Sustainable Built Environment National Research Centre AUSTRALIA

Benchmarking and Scaling-up Australia's Circular Economy Practices

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WA Case Study Literature Review (Draft)
Research Project 1.11.4

14 October 2026

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ABSTRACT

The review of 67 studies highlights the potential of circular design principles—including design for disassembly, modularity, adaptability, material efficiency and reuse—in prefabricated and precast concrete construction. Evidence suggests that prefabrication can substantially reduce construction waste (46–87%) and embodied carbon, although environmental benefits vary significantly across components and lifecycle stages. Building Information Modelling (BIM), material passports and lifecycle assessment tools are key enablers of circularity; however, the lack of standardised, interoperable and whole-lifecycle assessment frameworks remains a critical gap. Major adoption barriers are primarily techno-economic and institutional, including cost premiums, limited policy incentives and conflicting stakeholder priorities. In Australia, the absence of a locally validated, value-chain-wide framework highlights the need for an integrated, BIM-enabled, multi-criteria circular design framework that incorporates lifecycle carbon and cost assessments, material traceability, standardised modular design and stakeholder-specific decision-making, supported by appropriate policy incentives and industry collaboration. (TBC)

Keywords: *Circular Economy, Systematic Literature Review, Framework, benchmarking, indicators.*

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1. INTRODUCTION

The built environment, including the construction and infrastructure sector, faces significant decarbonisation challenges because it contributes substantially to global climate change. The circular economy is an innovative approach to tackling both resource and climate challenges and achieving global decarbonisation targets. The literature review focuses on circular economy practices in precast construction, particularly focusing on the following two areas:

i. Framework-Centric Analysis
ii. Indicators-Centric Analysis

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2. FRAMEWORK-CENTRIC ANALYSIS

Research question: How can a standardised framework integrate circular design principles into precast concrete systems, align stakeholder priorities, and support implementation across the Australian construction value chain?

Circular design principles can be integrated into Australian precast concrete systems through a standardised framework that combines component-level BIM-enabled carbon and cost analysis, material passports aligned with IFC and EN 15804 data standards, demountable connection and modular dimension requirements embedded at design inception, multi-criteria decision tools that explicitly reconcile the divergent priorities of developers, designers, manufacturers, and regulators, and a phased policy instrument pathway progressing from compulsory mandates to market-based incentives as industry capability matures.

2.1 Thematic Analysis

The evidence across the 65 sources clusters into six interconnected themes: (1) the state of circular design principles in prefabricated and modular construction; (2) the role of BIM as an enabling platform; (3) assessment methods and metrics for circular performance; (4) stakeholder priorities and their alignment across the value chain; (5) barriers and enablers shaping adoption; and (6) framework development and implementation pathways. These themes collectively address how circular design principles can be embedded in precast concrete systems and what a standardised framework enabling this integration would need to accomplish.

2.1.1 Theme 1: Circular Design Principles Applied to Precast and Modular Systems

The most consistently evidenced circular design principles across the literature are modularity, design for disassembly, waste reduction through prefabrication, and material efficiency. Their application to precast concrete systems is, however, uneven in depth and specificity.

Modularity and prefabrication as foundational circular strategies. Across the literature, prefabrication and modular construction are consistently framed as enablers of reduced onsite waste, improved resource efficiency, and enhanced sustainability performance. Wong et al. (2022) demonstrate across 38 projects spanning two decades that increasing prefabrication levels correlate significantly with improved environmental, social, and economic sustainability indicators, with Modular Integrated Construction achieving the highest composite sustainability scores [24]. Zhang et al. (2024) quantify that modular construction reduces overall onsite construction waste by an average of 78.8%, substantially outperforming nonmodular offsite approaches [6]. Pan & Zhang (2023) find that modular construction reduces waste by 46–87% compared to conventional practice in a high-density

urban context [5]. Tianyao Ping et al. (2026) report approximately 90% waste reduction in a steel modular apartment project [56]. These figures are broadly consistent, though they span different materials and construction systems, and the underlying methodologies for waste quantification vary, a gap explicitly noted by Zhang et al. (2024) [6].

Several studies examine specific precast element types and their relationship to circular outcomes. Shu Su et al. (2024) analyse six component types—shear walls, beams, floor slabs, stairs, balconies, and air-conditioning slabs—and find that the optimal combination for minimising costs and carbon emissions depends on the prefabrication rate and prevailing carbon trading price [23]. Dong et al. (2025) examine seven component types in a shear wall residential building and find that beams, stair landings, and stair flights offer the best combined cost and carbon performance when replaced with prefabricated counterparts, whereas composite floor slabs exhibit higher embodied carbon per unit volume of concrete than cast-in-place equivalents [1]. This finding is important: prefabrication does not universally reduce carbon emissions, and an optimal prefabrication rate of 3.8–10.6% is identified by Dong et al. (2025) for net carbon reduction, beyond which both cost and emissions increase [1]. Cheng et al. (2022) find that prefabrication reduces formwork waste by 59.68–71.83%, with potential increases to 90% under full prefabrication scenarios, and that the greatest reductions come from straight walls and slabs [25].

Design for Disassembly (DfD) and end-of-life recovery. DfD is discussed in a significant subset of studies as the circular design principle offering the greatest potential for improving reuse potential and environmental performance in the built environment [3, 10, 11]. Akinade et al. (2015) identify the use of prefabricated assemblies and demountable connections as the two most important design factors for deconstructability [3]. Atta et al. (2021) demonstrate that modular buildings with dry, bolted connections score markedly higher on deconstructability and recovery indices than those with cast-in-place wet connections, and that the choice of connection type is a primary determinant of circular performance [2]. Akanbi et al. (2019) develop the Disassembly and Deconstruction Analytics System (D-DAS) as a BIM plug-in that evaluates building designs for end-of-life performance, applying a Design for Deconstruction Advisor module to optimise material recovery pathways [11]. Mohammed et al. (2024) extend this for steel structures, developing BIM-DAS scores and salvage performance indicators, and highlight that high reuse rates—99% for steel components in their case study—are achievable when demountable connections and prefabricated assemblies are prioritised from the design stage [22].

Design for Adaptability. Baienat et al. (2026) provide the most comprehensive treatment of Design for Adaptability (DfAd) as a circular economy strategy, developing a framework that maps adaptability strategies—including modularity, reversibility, functional neutrality, expandability, and resilience—across building layers and evaluates their contribution to closed-loop material flows and

extended service life [4]. They argue that adaptability reduces the need for demolition and rebuilding by enabling buildings to accommodate changing functional needs, thereby extending asset utility and reducing construction waste across the lifecycle [4]. Cavalliere et al. (2019) propose BIM-based metrics for building flexibility, including structure modularity, geometrical regularity, and the use of removable building elements, arguing that these can be automatically calculated during the design process to guide sustainable choices [47]. Jiang et al. (2025) develop a BIM-based Circularity Assessment Tool (B-CAT) that specifically evaluates disassembly potential and material efficiency across project phases, finding a final material efficiency score of 0.51 in their renovation case study [10].

Material efficiency and waste minimisation. Across the studies that engage most directly with the material flows of precast systems, several specific circular design requirements emerge with consistent support. These include the use of demountable or bolted connections (rather than chemical or wet joints), standardised dimensions and modular components, the minimisation of material types and avoidance of composite or difficult-to-separate assemblies, the layering of building elements according to anticipated service life, and the use of prefabricated assemblies to reduce onsite waste [2, 3, 11, 22, 44]. Kanavaris et al. (2024) demonstrate that improvements in structural design alone—such as strict adherence to Eurocode loadings, use of post-tensioned slabs, and optimisation of concrete mixes with supplementary cementitious materials—can reduce embodied carbon in concrete-framed buildings by 40% in a transition scenario and 55% in an ambitious scenario for the residential sector [45]. Liu et al. (2018) show that rule-based automated BIM approaches for boarding layout design can significantly minimise material waste in light-frame construction by automating cutting-plan optimisation [61].

