 294 (2021) 126210, https://doi.org/10.1016/j.jclepro.2021.126210.
[58] M. Kamali, K. Hewage, R. Sadiq, Conventional versus modular construction methods: a comparative cradle-to-gate LCA for residential buildings, Energy Build. 204 (2019), https://doi.org/10.1016/j.enbuild.2019.109479.
[59] K. Shen, C. Cheng, X. Li, Z. Zhang, Environmental cost-benefit analysis of prefabricated public housing in Beijing, Sustain. Times 11 (2019), https://doi.org/10.3390/su11010207.
[60] G. Tumminia, F. Guarino, S. Longo, M. Ferraro, M. Cellura, V. Antonucci, Life cycle energy performances and environmental impacts of a prefabricated building module, Renew. Sustain. Energy Rev. 92 (2018) 272–283, https://doi.org/10.1016/j.rser.2018.04.059.
[61] S. Navaratnam, T. Ngo, T. Gunawardena, D. Henderson, Performance review of prefabricated building systems and future research in Australia, Buildings 9 (2019) 1–14, https://doi.org/10.3390/buildings9020038.
[62] A. Zolghadr, E. Gharaie, N. Naderpajouh, Barriers to innovation in the housing sector: economic justifiability of offsite construction for housebuilders, J. Build. Eng. 52 (2022) 104490, https://doi.org/10.1016/j.jobe.2022.104490.