2.1.2 Theme 2: BIM as an Enabling Platform for Circular Design Integration

Building Information Modelling emerges across virtually all studies as the primary technical platform through which circular design principles can be operationalised in precast and modular construction, and through which the information requirements of a standardised framework can be supported. BIM's enabling roles span design optimisation, lifecycle assessment, waste analytics, circularity assessment, and end-of-life planning.

BIM for design automation and generative design. Gan (2022) develops a BIM-based generative design system capable of producing 1,000–1,500 design options in approximately 30 minutes, identifying combinations that achieve a 30% reduction in embodied carbon and construction cost relative to reference buildings [8]. Wei et al. (2021) propose integrating generative design with BIM to automate module layout generation for residential buildings, arguing that this approach can

substantially accelerate early-stage feasibility evaluation of modular construction schemes [35]. Ma et al. (2025) use BIM-based quantity take-off in conjunction with multi-criteria decision-making (TOPSIS and C-OWA) to rank ten prefabricated technology schemes, providing developers with structured decision support under minimum assembly rate constraints [18]. Vargas et al. (2025) combine BIM-assisted analyses with Multicriteria Decision Analysis to compare conventional and off-site construction in a high-standard Brazilian multifamily building, reporting an 89% reduction in structural weight, a 6% cost reduction, and a 40% reduction in project duration under a fully off-site scenario [32].

BIM-LCA and BIM-LCC integration. A substantial cluster of studies develops or applies BIM-integrated lifecycle assessment frameworks. Cheng et al. (2022) propose a BIM-LCA framework following ISO 14040 and 14044 to quantify formwork waste reduction from prefabrication, with BIM providing the inventory data and LCA providing the assessment structure [25]. Ansah et al. (2021) develop a BIM-based LCA method for prefabricated buildings that automates assessment across all lifecycle phases, including end-of-life, and validate it against a Hong Kong residential case, reporting total cumulative energy demand of 30.22 GJ/m² and global warming potential of 4,141.70 $kgCO_2eq$ [9]. Ji et al. (2026) apply BIM and the Luban platform with the ReCiPe methodology to a ten-building prefabricated residential development in Shanghai, demonstrating that prefabricated construction is environmentally superior across most impact categories, with exceptions in acidification and mineral resource consumption [36]. Carvalho et al. (2021) develop a Dynamo-based automation tool within Autodesk Revit that performs LCA and LCC across 18 design scenarios, reducing the time and effort required for early-stage assessment and enabling real-time decision support [41]. Santos et al. (2020) develop the BIMEELCA tool and validate it in a 250-metre high-rise building, demonstrating the feasibility of automatic BIM-based LCA and LCC at early design stages [46]. Namaki et al. (2024) integrate BIM, LCA, and AHP in a six-step decision framework applied to a Canadian single-family house, comparing conventional steel, recycled steel, and timber, and find that recycled structural steel outperforms conventional steel and performs similarly to timber [14].

BIM for waste analytics and construction waste management. Akinade & Oyedele (2019) develop the A-WAS tool, an Adaptive Neuro-Fuzzy Inference System integrated into Autodesk Revit, which uses gross floor area and construction type as key predictors of construction waste generation, providing management routes for minimisation [12]. Won et al. (2016) find that BIM-based design validation prevented 4.3–15.2% of construction waste in two South Korean case projects by detecting design errors before construction [40]. Schamne et al. (2024) develop a conceptual BIM-CDW information model based on IFC standards to automate construction and demolition waste management across lifecycle phases, emphasising that the model's utility depends directly on the information available in the IFC model [48]. Meshref et al. (2023) apply system dynamics with BIM and lean design concepts

to model construction waste reduction in Egyptian industrial projects, proposing causal loop diagrams that capture the feedback relationships among design strategies, material productivity, and waste outcomes [44].

BIM for circularity and end-of-life assessment. Jiang et al. (2025) develop the B-CAT tool using a Design Science Research methodology, integrating three calculation models suited to different levels of project information (initiative, design, and construction phases), and validate it through twelve user-based evaluation sessions and a Dutch renovation project [10]. Akanbi et al. (2019) demonstrate that BIM capabilities can be extended to support circular economy goals by integrating end-of-life performance analysis into the design stage through the D-DAS plug-in [11]. Charef et al. (2020) identify 35 distinct BIM uses that can support circular economy adoption, including 7 new uses identified through expert interviews; material passports and digital end-of-life management tools are among those rated highest by practitioners [39]. Atta et al. (2021) demonstrate that the integration of Material Passports with BIM automates sustainability assessment and provides deconstructability, recovery, and environmental scores for building components, with modular buildings with dry connections consistently outperforming conventional alternatives [2].

Data standardisation challenges. A persistent limitation identified across the BIM-focused literature is the lack of data standardisation, both within BIM platforms and in the wider ecosystem of LCA databases and IFC schemas. Theißen et al. (2020) find that 94.5% of BIM objects for building services could only be linked to LCA datasets by applying one or more of six bespoke solution approaches, highlighting that non-standardised attributes and the limited machine readability of LCA datasets remain significant technical barriers [20]. Adetayo Onososen & Musonda (2022) find through interpretive structural modelling that unavailability of quality data, workflow and modelling errors, BIM technology limitations, and interoperability with LCA software are among the highest-ranked barriers to BIM-based lifecycle sustainability assessment [58]. Lee et al. (2015) note that an effective error rate of less than 5% can be achieved with BIM-based green template evaluation when validated against 2D quantity take-off, but the tool is limited by the absence of structural steel in the Revit Architecture environment and its grounding in standard Korean apartment typologies [34].

2.1.3 Theme 3: Assessment Methods and Metrics for Circular Performance

The literature reveals a wide diversity of assessment approaches, with LCA the most frequently applied framework, but with significant variation in system boundaries, functional units, and data sources. There is no convergent set of circularity-specific metrics across the studies, and the Material Circularity Indicator (MCI) is used in only one study [36]. This heterogeneity constitutes a critical gap for the development of a standardised framework.

LCA prevalence and variability. LCA is used in at least 25 studies, but the scope and phase coverage vary substantially—from cradle-to-site assessments focused on material production [7, 37] to more comprehensive cradle-to-grave or cradle-to-cradle approaches [9, 15, 26]. The standards most commonly cited are ISO 14040 and 14044 [7, 9, 15, 25], BS EN 15978 [20, 45], and the CML methodology [46]. The ReCiPe methodology is applied by Ji et al. (2026) [36]. Common impact categories reported include global warming potential (GWP), cumulative energy demand (CED), acidification potential, eutrophication potential, and abiotic depletion potential, though not all studies report the same set, limiting comparability. Li et al. (2025) extend the 5D BIM approach to monetise nine environmental impact categories into environmental costs using a willingness-to-pay method, finding that climate change potential accounts for 91.2% of total environmental costs (172.81 CNY/m²) for a prefabricated substation case study [37].

Circularity-specific assessment tools. Beyond LCA, a smaller set of studies uses tools specifically designed for circularity assessment. The BIM-DAS tool (Akinade et al., 2015; Mohammed et al., 2024) measures deconstructability as a score based on the types and proportions of prefabricated assemblies and demountable connections [3, 22]. The D-DAS system (Akanbi et al., 2019) extends this to provide whole-life performance analytics and a Design for Deconstruction Advisor module [11]. The B-CAT tool (Jiang et al., 2025) assesses material efficiency and disassembly potential across project phases, reporting material efficiency as a scalar score [10]. Atta et al. (2021) use three quantitative indicators—deconstructability score, recovery score, and environmental score—derived from material passport data and LCA [2]. Baienat et al. (2026) propose an Adaptation Intensity Index (AII), a Circular Adaptability Performance (CAP) index, and a Digital Adaptability Passport (DAP) as new instruments for quantifying adaptability's contribution to circular outcomes [4]. The eco-design tool of Yepes et al. (2022) uses Environmental Product Declarations and LCC to compare renovation alternatives through radar graphics, aligned with European Standard EN 15643 [33].

Cost-focused assessment. A large subset of studies assesses circular performance indirectly through cost metrics, reflecting the central concern of many stakeholders with the cost premium of prefabricated construction. Qi et al. (2018) develop a BIM-based incremental cost index system to identify that the largest cost increases in Chinese prefabricated buildings come from bearing and retaining wall component production, hoisting and grouting, post-poured concrete, and full decoration [29]. Luo et al. (2022) use Fuzzy Cognitive Map modelling to show that scale effect, degree of design standardisation, and construction management level have the greatest influence on prefabricated building cost, with scale effect identified as the primary root cause of elevated costs [16]. Jang et al. (2022) find that modular construction in South Korea reduces embodied carbon by approximately 36% but increases direct construction cost by approximately 8% relative to conventional reinforced concrete construction [7]. Pan & Zhang (2023) find that steel modular construction is 40% faster than

concrete modular construction but consumes 20% more electricity [5]. These trade-offs are central to the economic dimension of circular design integration and recur across the evidence base.

Composite sustainability indices. Wong et al. (2022) develop a Composite Sustainability Index (CSI) that aggregates environmental (carbon emissions, waste generation), social (human resource usage, accident rate), and economic (cost, construction period) sub-indices, validated through generalised linear models and sensitivity tests across 38 Hong Kong projects [24]. Tighnavard et al. (2026) apply a full life cycle sustainability assessment integrating LCA, LCC, and social LCA (SLCA) to compare concrete, steel, and timber modular construction, finding through PROMETHEE multi-criteria analysis that steel demonstrates the best overall performance, despite timber having the lowest GWP and lowest embodied energy [15].

2.1.4 Theme 4: Stakeholder Priorities and Value Chain Alignment

The literature consistently identifies a multi-stakeholder value chain for prefabricated and modular construction, comprising governments/regulators, developers, designers, manufacturers/PC suppliers, contractors, and end-users/clients. The priorities and concerns of these stakeholders diverge significantly, creating tensions that any standardised framework must address.

Government and regulator priorities. Across Asian contexts—particularly China, Hong Kong, and Singapore—government policy is identified as the dominant driver of prefabricated building adoption. Han et al. (2023) show through system dynamics modelling that compulsory policies play the greatest role in driving adoption in early stages but need to be withdrawn at the right time, while encouraging policies dominate in later stages [21]. Xu et al. (2019) find that Singapore has the most developed policy ecosystem for modular construction, including mandatory land supply incentives, the Construction Industry Transformation Fund, and authoritative guidebooks, whereas mainland China and Hong Kong lack comparable authoritative specifications [27]. Ma et al. (2025) note that minimum assembly rate requirements in China create a conflict between policy mandates and developer economic interests, requiring decision support tools that can identify technology schemes meeting both objectives simultaneously [18]. In the Australian context, Gounder et al. (2026) find that the critical barriers to sustainable materials adoption are cost considerations and lack of government policies and incentives, with techno-economic considerations identified as the single most significant barrier factor through multinomial logistic regression [19]. This is consistent with the general pattern in the broader literature: government policy is a necessary but not sufficient condition for adoption.

Developer and contractor priorities. Developers across multiple contexts prioritise incremental income, cost certainty, and risk management. Li et al. (2020) use evolutionary game theory to show

that the key to promoting prefabricated building adoption is increasing developers' incremental income, and that without effective incentive policies the system tends toward a suboptimal equilibrium [17]. Masood et al. (2020) find in a New Zealand survey that cost and quality challenges dominate critical factors for prefabricated house-building companies, with challenges related to features and flexibility rated comparatively less important [31]. Luo et al. (2022) identify that the factors most sensitive to changes that construction enterprises can control are PC supplier/engineer relationship (C6) and degree of standardisation (C4), with scale effect identified as the root cause but largely outside enterprise control [16]. Tighnavard et al. (2026) find that construction managers prioritise cost above all other sustainability criteria, followed by GWP, embodied energy, and social acceptance, whereas designers prioritise SLCA and academics prioritise embodied energy—a divergence with direct implications for any framework that relies on weighted multi-criteria approaches [15].

Designers and engineers. Designers are identified as critical gatekeepers for circular design integration, with their willingness to incorporate circular principles at early design stages determining a large share of lifecycle outcomes. Carvalho et al. (2021) argue that LCA and LCC analysis must be shifted to early design stages to be effective, since decisions made later in design are much more constrained [41]. The PARADIS renovation tool (Kamari et al., 2020) finds that architects are more open to iterative negotiation with stakeholders than engineers, who tend to favour absolute solutions, creating friction in interdisciplinary design processes [43]. The eco-design tool of Yepes et al. (2022) is explicitly directed at designers as its primary users, aiming to make environmental and economic data accessible during the design decision moment rather than retrospectively [33].

Manufacturers and PC suppliers. The literature identifies manufacturers as responsible for key decisions about connection types, standardisation, and production efficiency that directly determine circularity outcomes. Dong et al. (2025) note that optimal substitution sequences depend on the production capacity and standardisation of PC suppliers, and that supply chain inefficiency is a major contributor to the cost premium [1]. The supply chain integration literature (Akinade & Oyedele, 2019; Masood et al., 2020) identifies fragmented supply chains and the absence of early supplier involvement as systemic barriers [12, 31]. Atta et al. (2021) assign responsibility for material passport development and maintenance to manufacturers and contractors, emphasising that this requires comprehensive information covering all lifecycle stages [2].

Alignment mechanisms. Several studies propose mechanisms for aligning these divergent priorities within a structured decision process. Ma et al. (2025) use the C-OWA operator to weight indicator importance across stakeholder groups and TOPSIS for scheme ranking, providing a transparent and auditable process for selecting technology schemes that balance policy requirements with project benefits [18]. Tighnavard et al. (2026) use AHP to elicit weights from different stakeholder groups

(construction managers, designers, academics) and PROMETHEE to rank material alternatives, demonstrating that the optimal material choice shifts depending on whose priorities are weighted most heavily [15]. Pan & Zhang (2023) identify eight system boundaries—including density, functional boundary, and process boundary—that must be explicitly defined in any sustainability benchmarking exercise to prevent misleading comparisons between projects [5].

2.1.5 Theme 5: Barriers and Enablers to Circular Design Adoption in Precast Concrete Systems

The literature presents a detailed and broadly consistent picture of the barriers to integrating circular design principles into precast construction, and a smaller but growing body of evidence on what enables progress.

Economic barriers. The cost premium of prefabricated construction is the most frequently cited barrier across the evidence base [1, 7, 16, 17, 27, 29, 30]. This premium is attributed to several interacting factors: high initial capital investment in plants and moulds [1]; template amortisation fees and duplicated taxation for prefabricated components in China [29]; low economies of scale due to insufficient production volume [16]; transportation costs, particularly for large volumetric modules [32]; and the absence of whole-life-cost frameworks that would credit the environmental and social savings of prefabrication against its higher upfront costs. In the Australian context, Gounder et al. (2026) find that the cost premium of sustainable materials, unwillingness of key stakeholders to incorporate these materials, and lack of incentives and government policies constitute the three most critical barrier dimensions [19].

Technical barriers. Technical barriers include design complexity; manufacturing constraints; lack of skilled workers; incompatibility of connection and joint designs with disassembly; limited integration between BIM platforms and LCA tools; and non-standardised data attributes [20, 25, 27, 31, 58]. Xu et al. (2019) identify technical issues with water seepage, improper connections, and incompatibility between design and manufactured components as recurring problems in Asian modular construction practice [27]. Theißen et al. (2020) demonstrate in detail how the lack of standardisation in BIM object attributes and the non-standardised properties in IFC schemas create substantial friction in attempts to link building models with LCA data for building services [20]. Dong et al. (2025) show that not all component types benefit from prefabrication in carbon terms, with composite floor slabs exhibiting the highest carbon emissions per unit volume among the seven types examined [1] —a finding with direct technical design implications.

Regulatory and policy barriers. The evidence from predominantly Chinese and Southeast Asian contexts highlights that mandatory prefabrication rate requirements, while driving initial adoption,

can create perverse incentives when not accompanied by appropriate technical guidance on which component types and combinations achieve the best sustainability outcomes [18, 23]. Maqbool & Narayanan (2026) note the absence of comprehensive regulatory frameworks integrating circular economy principles with lean construction and BIM in the UK, and call for state-level strategies [28]. Adetayo Onososen & Musonda (2022) identify the absence of statutory regulations and government commitment as the most foundational structural barrier to BIM-based lifecycle sustainability assessment, driving other barriers in the ISM hierarchy [58].

Cultural and organisational barriers. Siloed working practices, resistance to change, lack of cross-field expertise, and poor stakeholder engagement at early design stages are identified across multiple studies as compounding barriers [28, 43, 52, 63]. Maqbool & Narayanan (2026) find quantitatively that lean construction does not appear to play a significant role in sustainability outcomes when analysed separately from BIM and circular economy integration, a finding contrary to qualitative evidence, potentially reflecting the difficulty of measuring lean outcomes independently in practice [28]. Ciribini et al. (2016) describe a "silo approach and cultural hindrances" as the primary source of difficulty in implementing an interoperable BIM-based process in an Italian residential project, requiring a tailored collaborative approach to overcome selfish and silo mindsets [63].

Key enablers. Against this barrier landscape, the evidence identifies several robust enablers. Government policy and incentives are consistently among the most powerful levers [17, 21, 27, 30]. Nourjalili & Forouzannia (2025) find through structural equation modelling that BIM has a positive and significant effect on sustainable project delivery methods, and that approximately 50% of BIM's total effect on sustainable delivery is mediated through circular economy principles [13]. Digital tools, particularly BIM platforms with embedded sustainability data libraries, are identified as key technical enablers across the evidence base [2, 8, 12, 25, 33, 39]. Design standardisation and scale effects are identified by Luo et al. (2022) and Lou & Guo (2020) as the factors with the greatest potential to reduce costs and unlock the economics of circular precast systems [16, 38]. Collaborative procurement approaches—early contractor and supplier involvement, integrated project delivery, and design-for-manufacture-and-assembly—are cited as enablers across multiple contexts [5, 12, 31, 56].

2.1.6 Theme 6: Framework Development and Implementation Pathways

A recurrent finding across the literature is that existing frameworks for assessing or implementing circular design in prefabricated construction are either conceptual and unvalidated, narrowly scoped (addressing only one lifecycle phase or one sustainability pillar), or not interoperable with standard BIM workflows. The development of a comprehensive, validated, and interoperable framework remains an open challenge.

Framework maturity spectrum. The frameworks reviewed span a broad maturity spectrum. Several are explicitly conceptual, having been developed through literature synthesis or expert consultation without empirical validation: the DfAd framework of Baienat et al. (2026) [4], the BIM performance framework of Alwan (2026) for housing refurbishment [50], and the BIM-circular economy framework of Rabia Charef et al. (2020) [39] are in this category. Others have been tested through prototype development and single case studies, including the BIM-DAS of Akinade et al. (2015) [3], the B-CAT of Jiang et al. (2025) [10], the D-DAS of Akanbi et al. (2019) [11], and the PARADIS renovation tool of Kamari et al. (2020) [43]. A smaller set has been validated through multiple case studies or user-based evaluation, including the BIM-LCA frameworks of Ansah et al. (2021) [9] and Carvalho et al. (2021) [41], and the BIMEELCA tool of Santos et al. (2020) [46]. None of the reviewed frameworks has been subjected to the kind of large-scale, cross-project, longitudinal validation that would be required to establish it as the basis for an industry-wide standard.

Value chain coverage. Most frameworks address one or two phases of the construction value chain. BIM-LCA tools predominantly cover the design and material production phases [9, 36, 41]. Cost analysis frameworks focus on design and construction stages [1, 18, 23, 29]. End-of-life tools such as BIM-DAS and D-DAS focus on the deconstruction phase [3, 11, 22]. Atta et al.'s (2021) Material Passport framework is among the few that explicitly covers all lifecycle stages [2]. The lack of cross-phase integration is a consistent limitation noted by multiple authors [9, 20, 37, 39, 46]. Jiang et al. (2025) specifically address this gap with the B-CAT tool's phased approach, which adapts calculation models to the level of information available at initiative, design, and construction phases respectively [10].

Standardisation requirements. Across the literature, several standards and data protocols are identified as foundational to any framework aspiring to cross-project or cross-jurisdictional applicability. ISO 14040 and 14044 for LCA [9, 15, 25, 37], BS EN 15978 for building-level LCA [20, 45], IFC/ISO 16739 for BIM data exchange [10, 20, 48, 63], and EN 15804 for environmental product declarations [20] are the most frequently cited. Material passports aligned with BAMB project protocols and BIM-embedded property sets are identified by Atta et al. (2021) and Charef et al. (2020) as important mechanisms for preserving material information across lifecycle phases [2, 4, 39]. In the Australian context, the Green Building Council of Australia rating system (Green Star), the National Australian Built Environment Rating System (NABERS), ISO 14024, and material passport documentation are identified by Gounder et al. (2026) as relevant standards and tools, although their specific applicability to precast concrete systems is not elaborated [19].

Multi-criteria decision-making integration. A significant methodological feature of the more advanced frameworks is their integration of multi-criteria decision-making tools to navigate the inherent tensions between cost, environmental performance, structural performance, and

constructability. Tighnavard et al. (2026) use PROMETHEE with AHP-derived stakeholder weights to rank material alternatives across sustainability pillars [15]. Ma et al. (2025) use TOPSIS with C-OWA weights to rank technology schemes across five primary and fifteen secondary indicators [18]. Namaki et al. (2024) use AHP integrated with BIM-LCA to rank material choices across environmental and social performance dimensions [14]. Vargas et al. (2025) use the Weighted Scoring Method as a transparent and adaptable form of MCDA to integrate results across cost, schedule, architectural limitations, and weight reduction criteria [32]. The consistent adoption of MCDM tools across these frameworks reflects the multi-objective nature of circular design integration and the impossibility of optimising for a single criterion without trade-offs.

Implementation sequencing. Several studies provide insights into the sequencing of implementation actions. Han et al. (2023) recommend a policy phasing model in which compulsory policies drive early adoption, are withdrawn as the market matures, and are replaced first by preferential policies and then by encouraging policies [21]. Ma et al. (2025) provide a detailed six-step implementation sequence for technology scheme selection: scoring indicator importance, disaggregating the building into elements, calculating incremental cost and duration, applying QFD for qualitative indicators, using modelling software, and aggregating data through TOPSIS [18]. Ansah et al. (2021) recommend integrating BIM-based LCA into early design stages and providing standardised assessment boundaries to enable designers to evaluate circular options without disproportionate effort [9]. For the Australian context specifically, Gounder et al. (2026) recommend a cohesive stakeholder effort combining database development for sustainable materials, policy and incentive reform, early professional engagement, and supply chain improvements as the primary pathway [19].

2.2 Synthesis

The evidence base supports a coherent but heterogeneous picture of the current state of circular design integration in precast concrete systems. Three apparent tensions in the evidence require resolution before firm conclusions can be drawn.

2.2.1 Tension 1: Does prefabrication reliably reduce environmental impact?

Several studies report substantial environmental benefits from prefabrication—including Jang et al.'s (2022) 36% reduction in embodied carbon [7], Ji et al.'s (2026) general finding of environment-friendly performance [36], and the Composite Sustainability Index evidence of Wong et al. (2022) [24] —while Dong et al. (2025) find that four of seven component types examined exhibit higher carbon emissions per unit volume than cast-in-place equivalents [1]. This apparent contradiction is largely resolvable through context and component-level analysis. The positive findings reflect either whole-building or system-level assessments where the benefits of reduced formwork, improved

quality control, and reduced onsite waste dominate, or studies focused on high-performing component types (such as beams and stairs). Dong et al.'s negative findings for composite floor slabs and some shear wall types reflect the additional material required for connection zones, additional reinforcement in precast elements, and the carbon cost of manufacturing processes. The resolution is that prefabrication's environmental performance is highly component-specific, and that optimising a prefabricated building for carbon reduction requires component-level analysis rather than whole-building prefabrication rate targets. An optimal prefabrication rate of 3.8–10.6% for net carbon benefit, as found by Dong et al. (2025) [1], suggests that mandatory prefabrication rate requirements—increasingly common in Chinese policy—may actively push buildings beyond the environmentally optimal range.

2.2.2 Tension 2: Is the cost premium of circular prefabricated construction a fundamental constraint or a temporary market failure?

Studies reporting cost premiums of 8% (Jang et al., 2022) [7], 15–20% (Xu et al., 2019) [27], and up to 25% for initial production phases (Dong et al., 2025) [1] sit alongside studies finding cost parity or advantage in more mature markets. Lou & Guo (2020) identify degree of design standardisation as the factor with the greatest leverage on cost reduction, followed by scale effect [38]. Luo et al. (2022) find that scale effect is the root cause of elevated costs, and that improvements in standardisation and PC supplier/engineer relationships are the most actionable levers within enterprise control [16]. The evolutionary game theory analysis of Li et al. (2020) demonstrates that the system can reach a sustainable equilibrium—with widespread prefabricated building adoption—only when incremental income for developers is positive, which requires either cost reduction through scale and standardisation or compensating policy incentives [17]. The evidence suggests that the cost premium is not fundamental but market-contingent: it diminishes as scale increases, standardisation improves, and the full lifecycle benefits (including reduced construction time, improved quality, and lower onsite accident rates) are internalised into project economics. Vargas et al. (2025), in a Brazilian context far from cost-mature modular markets, still find a 6% overall cost reduction under full off-site construction [32], suggesting that whole-project economics can be favourable even before market maturity is achieved, provided that savings in project duration and structural weight are properly valued.

2.2.3 Tension 3: Is BIM alone sufficient to enable circular design integration, or are institutional and organisational changes equally critical?

The structural equation modelling of Nourjalili & Forouzannia (2025) shows that BIM has a significant positive effect on sustainable project delivery, with roughly half of the effect mediated through circular economy principles [13]. However, the qualitative and ISM-based evidence of

Maqbool & Narayanan (2026) [28], Adetayo Onososen & Musonda (2022) [58], and Tian et al. (2023) [52] consistently shows that technical BIM capability is insufficient without commensurate organisational change, stakeholder education, policy support, and contractual frameworks that accommodate multi-party collaboration. In the Australian context, Gounder et al. (2026) find that even basic sustainable material adoption is constrained primarily by economic and organisational barriers rather than technical ones [19] —suggesting that BIM-enablement, while necessary, addresses a secondary rather than primary constraint. The Mandičák et al. (2024) survey across Slovakia, Slovenia, and Croatia finds that trends towards sustainability improvement through BIM are not statistically significant at the 0.05 level, despite descriptive indicators suggesting positive direction, implying that the BIM-circularity relationship is real but mediated by implementation quality and organisational context [42].

The resolution of these tensions points toward a framework for circular design integration in precast concrete systems that must simultaneously: operate at the component level rather than the whole-building level for environmental optimisation; be grounded in lifecycle economics that capture the full value of prefabrication; use BIM as an enabling platform but be accompanied by standardised data protocols, contractual mechanisms, and policy incentives; and provide for transparent multi-criteria decision-making that acknowledges the different priorities of different stakeholder groups across the value chain. No single existing framework satisfies all four requirements simultaneously, which constitutes the primary implementation gap identified across the literature [2, 9, 10, 14, 15].

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3. INDICATOR-CENTRIC ANALYSIS

Circular design principles can be integrated into precast concrete systems through a BIM-enabled framework combining whole-lifecycle indicators—deconstructability scores, GWP, waste generation, and material efficiency—standardised to common functional units and cradle-to-grave system boundaries, but no such framework currently exists in validated form for the Australian construction value chain, and developing one requires resolving the cost-circularity tension through phased policy support, establishing agreed indicator definitions across stakeholder groups, and conducting dedicated Australian case study validation rather than assuming transferability from the predominantly East Asian and European evidence base.

3.1 Thematic Analysis

The overwhelming majority of studies are primary empirical investigations, typically combining tool or framework development with single-building or single-project case study validation. Only Ayman M I Raouf et al. (n.d.) is explicitly a literature review [58]. A notable characteristic of the corpus is that virtually all studies were conducted outside Australia, with only Gounder et al. (2026) directly examining Australian construction practice, and specifically from the perspective of barriers to sustainable material adoption rather than circular design integration in precast systems [20]. This geographic concentration significantly constrains direct applicability to the Australian context.

3.1.1 Theme 1: Circular Design Principles Applied to Precast and Prefabricated Construction

The literature converges on a common set of circular design principles as applied to precast and prefabricated construction, broadly organised around the waste hierarchy of reduce, reuse, recycle, and recover. Prefabrication is consistently identified as a primary mechanism for waste reduction. Yang Zhang et al. (2024) found that modular construction reduced overall construction waste by an average of 78.8% compared to stick-built construction, outperforming other offsite approaches, with the level of prefabrication identified as the most influential driver of waste reduction [2]. Baoquan Cheng et al. (2022) quantified that prefabrication can reduce formwork waste specifically by 59.68% to 71.83%, with potential for reduction to 90% under greater prefabrication penetration [11]. Wei Pan and Zhiqian Zhang (2023) found concrete modular construction reduced waste by 46% and steel modular construction by 87% compared to conventional practice [1]. Tianyao Ping et al. (2026) reported an 87% reduction in on-site disposed waste alongside a 52% waste recycling rate for a 17-story steel modular project in Hong Kong [23].

Beyond waste reduction, reuse and end-of-life recovery emerge as central circular design objectives

for precast systems. Akinade et al. (2015) explicitly frame Design for Deconstruction (DfD) as a means of recovering materials through mechanical joints and demountable connections, prioritising recycling over landfill for materials such as concrete while enabling separation of reinforcement steel for recycling [5]. Lukman A Akanbi et al. (2019) extend this by positioning the entire building as a material bank, with the goal of maximising utility through recycling and direct reuse across a building's whole lifecycle [9]. Alaa Mohammed et al. (2024) introduce the concept of layering components based on lifespan and using prefabricated modules such as precast concrete panels as a core DfD strategy [6]. Saba Baienat et al. (2026) add a further dimension through Design for Adaptability (DfAd), arguing that modularity, disassembly systems, and reversible construction methods enable closed-loop material flows that prolong asset utility and reduce demolition waste [21].

Material efficiency measures documented across studies include standardisation and modularisation of components to ensure purer material flows [13], optimisation of prefabrication rates and component combinations to simultaneously reduce cost and carbon emissions [29], and the use of supplementary cementitious materials such as GGBS and fly ash to reduce Portland cement content and associated embodied carbon in concrete-framed structures [4]. Vargas et al. (2025) reported an 89% reduction in structural weight for a Brazilian case study adopting off-site lightweight steel framing relative to a conventional concrete structure, directly reducing embodied carbon through material substitution [16].

End-of-life considerations in the literature extend from straightforward recycling to more sophisticated circular pathways. Ali Tighnavard et al. (2026) demonstrate that end-of-life steel recycling offsets 30% of total production embodied energy for steel modular construction, timber combustion for energy recovery offsets 20%, and concrete recycling provides only a 14% offset, making material choice at design stage a critical determinant of circular performance [17]. This finding directly implicates connection type, material choice, and structural system in the achievable circularity outcomes for precast concrete relative to steel or timber prefabricated alternatives.

3.1.2 Theme 2: Integration Frameworks and Assessment Tools

A substantial body of the literature is oriented toward the development and validation of specific frameworks or tools for assessing and supporting circular design integration. These can be grouped into several functional categories.

Deconstructability and End-of-Life Assessment Tools. The Building Information Modelling-based Deconstructability Assessment Score (BIM-DAS) was independently developed by Akinade et al. (2015) and subsequently extended by Alaa Mohammed et al. (2024) for steel structures. BIM-DAS uses mathematical modelling rooted in material demand planning to produce a score ranging from 0 to 1, where 1.0 represents maximum deconstructability [5, 6]. In the original UK-based case study, a

steel structure achieved a DAS score of 0.935, the highest among steel, timber, and concrete alternatives, reflecting the contribution of prefabricated assemblies and demountable connections [5]. Atta et al. (2021) introduce a comparable but broader Material Passport (MP) framework incorporating three quantitative indicators—deconstructability score, recovery score, and environmental score—implemented via Autodesk Revit and Dynamo [7]. Akanbi et al. (2019) developed the Disassembly and Deconstruction Analytics System (D-DAS) as a four-layer plug-in for Revit 2017, providing whole-life performance analytics, element deconstruction analytics, and a Design for Deconstruction Advisor module [9]. Li Jiang et al. (2025) contribute the BIM-based Circularity Assessment Tool (B-CAT), a standalone tool using IFC as information carrier, capable of assessing material efficiency and disassembly potential across initiative, design, and construction phases [13]. In a university renovation case study in the Netherlands, B-CAT returned a material efficiency score of 0.51 and a disassembly potential score of 0.10, illustrating the gap between the achievable and current baseline circularity performance of existing buildings [13].

Life Cycle Assessment and Life Cycle Costing Frameworks. Numerous studies integrate BIM with LCA and/or LCC to assess environmental and economic performance across defined lifecycle boundaries. These range from cradle-to-gate assessments focused on the manufacturing stage [3, 15] to cradle-to-grave assessments [10, 17, 35]. Mark Kyeredey Ansah et al. (2021) developed an automated BIM-based LCA method using Autodesk Revit and Dynamo, validated on a 40-floor prefabricated residential building in Hong Kong with 40% precast elements, and structured around ISO 21931-1:2010, ISO 14040, and ISO 14044 [10]. Baoquan Cheng et al. (2022) applied a BIM-LCA framework using GTJ 2018 software based on ISO 14040 and ISO 14044, with BIM providing an automated inventory for the LCA [11]. José Pedro Carvalho et al. (2021) developed a Dynamo-based tool within Autodesk Revit to automate LCA and LCC analysis, applied to 18 simulation scenarios for a Portuguese residential building [12]. Xiaojuan Li et al. (2025) extend the concept to a 5D BIM framework that monetises environmental impacts into environmental costs denominated in CNY/m², enabling spatiotemporal analysis of environmental cost distribution across construction phases [27]. At the component level, Yifan Dong et al. (2025) employed Revit and Glodon software to calculate carbon emissions in kg CO_2/m³ of concrete for seven types of structural components in a prefabricated shear wall structure, identifying optimal prefabrication rates and component replacement sequences [18, 18].

Multi-Criteria and Decision Support Frameworks. Several studies frame circular design integration within multi-criteria decision-making (MCDM) contexts. Ali Tighnavard et al. (2026) apply a four-stage life cycle sustainability assessment combining LCA, LCC, social LCA, and PROMETHEE/AHP-based MCDM, determining that steel offers the best overall performance when all three sustainability pillars are considered despite timber's environmental advantages [17].

Shengbin Ma et al. (2025) contribute a TOPSIS-based PRB technology scheme decision-making framework with five primary indicators (construction cost, construction duration, structural performance, building performance, constructability) applied to a Chinese prefabricated shear wall project [24]. Parsa Namaki et al. (2024) demonstrate an integrated BIM-LCA-MCDM framework using AHP and OneClick LCA software, finding that recycled steel outperforms conventional steel and approaches the performance of timber in a Canadian residential case study [51]. Vargas et al. (2025) employ the Weighted Scoring Method (WSM) to integrate cost, schedule, structural weight, and architectural-logistical performance in a Brazilian off-site modular construction case study [16].

Green Building Rating System Integration. Jalaei and Jrade (2015) and Jalaei et al. (2019) developed BIM-LEED plug-ins using Autodesk Revit's API and K-Nearest Neighbour data mining to automate LEED credit calculation at the conceptual design stage [49, 59]. Ilhan and Yaman (2016) contributed GBAT, an IFC-based tool generating BREEAM material category scores [63]. These tools integrate sustainability rating criteria into BIM workflows but are oriented toward green certification rather than explicitly circular design outcomes.

Waste Analytics and Design Validation Tools. Akinade and Oyedele (2019) developed the A-WAS tool, an ANFIS-based waste prediction model integrated into Autodesk Revit, identifying gross floor area and construction type as the two key predictors of construction waste generation [40]. Won et al. (2016) demonstrated that BIM-based design validation could prevent 4.3% to 15.2% of construction waste that would otherwise have been generated through design errors [60]. Hexu Liu et al. (2018) presented a rule-based BIM system for boarding layout and material cutting optimisation in light-frame residential buildings, achieving material waste below industry benchmarks [39].

3.1.3 Theme 3: Performance Indicators and Metrics for Circular Design Integration

The included studies employ a heterogeneous set of performance indicators to evaluate circular design integration, which reflects the absence of a standardised indicator framework across the field. Indicators can be grouped into five broad categories.

Environmental Indicators. Global Warming Potential (GWP) expressed in kg CO_2-eq is the most universally reported environmental indicator across the corpus, appearing in LCA-oriented studies from China [10, 18, 25, 29], Hong Kong [17], South Korea [3], Portugal [12], and elsewhere. Waste generation, expressed variously as kg/m², tonnes per GFA, or as a percentage reduction relative to conventional construction, is the second most common environmental indicator [1, 2, 11, 30, 60]. Embodied energy (MJ) and abiotic depletion, acidification, eutrophication, ozone depletion, and photochemical ozone creation potentials appear in more comprehensive LCA studies that report a full set of midpoint impact categories [10, 12, 27, 53, 54]. Fragkoulis Kanavaris et al. (2024) focus exclusively on embodied carbon per building, reporting potential reductions of 40% for residential

and 29% for office buildings in a transition scenario, rising to 55% and 61% respectively in an ambitious scenario, using PECC and BS EN 15978 [4].

Economic Indicators. Construction cost and incremental cost are the most commonly reported economic indicators across the corpus, particularly in Chinese studies addressing the cost premium of prefabricated construction. Yuan Qi et al. (2018) calculated an incremental cost of 654.58 yuan/m² (43.7% of total construction cost) for a Shanghai prefabricated project [34]. Hanbyeol Jang et al. (2022) found modular construction in South Korea to be approximately 8% more expensive than conventional reinforced concrete in direct construction cost terms, despite achieving a 36% reduction in embodied carbon emissions [3]. Vargas et al. (2025) reported a 6% overall cost reduction for fully off-site construction in Brazil [16]. Tianyao Ping et al. (2026) found a 7% unit cost reduction and 40% lower cost for the modular area in a Hong Kong steel modular project [23]. Life cycle cost (LCC) frameworks that extend beyond construction costs to include operation, maintenance, and end-of-life are employed by fewer studies, with Abouhamad et al. (2019) and Carvalho et al. (2021) providing notable examples using ISO and EN 15978/15686-5 standards respectively [12, 35].

Technical and Deconstructability Indicators. Score-based composite indicators for deconstructability and circularity represent a distinct cluster within the literature. The BIM-DAS score (0 to 1) [5], the Atta et al. (2021) deconstructability, recovery, and environmental scores (0 to 1) [7], and the B-CAT material efficiency and disassembly potential scores [13] all attempt to reduce complex circularity concepts to a single or small set of normalised scores suitable for design-stage comparison. Cavalliere et al. (2019) propose six BIM-based flexibility metrics (three distance-based and three percentage-based) to quantify functional flexibility [41]. Baienat et al. (2026) propose the Adaptation Intensity Index (AII) and Circular Adaptability Performance (CAP) index to link adaptability with circular outcomes including material retention and embodied carbon reduction [21].

Social Indicators. Social indicators receive substantially less attention than environmental or economic ones across the corpus. Wei Pan and Zhiqian Zhang (2023) measure safety (accident rate), welfare of employees (training opportunities), and impacts on the local community (delivery trips) [1]. Tianyao Ping et al. (2026) report a 62% reduction in vehicle movements and zero accidents for the steel modular case study [23]. Ali Tighnavard et al. (2026) include a formal Social Life Cycle Assessment (SLCA) in their framework, covering workers, local communities, society, and consumers [17], although social indicators are rarely quantified with the same precision as environmental or economic ones.

Functional Units and System Boundaries. Functional units are inconsistently reported across the corpus: many studies normalise per m² of gross floor area [3, 23–25, 27, 30, 34], while others report per building [4, 35] or per project [11], and several do not report a functional unit at all [5, 7, 15, 16].

System boundaries vary from manufacturing-only or cradle-to-gate [3, 4, 15, 25] to whole-lifecycle or cradle-to-grave [1, 9, 10, 17, 21]. This heterogeneity in functional units and system boundaries significantly limits cross-study comparability of reported performance values, a pattern that has been noted as a fundamental methodological challenge in BIM-LCA integration [19].

3.1.4 Theme 4: Stakeholder Roles, Priorities, and Conflicts in Circular Design Implementation

Across the corpus, a consistent set of stakeholders is identified as relevant to circular design integration in prefabricated and modular construction: government and regulatory bodies, developers and clients, designers and architects, contractors and builders, manufacturers and component suppliers, and end-users or communities. However, the alignment of their priorities is frequently identified as a source of tension rather than convergence.

The most frequently documented conflict in the literature is between the incremental cost of prefabrication or circular design and the financial expectations of developers. Xiaojuan Li et al. (2020) model this using evolutionary game theory, showing that the key to promoting prefabricated building projects is to increase the incremental income of developers, which requires either government subsidies or sufficiently large policy incentives [31]. Yanhu Han et al. (2023) demonstrate through system dynamics modelling that compulsory policies are most effective in early stages of prefabricated building market development, while preferential and encouraging policies become more effective in middle and later stages, requiring a carefully managed policy transition to sustain market momentum [22]. Zhao Xu et al. (2019) note that Singapore has developed a relatively effective policy system to promote modular construction, including Construction Innovation and Technology Fund (CITF) and Construction Procurement Certification Fund (CPCF) mechanisms, in contrast to mainland China and Hong Kong where authoritative specifications remain absent [32]. Sheetal Gounder et al. (2026) identify, in the Australian context specifically, that the critical barriers to sustainable materials use are cost and profit considerations, unwillingness of key stakeholders to incorporate these materials, and lack of incentives and government policies, with techno-economic considerations identified as the main barrier factor through multinomial regression analysis [20].

Manufacturers face distinct priorities including intellectual property protection for proprietary modular systems [32], while contractors focus on site logistics, supply chain integration, and the management of transportation constraints for large precast elements [16]. Baienat et al. (2026) note that practitioners have limited awareness of adaptability strategies, and their framework attempts to address this through a consolidated set of criteria as an accessible design reference [21]. Designers, noted as key circular design decision-makers, are impeded by the late-stage conduct of sustainability assessments and the absence of integrated tools that provide real-time circular performance feedback

at early design stages [8, 12].

Rabia Charef et al. (2020) identify 35 BIM uses with potential to foster circular economy adoption, based on literature review and interviews with 20 experts, including seven new BIM uses identified from interview data: digital model for supported end-of-life, material passport development, project database, data checking, circularity assessment, materials recovery processes, and materials bank [8]. This finding underscores that the BIM platform itself is under-utilised for end-of-life and circular economy purposes, despite its technical capacity.

Stakeholder engagement approaches documented in the literature range from expert interviews and Delphi surveys [33, 34] to focus group meetings [23] and user-based tool evaluation sessions [13]. The mixed-methods Delphi-ISM approach employed by Rashid Maqbool and Haritha Narayanan (2026) in the UK context finds that BIM and circular economy implementation together positively support sustainable construction, while lean construction's role is statistically uncertain, with a discrepancy between quantitative and qualitative findings for this construct [33]. Adetayo Onososen and Innocent Musonda (2022) use interpretive structural modelling to rank barriers to BIM-based life cycle sustainability assessment, identifying lack of client and top management interest and absence of statutory regulations as the most fundamental drivers of non-adoption [19].

3.1.5 Theme 5: Technology Integration—BIM as an Enabling Platform

BIM is the dominant technological platform across the corpus, functioning variously as a data repository, an interoperability interface, a design automation engine, and a sustainability assessment hub. The primary BIM authoring tool referenced across studies is Autodesk Revit, supplemented by Dynamo for parametric scripting and automation [7, 10, 12, 15, 44]. Industry Foundation Classes (IFC) serve as the primary open data exchange format for interoperability between BIM and analytical tools [13, 14, 53, 63].

The integration of BIM with LCA tools is documented as a technical challenge requiring standardised data exchange protocols. Theißen et al. (2020) demonstrate that only 5.5% of 7,312 BIM objects for building services could be linked directly with LCA datasets without adaptive interventions, and six solution approaches were required to achieve a 94.5% linkage rate, revealing significant interoperability gaps in current open BIM practice [53]. Adetayo Onososen and Innocent Musonda (2022) identify lack of expertise, interoperability issues between BIM tools and LCA software, and region-oriented database limitations as key barriers to BIM-based lifecycle sustainability assessment [19].

Digital automation extends beyond LCA linkage to encompass automated quantity take-off [61], automated LEED credit calculation using K-Nearest Neighbour data mining [59], AI-based waste

prediction using ANFIS neural networks [40], generative design algorithms for rapid exploration of modular design options [15, 44], and rule-based model checking using Business Rule Management Systems and Drools rule language [66]. Vincent Gan (2022) demonstrated that BIM-based generative design could produce 1,000 to 1,500 new design options in approximately 30 minutes, with the best options achieving 30% lower carbon footprint and construction cost than reference buildings from the literature [15].

The 5D BIM concept—integrating three-dimensional geometry, time (4D), and cost (5D)—is applied by Xiaojuan Li et al. (2025) to monetise environmental impacts into spatiotemporal cost distributions, and by Gouda et al. (2024) to integrate Value Engineering with real-time cost modelling [27, 57]. Material passports, identified by Charef et al. (2020) and Atta et al. (2021) as a key BIM use for circular economy, embed end-of-life and recovery information into BIM objects, enabling automated retrieval during deconstruction planning [7, 8]. Baienat et al. (2026) propose a Digital Adaptability Passport embedded within the IFC schema as a mechanism for encoding adaptability and circularity information for long-term lifecycle management [21].

3.1.6 Theme 6: Implementation Strategies and Policy Considerations

Implementation strategies documented across the corpus cluster around three levels: project-level technical adoption, organisational process change, and policy and regulatory enablement.

At the project level, the literature consistently identifies early-stage design integration as the critical intervention point for circular outcomes. Prefabrication decisions made during the conceptual or schematic design stage have the greatest influence on achievable deconstructability, waste reduction, and embodied carbon performance, while late-stage changes incur higher costs and reduced effectiveness [9, 10, 12, 49]. Several studies propose phased implementation pathways: Yanhu Han et al. (2023) demonstrate through scenario simulation that policy interventions should transition from compulsory to preferential to encouraging as market maturity increases [22]; Shu Su et al. (2024) show that different prefabrication rates correspond to different optimal component combination schemes, with construction cost and carbon emission curves following non-linear trajectories as prefabrication rate increases [29]; and Yifan Dong et al. (2025) identify an optimal prefabrication rate range of 3.8% to 10.6% within which carbon reduction is achieved without excessive cost escalation, with both cost and carbon increasing above the 10.6% threshold [18].

At the organisational level, training and capacity building for BIM-based circular design tools is consistently identified as a prerequisite for adoption [5, 6, 10, 40, 46]. Alaa Mohammed et al. (2024) recommend extensive training and education as the primary enabling strategy for BIM for Deconstruction (BIMfD) deployment [6]. Lan Luo et al. (n.d.) identify the standardisation degree of building designs as the most influential controllable factor for prefabricated building cost reduction,

recommending the adoption of EPC contracting modes to facilitate efficient communication among project units [26]. Na Lou and Jingjuan Guo (2020) rank the degree of design standardisation as the most influential cost driver, followed by unit price, prefabrication rate, information technology level, and transportation mode [28].

At the policy level, multiple studies identify regulatory requirements as the initial driver for prefabricated building adoption, particularly in the Chinese context where mandatory assembly rate requirements shape developer decisions [22, 24]. Zhao Xu et al. (2019) note that Singapore's policy system—including specific fund mechanisms, Integrated Construction and Prefabrication Hubs (ICPHs), and authoritative technical specifications—provides a more enabling environment than currently exists in mainland China or Hong Kong [32]. In the Australian context, Gounder et al. (2026) find that overcoming barriers to sustainable material adoption requires coherent effort at project, industry, and policy levels simultaneously, including central databases for sustainable materials, integration of sustainability into professional education curricula, and government-facilitated incentive mechanisms [20].

3.2 Synthesis

3.2.1 Reconciling the Cost-Circularity Tension

The most pervasive apparent contradiction across the included studies is between the environmental benefits of prefabrication and circular design on one hand, and their economic costs on the other. Multiple studies confirm that modular and prefabricated construction commands an initial cost premium over conventional cast-in-situ construction: Jang et al. (2022) found an 8% cost increase for modular construction in South Korea despite a 36% embodied carbon reduction [3]; Yuan Qi et al. (2018) calculated a 43.7% incremental cost premium for a prefabricated project in Shanghai [34]; and Zhao Xu et al. (2019) reported cost premiums of 15–25% for volumetric prefabricated construction in Singapore and Hong Kong [32]. Yet other studies in the same corpus report cost savings: Vargas et al. (2025) found a 6% overall cost reduction in Brazil [16]; Tianyao Ping et al. (2026) found a 7% unit cost reduction in Hong Kong [23]; and X L Zhu and H Zhang (2018) reported that prefabricated residential buildings were less costly than traditional concrete buildings in their Chinese case study [38].

This apparent contradiction can be resolved through careful attention to scale, market maturity, and what costs are included. The studies reporting cost premiums predominantly reflect early-stage markets with limited manufacturing scale, high transportation costs, and immature supply chains—the conditions documented for China in the 2018–2022 period and for Singapore's transition to MiC. Lan Luo et al. (n.d.) model this explicitly using Fuzzy Cognitive Maps, demonstrating that scale effect

is the most influential factor driving prefabricated building costs downward, constituting the root cause of high costs in immature markets [26]. Na Lou and Jingjuan Guo (2020) confirm this through system dynamics modelling, identifying market scale and standardisation as the dominant cost levers [28]. Studies reporting cost savings, by contrast, typically involve more mature markets, higher prefabrication rates, or include whole-lifecycle cost savings from reduced labour, faster construction, and reduced waste disposal [16, 23]. This pattern suggests that the cost-circularity tension is transitional rather than fundamental: it reflects the current state of market development rather than an inherent property of circular design in precast systems.

3.2.2 Explaining Heterogeneity in Environmental Performance Findings

A secondary contradiction concerns the environmental performance of prefabrication. Several studies demonstrate net environmental benefits across multiple impact categories [10, 25, 30], while others show that prefabrication increases certain impacts. Yingbo Ji et al. (2026) find that prefabricated construction demonstrates environment-friendly performance with the exceptions of acidification and mineral resource consumption [25]. Yifan Dong et al. (2025) show that four of seven prefabricated component types exhibit higher carbon emissions per unit volume of concrete than their cast-in-situ counterparts, with composite floor slabs reaching 86.2 kg CO_2/m^3 compared to cast-in-situ equivalents, and that carbon reductions are only achieved within an optimal prefabrication rate range of 3.8–10.6% [18]. Hanbyeol Jang et al. (2022) find a 36% reduction in embodied carbon for modular construction, but their assessment is limited to the production phase and uses a cradle-to-gate boundary [3].

The mechanism resolving these divergent findings is system boundary selection combined with component-level versus building-level aggregation. Studies measuring only production-phase carbon at the component level frequently find that prefabricated concrete components are more carbon-intensive than cast-in-situ equivalents due to factory energy use, additional reinforcement, and transportation [18]. Studies using whole-lifecycle boundaries that include use-phase savings from better thermal performance, reduced maintenance, and end-of-life recovery consistently find net environmental advantages for prefabricated systems [10, 17]. Ali Tighnavard et al. (2026) are particularly instructive here: at the production stage, concrete has lower emissions than steel, but over the whole lifecycle, including maintenance and end-of-life recycling credits, steel outperforms concrete because steel recycling offsets 30% of production embodied energy while concrete landfilling provides no benefit [17]. This finding has direct implications for the design of a circular indicator framework: production-stage metrics alone are insufficient and may actively mislead circular design decisions for precast concrete systems.

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3.2.3 The Measurement Standardisation Gap and Its Implications

A third contradiction lies between the proliferation of assessment tools and frameworks documented in this corpus and the persistent absence of a standardised approach. The 67 included studies collectively present at least 20 distinct bespoke frameworks or tools (BIM-DAS, D-DAS, B-CAT, A-WAS, BIMEELCA, PARADIS, BIM-CDW Info Model, GBAT, Green Template, IMOMA, etc.), each demonstrating feasibility in a single or small number of case studies, yet none achieving demonstrated uptake across the broader construction industry. The confidence assessments for benchmarking information range from high to low, with many studies rated medium due to missing functional units or ambiguous system boundaries [7, 9, 13, 16, 25, 41].

This fragmentation has a clear mechanistic explanation: the construction industry operates in highly context-specific regulatory, climatic, and market environments, and the dominant BIM platforms have not standardised the data schemas required for circular design information exchange [19, 53]. IFC remains the most promising open standard for cross-platform data exchange, but as Theißen et al. (2020) demonstrate, even within an IFC-based workflow, 94.5% of BIM objects required adaptive interventions before they could be linked with LCA data [53]. The B-CAT tool (Jiang et al., 2025) and the IFC-based BIM-CDW Info Model (Schamne et al., 2024) represent the most recent attempts to address this through open-standard, platform-independent circularity assessment, but both are prototypical tools validated in single case studies in the Netherlands and Brazil respectively [13, 14].

For the Australian construction context specifically, where Gounder et al. (2026) document that techno-economic considerations constitute the primary barrier factor to sustainable material adoption [20], this measurement fragmentation has a practical implication: without standardised indicators with agreed functional units, system boundaries, and reporting formats, cost-benefit comparisons across different precast circular design strategies cannot be made reliably, reinforcing developer reluctance to invest in circular design measures whose returns cannot be confidently quantified. The absence of Australian-specific case studies in this corpus—beyond the barrier analysis of Gounder et al. (2026)—means that the performance values reported (e.g., waste reduction percentages, embodied carbon savings, cost premiums) cannot be assumed to transfer directly to the Australian regulatory environment, supply chain structure, or construction market conditions without dedicated validation.

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